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# Non-conscious processing, attentional amplification and conscious access : experimental investigations in healthy controls and patients with schizophrenia

Lucie Berkovitch

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Lucie Berkovitch. Non-conscious processing, attentional amplification and conscious access : experimental investigations in healthy controls and patients with schizophrenia. *Neurons and Cognition [q-bio.NC]*. Sorbonne Université, 2018. English. NNT : 2018SORUS405 . tel-02885981

**HAL Id: tel-02885981**

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Sorbonne Université

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*Neurospin / Unicog*

**Non-conscious processing, attentional amplification  
and conscious access:**

***Experimental investigations  
in healthy controls and patients with schizophrenia***

Par Lucie Berkovitch

Thèse de doctorat de Neurosciences

Dirigée par Stanislas Dehaene et Raphaël Gaillard

Présentée et soutenue publiquement le 23/11/18

Devant un jury composé de :

Jardri Renaud, Rapporteur  
Uhlhaas Peter, Rapporteur  
Sergent Claire, Examineur  
Sitt Jacobo, Examineur  
Dehaene Stanislas, Examineur  
Gaillard Raphaël, Examineur



*A mes proches*



## Remerciements

De 26 à 30 ans, quatre années à faire de la recherche. Une sacrée parenthèse dans une vie d'interne. Une épopée. La découverte d'un nouvel univers, de personnalités hors du commun et d'une parcelle méconnue de l'Ile de France. De nombreux événements professionnels et personnels aussi. Autant de choses qui font, en quelque sorte, partie de ce manuscrit.

Je tiens à remercier Stanislas Dehaene, qui m'avait, il y a fort longtemps, inspirée dans ses cours du collège de France et qui m'a fait l'honneur de m'accueillir, m'accompagner et m'encadrer dans mon travail, son œil rieur et sa moue dubitative, sa connaissance encyclopédique, son goût pour la transmission, son énergie et son pragmatisme. J'ai eu une chance inouïe de pouvoir travailler à tes côtés, tu m'as beaucoup appris et j'espère avoir été à la hauteur.

Je remercie Raphaël Gaillard qui m'a attirée sur le chemin accidenté de la recherche en psychiatrie, aux confins de la folie, de la science et de la philosophie. La force de nos affinités intellectuelles n'a d'égal que l'intensité de nos divergences politiques. Espiègle derrière ton air autoritaire, tu m'as parfois poussée dans mes retranchements pour affuter mon esprit critique. Nos échanges ont toujours été incroyablement stimulants et enrichissants et j'espère que cette émulation durera.

Je remercie Claire Sergent, Renaud Jardri, Jacobo Sitt et Peter Uhlhaas d'avoir accepté de faire partie de mon jury. Vous êtes, les uns et les autres, des références dans le champ des neurosciences de la conscience ou de la schizophrénie. C'est avec crainte et hâte que j'attends vos avis sur mon travail.

Je remercie la Fondation pour la Recherche Médicale et l'Année recherche qui ont financé ma recherche et m'ont accordé leur confiance, ainsi que l'INSERM, avec qui j'ai dû batailler, mais qui m'a finalement grassement payée.

Je remercie Maxime Maheu, mon mystérieux ami et collaborateur. Tu es sans nul doute la personne avec qui j'ai passé le plus de temps ces dernières années et tu as été un modèle pour moi dans la recherche. Sans toi, je n'en serai probablement pas venu à bout, tu m'as si souvent sortie d'impasse. Rigoureux au travail, incouchable dans la vie, j'aime nos discussions qui se

décourent au fil de la nuit, notre goût commun pour la contemplation esthétique et surtout ta consternation amusée quand je raconte ou fais n'importe quoi, ce qui, cela va sans dire, est un dangereux pousse-au-crime.

Je remercie Fosca Al Roumi, amie et collègue, pour son enjouement inaliénable, son goût pour la bonne chère et la fête, ses attentions généreuses qui ont changé le visage du labo pour en faire un lieu de partage familial plus qu'un lieu de travail. Ta curiosité et ton émerveillement permanents sortent le monde de sa banalité et je n'oublierai pas ces pauses café censées durer 10 minutes, s'étirant finalement sur la longueur de l'après-midi, entre confessions intimes et récits d'anecdotes exaltés.

Je remercie mes autres copains et collègues du labo : Gaël, génie un peu fou, trublion-geek de Neurospin, nos discussions sur les voyages et les sports extrêmes, ton rire sonore, tes fins de soirée que je ne qualifierai pas. Pedro, ton hédonisme et ton sourire malicieux à l'évocation des bonnes choses de la vie. Marie, pour tes moments de joie et de tristesse, avec toi, tout événement devient une mésaventure souvent drolatique et tout secret, une annonce officielle. Florent, allure discrète et regard coquin, parfois un peu bougon, mais le plus souvent bien trop tolérant à mon humour bancal. Josselin, pour ta bonhomie, ta sympathie, et le temps infini que tu m'as laissé pour écrire un unique article. Darinka, Laetitia, Benoît, Baptiste, Martin, Tadeusz qui étaient là à mon arrivée au labo et m'ont chaleureusement accueillie. Sébastien, qui m'a donné un bon coup de main et avec qui on a passé d'agréables soirées dans l'air de Pékin, je croise les doigts pour toi. Milad, improbable garnement. Chantal, les deux Séverine, Véronique, Laurence et Gaëlle pour leur bonne humeur et leur aide lors de mes manip. Leila, Evelyn, Christophe, Ghislaine, Virginie, François, Antonio, Marie, Bianca, Charles, Théo, Mathias, Pauline, Ana, Anna, Edouard, Vanna, Laurence pour leur aide, conseil, présence.

Je remercie mes collaborateurs hors les murs : Antoine Del Cul qui a bien voulu me laisser exploiter ses données et avec qui je prends toujours plaisir à discuter, Alexandre Salvador, pour sa bienveillance et sa capacité à supporter mes relectures obsessionnelles, Fabien Vinckier, pour sa franchise, sa gentillesse et ses conseils avisés en matière de whisky, Lionel Naccache, pour sa sympathie et son inventivité inspirante, Valentin Wyart qui s'est toujours montré ouvert et de bon conseil. Je remercie Isabelle Brunet pour son efficacité et sa disponibilité lorsqu'on veut organiser des passations à l'ENS, Jean-Rémi King et Lucie Charles pour leur rapidité à répondre à mes problèmes par mail.

Enfin, je remercie ma famille et mes amis qui ont été à mes côtés tout au long de ces années, mon père qui m'a laissée en cours de route, j'aurai aimé que tu sois là, Damien avec qui j'ai partagé ma vie les premières années. Je remercie en particulier les personnes qui m'ont logée, nourrie, blanchie, soutenue, lors de mes longues heures de rédaction et alors que je n'étais guère fréquentable. Amélie Charvériat et ses parents et neveux en Bretagne, à faire des pâtés de sable avant de s'assourdir dans un festival régressif. Morgan Verdeil et sa famille au sens corse du terme : parents, sœur, oncles, cousins, copains, dans cette nature sauvage et intimidante, je m'y suis sentie comme chez moi. Ma mère, mes deux frères, vous êtes mes trésors, Denise, Pierre, Pascal, Marta et Edouardo à l'Ile de Ré, mon île, celle de mon père, ses balades à vélo et ses baignades glacées qui sentent la fin de l'été.





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# Introduction

Consciousness is a multifaceted concept that may refer to a state of wakefulness, to the phenomenology of being aware of something or to the ability to generate and maintain accessible and reportable mental representations. Conscious representations can emerge in response to an external object or come to mind without any stimulation, for example when retrieving memories or dreaming. The nature and the causes of consciousness constitute a fundamental topic in philosophy and science. However, consciousness corresponds in essence to a subjective experience and the first method used to explore it was introspection, which seems at first glance incompatible with a scientific approach.

## Is consciousness a scientific object?

### Is consciousness material?

A first obstacle to scientific study is that consciousness was long considered as immaterial. Indeed, relying on our subjective feelings, it seems that our consciousness and thoughts are intangible, contrary to our body. In the seventeenth century, Descartes attempted to demonstrate that consciousness had a different nature from the body. In *Meditations of First Philosophy*, he applied methodical and hyperbolic doubt, and noted that being conscious of ourselves was the only thing that could not be called into question.

« *Y a-t-il rien de tout cela qui ne soit aussi véritable qu'il est certain que je suis, et que j'existe, quand même je dormirais toujours, et que celui qui m'a donné l'être se servirait de toutes ses forces pour m'abuser ? Y a-t-il aussi aucun de ces attributs qui puisse être distingué de ma pensée, ou qu'on puisse dire être séparé de moi-même ? Car il est de soi si évident que c'est moi qui doute, qui entends, et qui désire, qu'il n'est pas ici besoin de rien ajouter pour l'expliquer.* »

He drew two conclusions from this thought experiment: 1) our self is defined by the subjective experience of thinking: *cogito ergo sum*; 2) mind and body are different in nature and are fully dissociable. In particular, the former is delimited in space whereas the latter is



immaterial (Descartes, 1993). Obviously, if consciousness is not reducible to a material substance, it cannot be fully apprehended by scientific physical methods.

Nevertheless, progress in medicine and science gradually shed light on links between cognition and brain. In 1747, La Mettrie wrote a book entitled *Man a Machine*, in which he rejected Descartes introspective method and intended to reinstate an empirical approach to solve the mind-body problem. He studied physical properties of organs and noticed that mental states were accompanied by physical modifications. For instance, some emotions can be associated with sweat, increased heart rate, etc. From these observations, he concluded that states of mind should rely on physical properties of the organism, a theory termed as mechanical materialism (de La Mettrie, 1748).

In the beginning of the nineteenth century, Flourens conducted experiments on rabbits and pigeons and showed that localized brain lesions had an impact on the sensibility, the motricity and the behaviour (Flourens, 1842). Broca then extensively investigated aphasia and found that a specific region in the left frontal lobe was involved in language production (Broca, 1861). In the twentieth century, technical development of neuroimaging and neurostimulation provided precise descriptions of neuroanatomy and confirmed the strong correlation between mental states and cerebral activity. A striking example of this progress is the discovery that temporal cortex could be functionally divided into several subparts dedicated to precise visual-categories, such as faces or words (Cohen et al., 2000; Kanwisher et al., 1997). Within these areas, single neurons selectively fired in response to images depicting specific categories of objects (Kreiman et al., 2000). Remarkably, their activation depended on the abstract representation of the object rather than the sensory input itself. For instance, very different pictures of a celebrity and even his/her written name were sufficient to induce the very same pattern of activation (Quiroga et al., 2005). These results suggested that mental representations are implemented in the brain and paved the way to the study of neural signatures of conscious perception.

### **Are subjective reports reliable?**

Even accepting that consciousness is underpinned by brain circuitry, the simple fact that it does not fit our subjective feelings raises a second problem, namely the trustworthiness of subjective reports. One of the main reasons of this feeling of immateriality is the impossible reflexivity towards conscious processing. Indeed, we are deeply and permanently embedded

into our conscious representations. We do not access anything but them and do not consciously perceive the processes they originate from (Crick et al., 1990; Nisbett et al., 1977).

Interestingly, the question of materiality is quite dissociable from the notion of agency. Indeed, we distinctly perceive our body as belonging to ourselves and nevertheless do not have any problem to consider it as material. A crucial difference between body and consciousness is that many body parts directly interact with the outside. Accordingly, a causal link between these interactions and sensations appears obvious. For body parts that are not in contact with the outside, we usually perceive their materiality (and sometimes even their existence) when their states change. For instance, a feeling of pain can undoubtedly awaken awareness of some hidden parts of our organism. By contrast, we cannot compare times when we are conscious to times where we are not. Fluctuations of consciousness can at most induce distortions of perception, e.g. auras before a seizure or psychotic-like symptoms under drugs, but most of the time, we are totally blind to the variations in our consciousness level and do not notice that we are distracted or falling asleep.

Thus, subjective reports of conscious states seem quite inoperable in science. Furthermore, it was shown that they could be easily manipulated or influenced by an experimenter. In a funny experiment (Johansson et al., 2005), participants were presented with two cards representing faces and were asked to choose the one they found the most attractive. By a magic trick, the card they picked was replaced by the one they rejected. Most participants did not notice that the cards had been swapped and explained without batting an eyelid, the reasons why the face they did not choose was more attractive than the other one!

To avoid pitfalls of subjective introspection, behaviourists, like Watson and Skinner, focused their psychological studies on behaviour. They argued that conscious representations should be investigated from an external point of view to avoid any bias (Skinner, 2011; Watson, 1913). Nevertheless, conscious representations cannot be directly observed by an experimenter: they are personal and private. Thus, behaviourists considered that consciousness should rather be excluded from psychology studies.

*“An organism behaves as it does because of its current structure, but most of this is out of reach of introspection. At the moment we must content ourselves, as the methodological behaviorist insists, with a person's genetic and environment histories. What are introspectively observed are certain collateral products of those histories.”*

*“Psychology as the behaviorist views it is a purely objective experimental branch of natural science. Its theoretical goal is the prediction and control of behavior. Introspection forms no essential part of its methods, nor is the scientific value of its data dependent upon the readiness with which they lend themselves to interpretation in terms of consciousness.”*

Watson, *Psychology as the Behaviorist Views It*

Alternatively, subjective reports can be considered as full-blown observations that have to be scientifically explained, in particular when they are discrepant with reality. Following Wilhem Wundt and William James, Baars believed that consciousness was an unavoidable topic in psychology. In the preface of *A Cognitive Theory of Consciousness* (1993), he says:

*“In truth, the facts of consciousness are all around us, ready to be studied. Practically all psychological findings involve conscious experience. Modern psychologists find themselves in much the position of Moliere's Bourgeois Gentleman, who hires a scholar to make him as sophisticated as he is wealthy. Among other absurdities, the scholar tries to teach the bourgeois the difference between prose and poetry, pointing out that the gentleman has been speaking prose all his life. This unsuspected talent fills the bourgeois gentleman with astonished pride - - speaking prose, and without even knowing it! In just this way, some psychologists will be surprised to realize that they have been studying consciousness all of their professional lives. The physicalistic philosophy of most psychologists has tended to disguise this fundamental fact, and our usual emphasis on sober empirical detail makes us feel more secure with less glamorous questions. But a psychologist can no more evade consciousness than a physicist can side-step gravity.”*

Along with the development of scientific study of consciousness, researchers and philosophers investigated the reasons why consciousness gave such the impression to be immaterial or irreducible to brain structures. According to Chalmers (1995), it remains inexplicable that vivid and subjective aspects of conscious experience, the qualia, emerge from brain structure. This constitutes the “hard problem” of consciousness study.

*“It is undeniable that some organisms are subjects of experience. But the question of how it is that these systems are subjects of experience is perplexing. Why is it that when our cognitive systems engage in visual and auditory information-processing, we have visual or*

*auditory experience: the quality of deep blue, the sensation of middle C? How can we explain why there is something it is like to entertain a mental image, or to experience an emotion? It is widely agreed that experience arises from a physical basis, but we have no good explanation of why and how it so arises. Why should physical processing give rise to a rich inner life at all? It seems objectively unreasonable that it should, and yet it does.”*

Chalmers, *Facing Up to the Problem of Consciousness*

Qualia have previously been described as private and ineffable, suggesting that they were inaccessible to scientific study (Jackson, 1982; Levine, 1993; Lewis, 1956; Nagel, 1974). Specifically, Ned Block (1995) distinguished access-consciousness from phenomenal-consciousness. The former was characterized by its availability: its contents were verbally reportable, so it could be explored scientifically. By contrast, phenomenal-consciousness corresponded to qualia that were subjectively experienced but not verbally reportable because their content was too rich and “overflowed” access (Block, 1995).

This proposal has been vigorously opposed by Dennett and many other philosophers or neuroscientists, who argued that the hard problem is a conceptual problem that could be overcome by the discovery of the neural structures involved in consciousness, including those giving rise to subjective feelings (Bennett et al., 2003; Churchland, 1985; Crick et al., 1990; Damasio, 2000; Dehaene, 2014; Dennett, 2017, 2018; Kouider et al., 2010a).

## **How can we scientifically study consciousness?**

Contemporary scientific study of consciousness inherited from both introspectionism and behaviourism. Following behaviourism, it uses an objective approach of mental states and considers consciousness as reducible to brain structures, while borrowing to introspectionism, it gives a prominent place to subjective reports.

### **The contrastive method**

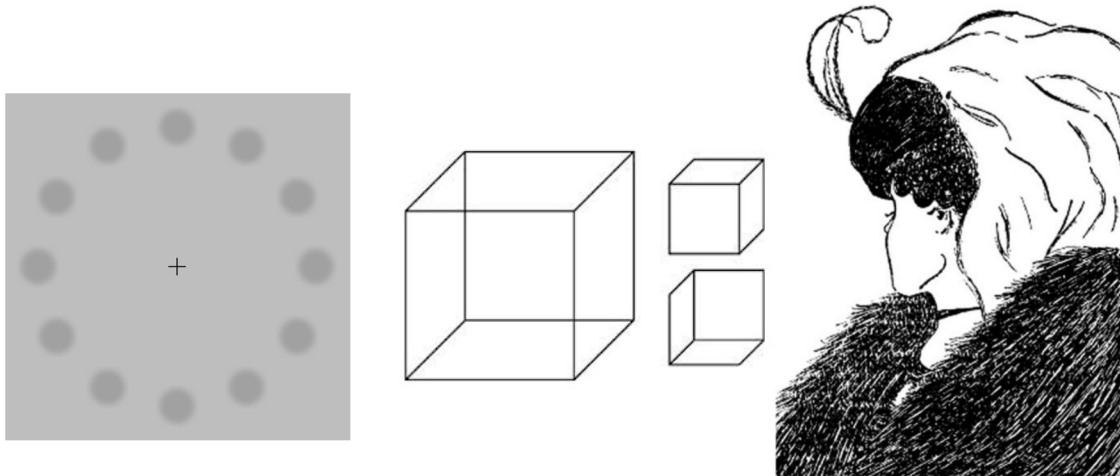
To scientifically study consciousness, to the experimenter has to control whether a participant will be conscious of a stimulus or not. Remarkably, scientists discovered that they could precisely manipulate perception and that some specific experimental conditions systematically prevented subjective perception. Following William James's book, *The Principles of Psychology* (1890), Baars proposed in 1988 a contrastive method to study

consciousness in his book *A Cognitive Theory of Consciousness*. It consisted in obtaining conscious and non-conscious perception from closely comparable or even similar stimuli. Subjective reports were therefore indispensable to contrast conscious and unconscious perception. By doing so, subjective reports were considered as full-blown experimental data and could be integrated into the objective study of consciousness.

Conscious access can be assessed in several ways: first, by the measure of objective performance in detecting the presence of a stimulus, i.e. the ability to say that it was present when it was indeed the case, or in identifying some of its properties (Merikle et al., 1998), second using a subjective visibility scale with which participants have to rank how much they saw the stimulus (Ramsøy et al., 2004; for a review of consciousness measures, see: Seth et al., 2008). Nevertheless, the use of subjective reports to study consciousness rests upon some conceptual premises. The first one is that there should be a physical difference between cases in which participants are able to perceive a stimulus and cases where they are not (Crick et al., 1990; Merikle et al., 1998). A second assumption is that mechanisms involved in consciousness should be independent of its contents and that there must be a common neural substrate to all conscious representations (Crick et al., 1990; Damasio, 2000; Dennett, 2017; Edelman, 1992).

### **Change subjective perception: how to render a stimulus subliminal?**

For a long time, visual illusions provided evidence that perception could fluctuate or be tricked. For instance, in Troxler's fading illusion (1804), staring at a central point makes peripheral circles randomly appear and disappear from sight (Figure 1). Similarly, ambiguous pictures can induce multiple or bistable perception, i.e. alternation between two or more percepts whilst the visual stimulus is constant (e.g. Necker's cube, 1832, "wife and mother-in-law" illusion, 1888, see Figure 1). Fluctuations in visual perception can also be obtained by presenting very different pictures to each eye, a phenomenon referred to as binocular rivalry (Porta, 1593). The brain cannot merge the two pictures so subjective perception alternates between the two images. Nevertheless, these ways of manipulating conscious perception were not sufficiently controlled: fluctuations in perception could occur at any time and varied between participants.



*Figure 1.* Examples of visual illusions and bistable perception. In the Troxler's fading illusion, staring at a central point makes peripheral circles randomly appear and disappear from sight. The cube presented in the middle can be seen with two possible orientations: with the lower-left or the upper-right square in the front. The wife and mother-in-law illusion can be interpreted either as a young girl looking away or an old woman in a profile view (the "wife" and the "mother-in-law", respectively).

More robust and reproducible psychophysics methods to render stimuli invisible were then developed. The most canonical one is probably visual masking (for a review see: Breitmeyer et al., 2006; Enns et al., 2000). A visual stimulus, the target, is briefly displayed on the screen and preceded and/or followed by another visual stimulus close in time and space, the mask, which interferes with target visibility. The mask can be contiguous to the target, i.e. metacontrast masking (Stigler, 1910) or overlapping it, i.e. pattern masking (Kinsbourne et al., 1962) (Figure 2). The effect of the mask on target visibility depends both on the type of mask and on the delay between the target and the mask (stimulus onset asynchrony, SOA) (Breitmeyer et al., 1976). With pattern backward masking, the visibility of the target increases with the delay between the target and the mask (Kinsbourne et al., 1962) while with metacontrast, masking strength is not monotonic as a function of target-mask delay (Kolers et al., 1960).

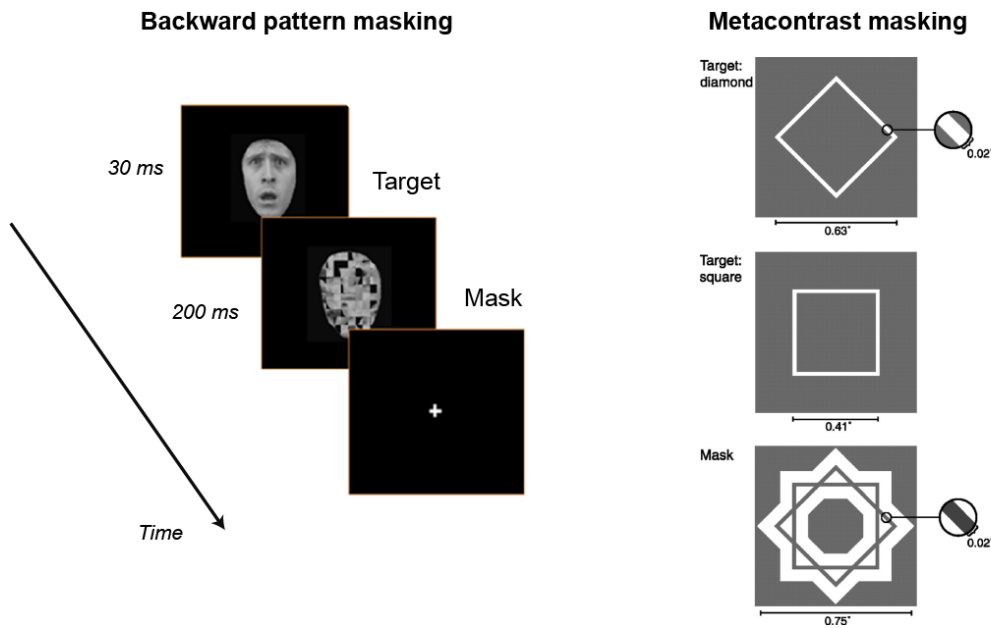
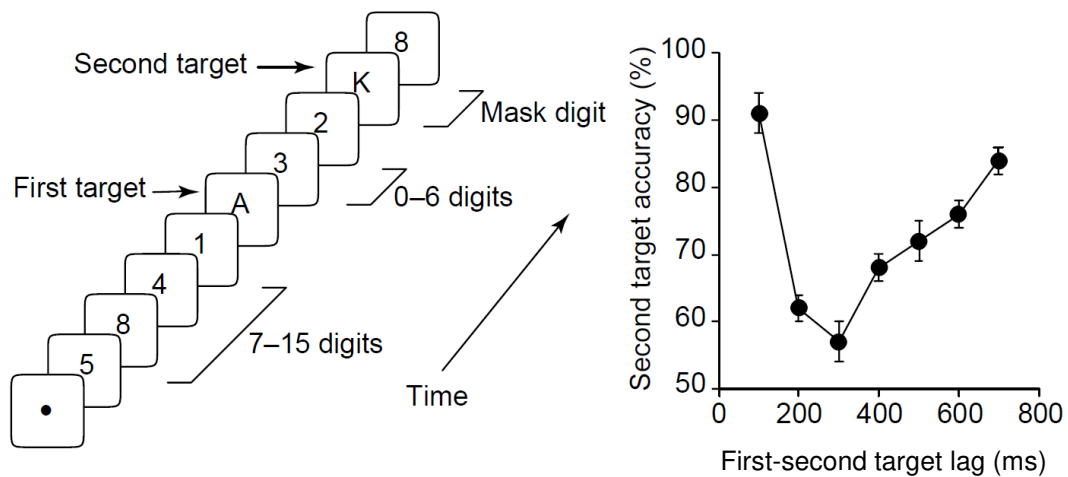


Figure 2. Examples of pattern and metacontrast masking. Left. In backward pattern masking, the target (here a face) is followed by an overlapping image. Right. In metacontrast masking, the mask surrounds the target shape without touching it. These masks hinder the conscious perception of the target.

Interestingly, metacontrast masking is more efficient when the stimulus is not presented in the centre of the visual field (Alpern, 1953). This phenomenon highlights the importance of spatial attention in the perception of a masked target: it is easier to consciously see a stimulus when attention is focused on it (Enns et al., 2000). Another masking technique called object substitution (Di Lollo et al., 1993), confirmed the crucial role of attention in conscious perception. A target and a surrounding mask are displayed on the screen at the same time. The target is then turned off while the mask remains on screen alone. The masking effect increases with the duration of the mask alone and with the number of possible locations for the target. In particular, masking is very weak or even inexistent if the target appears at a predictable location, suggesting that spatial attention is a key factor for conscious perception (Di Lollo et al., 2000).

Temporal attention also plays an important part in conscious perception. Shapiro and colleagues presented participants with a rapid stream of visual stimuli, e.g. letters or digits, and showed that the processing of a first target drastically reduced the detection of a second target displayed shortly after, a phenomenon termed as “attentional blink” (Raymond et al., 1992; Shapiro, 1991) (Figure 3). Because attention can be focused on one stimulus at a time, the second stimulus is either missed or perceived with a slight delay called the psychological

refractory period (Welford, 1952). Variants of attentional blink, such as inattention blindness (Rock et al., 1992; for a review, see: Simons, 2000; Simons et al., 1999) or change blindness (Grimes, 1996; O'Regan et al., 1999; for a review, see: Simons et al., 1997, 2005) also induce invisibility by distracting attention.



*Figure 3.* Example of attentional blink paradigm. Participants are asked to identify the two letters embedded in a stream of digit. They are perfectly able to identify the first one but when the lag between the two letters is around 300 ms, accuracy to detect and/or identify the second letter is drastically reduced (Enns et al., 2000).

Other masking techniques rely on a competition between two stimuli. In crowding, perception of a peripheral stimulus is impaired by contiguous stimuli that are more salient (Korte, 1923). In continuous flash suppression, flickering changing abstract patterns are projected into one eye and masked for a few seconds a picture projected into the other eye (Tsuchiya et al., 2005).

### **Neuropsychopathology contributions**

In parallel, clinical observations in neurology revealed that information reported as unperceived could influence patients' behaviour. Specifically, Gazzaniga (1967) extensively studied split-brain patients, i.e. patients whose connection between the two cerebral hemispheres, the corpus callosum, was surgically removed for neurological reasons. After the surgery, their left and right hemispheres could not communicate any more. Clinically, when



showing them a picture to the left visual hemifield (i.e., to the right cerebral hemisphere), they were not able to verbally report it, because language regions located in the left hemisphere were blind to what was perceived in the right hemisphere. Nonetheless, their behaviour indicated that they had processed the picture. Indeed, if they were presented with nude pictures in the left visual hemifield, they had emotional reactions such as smiling or chuckling, but were not able to explain it. Even more striking, other patients can have specific occipital lesions which provoke acquired blindness. Still, when they are asked to guess the shape or the location of a stimulus that they cannot see, their accuracy is far above chance (Pöppel et al., 1973; Weiskrantz et al., 1974). This dissociation between objective performance and subjective report is called “blindsight”.

## **What characterizes unconscious processing?**

### **Subliminal priming**

In the 70s, masking methods were used to investigate behavioural consequences of subliminal processing in healthy controls (Dixon, 1971; Marcel, 1983). In particular, visual masking was coupled with priming (Figure 4). As demonstrated by Meyer and Schvaneveldt, when two words are presented in succession, decisions on the second word are faster when the two words are semantically related than when they are not (Meyer et al., 1972). Similarly, in imagery, when related or similar stimuli are successively presented, cerebral activity evoked by the second stimulus is reduced in the cerebral area coding for the common features between the two stimuli (Desimone, 1996; Miller et al., 1991). This phenomenon, termed repetition suppression, suggests that less activation is needed to process the second stimulus because it has been primed by the first one. The same principle is applied in subliminal priming, except that the first stimulus is masked and therefore unconscious. Accordingly, by examining its effects on the subsequent stimulus, one can assess the depth of subliminal processing.

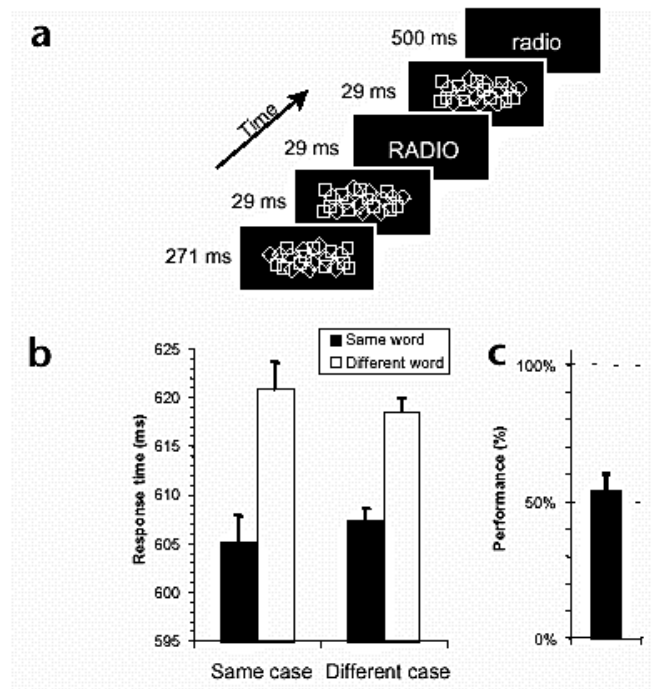


Figure 4. Subliminal priming. (a) The masked prime (“RADIO”) is followed by a visible target-word (“radio” in lower case). Participants had shorter response times to categorize the target when preceded by a consistent prime (b) but were unable to consciously perceive the prime (performance at chance-level in a forced-choice identification task (c)) (Dehaene, Naccache, et al., 2001).

### Richness and limits of unconscious processing

From that point, many experiments used masking or attentional manipulation to explore subliminal processing. It was shown that the brain could unconsciously process semantic (Dehaene, Naccache, et al., 1998, 2001; Van den Bussche et al., 2007, for a review, see: 2009), emotional faces and words (Naccache et al., 2005; Whalen et al., 1998), money values (Pessiglione et al., 2007), but could also calculate (Van Opstal et al., 2011), exert inhibitory control (Gaal et al., 2008), accumulate evidence (Vlassova et al., 2014), detect syntax errors (Batterink et al., 2013), monitor its own errors (Charles et al., 2013), use working memory (Trübtschek et al., 2017)... However, subliminal processing has limits. On the basis of the definition of conscious-access, information unconsciously perceived cannot be verbally reported. Nevertheless, some unconscious information can be transiently accessible. Sperling (1960) conducted an experiment in which participants were briefly presented with a  $3 \times 4$  matrix of letters. Immediately afterwards, they were asked to report as many letters presented in the matrix as possible (“whole report”). Participants were always able to report on average five

letters randomly distributed in the matrix. In a second version of the task, they were instructed after the matrix disappeared to report letters located in a specific row (“partial report”). Strikingly, participants performed perfectly at reporting any row, but this performance sharply decreased with time, suggesting that they accessed the whole matrix for a short duration but could not maintain that information over time (Gegenfurtner et al., 1993) (Figure 5).

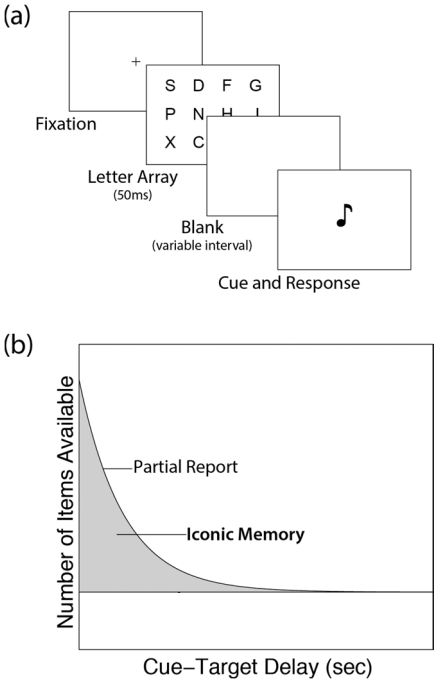


Figure 5. (a) Sperling experiment: a letter array is presented for a short duration and participants are asked to report any letter of the array (whole-report condition) or a specific row (partial report), (b) Number of items available in the partial report condition as a function of cue-target delay showing that ability to report any given row quickly decays with time (figure adapted from Baek et al., 2016).

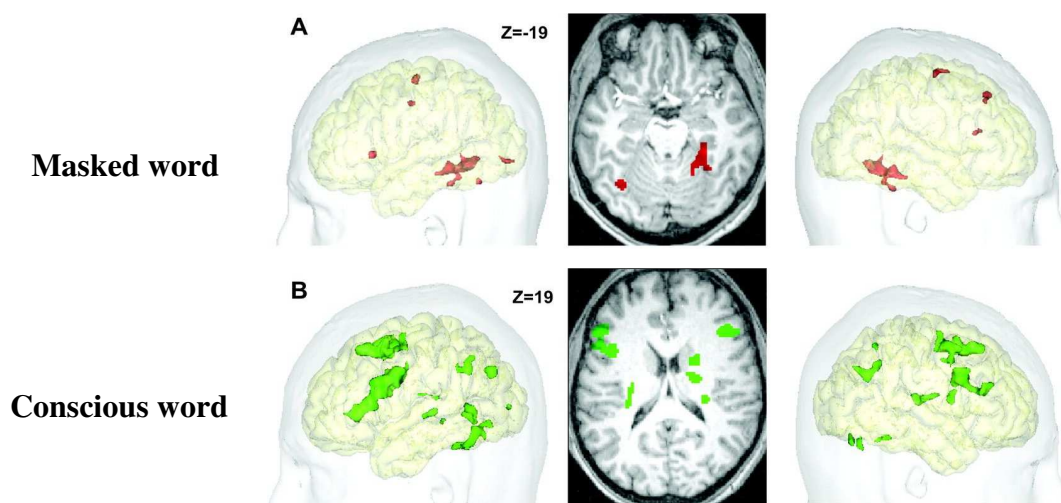
Another limit of unconscious processing concerns the generation of strategies. When genuine strategies should be applied to subliminal stimuli to succeed in a task, participants essentially reiterate the strategies applied to conscious stimuli (de Lange et al., 2011; Greenwald et al., 2003a; Merikle et al., 1995). Unconscious processing also fails to chain series of consecutive operations, probably because each stage cannot be stored before the subsequent one is performed (Sackur et al., 2009). To sum up, consciousness seems to be required to realize complex mental reasoning, to maintain information or to combine multiple cognitive functions.

## Cerebral activity of conscious versus unconscious processing

By contrasting seen and unseen trials while recording cerebral activity, neural correlates of consciousness could be progressively clarified.

In 1989 and 1996, Logothetis recorded neurons in monkeys exposed to binocular rivalry (Leopold et al., 1996; Logothetis et al., 1989). He found that some neurons, especially in V1, fired according to retinal stimuli whereas neuronal activity in V4 rather correlated with monkeys' subjective perception, suggesting that conscious representations may activate more anterior subparts of the visual cortex. Such a correlation between activity location in the visual cortex and subjective reports was replicated in humans with fMRI studies (Haynes et al., 2005; Polonsky et al., 2000; Tong et al., 1998).

In addition to this difference in location, various studies on subliminal processing evidenced that unconscious stimuli induced less intense, diffuse and sustained cerebral activity than conscious stimuli, e.g. in backward masking (Dehaene et al., 2001; Del Cul et al., 2007; Grill-Spector et al., 2000; Kouider et al., 2007), metacontrast masking (Lau et al., 2006) attentional blink (Marois et al., 2004; Sergent et al., 2005), change blindness (Beck et al., 2001), threshold stimuli (Carmel et al., 2006; Pins et al., 2003) (Figure 6).



*Figure 6.* Differences of cerebral activations between subliminal (A) and conscious words (B) in fMRI (Kouider, Dehaene, et al., 2007).

These findings were further investigated to explore how cerebral activity was influenced by factors that supposedly modulated conscious access according to behavioural studies. Del Cul et al. (2007) systematically varied the delay between a digit and a metacontrast mask (SOA) while recording brain activity by electroencephalography. They found that early cerebral activations in occipito-temporal regions were proportional to the SOA while the last components, in particular P3 in fronto-parietal areas, were elicited in an all-or-none fashion, i.e. absent when the digit was not seen, and present when the digit was seen.

Still, such results may be attributed to the differences in stimuli inputs for long and short SOA stimuli. To control for this parameter, Sergent et al. (2005) used attentional blink and manipulated participants' attention so that rigorously identical stimuli were sometimes seen and sometimes missed. Again, early potentials with similar amplitude were observable in posterior perceptual areas both for conscious and unconscious perception, suggesting that they essentially reflected visual stimulation, while central and frontal late components tightly correlated with subjective visibility.

Consistently, an activation of the fronto-parietal cortex was reproducibly observed for conscious trials only (Carmel et al., 2006; Dehaene, Naccache, et al., 2001; Del Cul et al., 2007, 2009; Gaillard et al., 2009; Lafuente et al., 2006; Lamy et al., 2008; Lau et al., 2006; Persaud et al., 2011; Salti et al., 2015; Sergent et al., 2005; van Vugt et al., 2018).

In addition, neurophysiological studies revealed that subjective perception was associated with transient synchronization of neuronal activity in distributed areas. Oscillating at a given frequency allows distant cerebral areas to communicate with each other. Such a synchronization was observed at gamma-band frequency ( $> 30$  Hz) for seen stimuli in many different paradigms like binocular rivalry (Doesburg et al., 2005; Tononi, Srinivasan, et al., 1998), visual masking (Fisch et al., 2009; Gaillard et al., 2009; Melloni et al., 2007), threshold stimuli (Wyart et al., 2008) and face detection in ambiguous pictures (Rodriguez et al., 1999). Synchronization at beta-band frequency (13–30 Hz) was also correlated to consciousness during attentional blink (Gross et al., 2004) and masking (Gaillard et al., 2009). Finally, other measures of information sharing and causal relations between cerebral electrodes were shown to be increased during conscious access (Gaillard et al., 2009; King, Sitt, et al., 2013).

Overall, contrary to subliminal processing conscious access seems to involve a broad activation of fronto-parietal regions and a synchronization of disseminated cerebral areas.

## **Consciousness properties and theoretical approaches of consciousness**

Many theoretical models of consciousness have been proposed (for a review, see: Seth, 2007) and a constant dialogue between theoretical models and empirical data allowed them to enrich each other. On the one hand, empirical findings shed light on consciousness properties and gave rise to new theoretical proposals, and on the other hand, some experiments were specifically designed to test models predictions.

### **Limited capacity and serial conscious processing**

First, behavioural experiments indicated that at least two conditions were necessary to consciously perceive a stimulus: 1) a sufficient duration of exposition, 2) the availability of attentional resources. Moreover, conscious information was processed serially: attentional resources could be devoted to one stimulus at a time and consciousness had a limited capacity.

Broadbent (1957) proposed a two-level model in which perceptual information was temporarily stored in parallel before being selected by attention to enter a unique limited-capacity sensory channel. Importantly, Broadbent listed several factors that may favour perception of a stimulus among multiple incoming information: timing (the first information to arrive is preferentially processed), intensity, availability of the limited-capacity channel, and relevancy.

This theoretical model accounts for many empirical findings, such as masking (Enns et al., 2000), attentional blink (Raymond et al., 1992; Shapiro, 1991), psychological refractory period (Welford, 1952) and the cocktail party effect, which refers to the capacity to focus attention on a single conversation in a noisy place while still being able to detect relevant words among unattended stimuli (Cherry, 1953). Another important property of consciousness underlined by Broadbent's model is that conscious information can be maintained throughout time.

### **Conscious percept is selected by a supervisory system**

Posner and Snyder (1975) further insisted on the role of attention in selecting information. They supposed that, when directed to a particular input, attention was able to reduce interference induced by other signals. In an attentional selection model of action, Norman and Shallice (1986) introduced the distinction between automatic schemas, that are

used in routine, and consciously controlled schemas elicited by unusual situations. In their model, conscious schemas supersede unconscious schemas when they are insufficient to face a new situation. Furthermore, conscious schemas would be selected by a supervisory attentional system. Importantly, action processing that initially required conscious schemas could be automatized with learning and thereafter guided by unconscious schemas that could run in parallel. In accordance with neuropsychological observations, Norman and Shallice suggested that prefrontal cortex was a key node in this system.

More recently, Crick and Koch (2003) proposed to distinguish between the “front” of the cortex and the “back” of the cortex, the former being “looking at” the latter which contains sensory systems. Lau and colleagues also argued that consciousness depended on higher-order mental representations representing oneself as being in particular mental states (Lau et al., 2011; Lau, 2008).

One of the main criticisms of hypotheses involving a supervisory system is that it can lead to an infinite regress: if a supervisory system selects conscious information, the how is this supervisory system itself supervised? This criticism relates to the “homunculus argument” and the “Cartesian theatre” proposal made by Dennett (2017). The theatre metaphor compares consciousness to a scene on which only few actors play (conscious representations) while others are waiting their turn (unconscious information). Dennett wonders who is watching the scene and how this entity works, suspecting that this “spectator” – or supervisory system – either appeals for another level of description, raising the very same problem, or needs to have additional specific properties, which may lead back to Cartesian-dualism.

### **Consciousness as an integrative system**

Other hypotheses assumed that the role of attention and consciousness was to bind separable perceptual features, such as shape or colour, in order to build a unified percept (Singer et al., 1995; Treisman, 1996; Treisman et al., 1980). Treisman (1980) reckoned that separable features were processed unconsciously and in parallel. When attention focused on an object, its different features would be serially processed and subsequently “glued” into a unitary object. These unified objects would be maintained allowing us to progressively build up and apprehend complex percepts.

Actually, the idea that consciousness enables information integration is shared by most of the theoretical models of consciousness. However, the underpinning mechanisms differ according to the models: gamma-band oscillations (Crick et al., 1990; Llinás et al., 1998), long-distance synchrony (Engel et al., 2001; Melloni et al., 2010; Tononi et al., 2008; Treisman, 1996; Ward, 2003), re-entrant connections or recurrent processing (Crick et al., 2003; Edelman et al., 2000; Lamme et al., 2000; Supèr et al., 2001).

In more details, Edelman proposed that binding relies on re-entrant connections, in the thalamo-cortical system, creating differentiated metastable groups of neurons that constituted a functional cluster called “dynamic core” (Edelman, 1989; Edelman et al., 2000; Tononi & Edelman, 1998). This theory reckoned that conscious contents were at once highly differentiated (i.e. unique and one out of many possibilities) and integrated (i.e. unified and impossible to decompose). The *integrated information theory* further proposed a quantitative measure of the irreducibility of a system composed of multiple parts called  $\Phi$ . In short, it quantifies the information generated by a composite system that is not reducible to the sum of the information generated by its subparts. The more integrated a system is, the higher this variable will be, since reducing this system into subparts would correspond to a more important loss of information (Tononi, 2004, 2008; Tononi et al., 2016).

Relying on neurophysiological observations of the visual system, Lamme (2000) proposed that consciousness was tightly linked to recurrent processing. According to him, any stimulus quickly activates sensory areas through feedforward connections, inducing a feedforward sweep. Neuronal activation propagates to higher-level areas and causes feedback and recurrent processing, which modify neuronal tuning, maintain cerebral activity and allow integration of information into a coherent perceptual interpretation of the stimulus (Lamme, 2003; Lamme et al., 2000; Supèr et al., 2001).

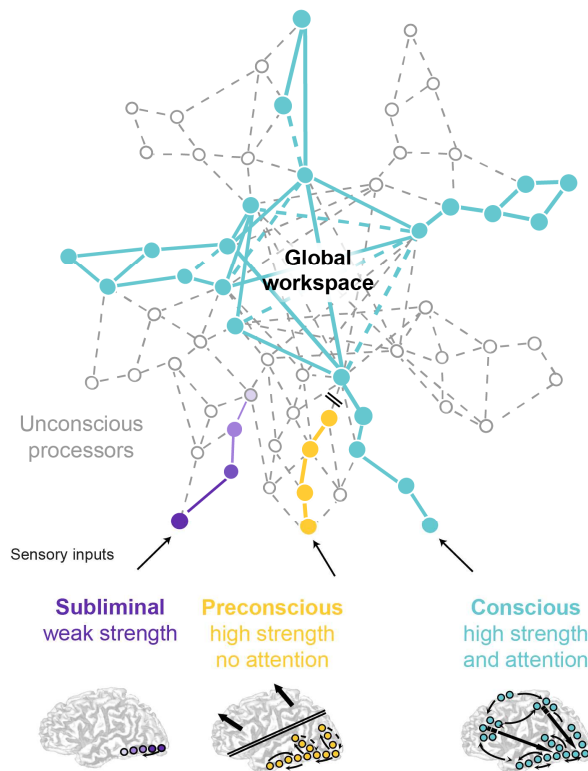
In a similar proposal, Crick and Koch (2003) distinguished between a zombie mode and a conscious mode. In the zombie mode, responses to sensory inputs were rapid, automatic, unconscious, and mainly underpinned by feedforward processing whereas in the conscious mode, the flow of cerebral activity is bidirectional. They proposed that consciousness involved reverberating activity in coalitions of neurons among competing neurons assemblies (Crick et al., 2003).



## Consciousness as a global workspace

Consciousness allows to integrate information but also involves access to many processing resources: conscious information can be reported, manipulated, memorized, etc. (Navon et al., 1979). This introduces a kind of contradiction between the ability for consciousness to synthesize information and, in the same time, to make information available to a higher-level of processing that enriches its content. To reconcile these views, Baars proposed in *a Cognitive Theory of Consciousness* (1993) that consciousness was a limited-capacity workspace strongly connected to specialized processors. In his model, unconscious level allowed an automatic parallel processing of a huge amount of information by modular processors (Fodor, 1983) and conscious access starts when a selected piece of information is broadcast within a *global workspace* composed of many specialized processors and equipped with working memory, able to maintain, manipulate and report it. Baars thus suggested that consciousness corresponded to a particular state of communication between several processors. When functioning in isolation, specialized processors would have an activity that remains unconscious whereas when interacting, their synchronized activity would become conscious. Moreover, Baars assumed that processing resources selected themselves whenever required and showed up to participate to the conscious activity. Therefore, the consciousness architecture proposed by Baars incorporated many properties previously stated: 1) a parallel processing at the unconscious level, 2) a narrow bottleneck between conscious and unconscious level, 3) a serial processing at the conscious level with a widely diverging processing capacity.

A revisited version of Baars's global workspace model, the *global neuronal workspace*, was proposed by Dehaene, Changeux and Naccache (Dehaene et al., 2006; Dehaene, Kerszberg, et al., 1998; Dehaene & Naccache, 2001, 2001) (Figure 7). Crucially, it included a neurophysiological description of conscious access, based on empirical data and computer simulations (Dehaene et al., 2003, 2011). The neuronal workspace would rest upon a dense network of interconnected neurons disseminated in prefrontal and parietal regions, and thalamocortical loops. In this proposal, conscious access is thought to start when top-down attention amplifies a given piece of information which enters the global neuronal workspace and triggers sustained activity within a reverberating assembly of long-range connected neurons, a phenomenon termed ignition. The global availability of this information to many cognitive processes such as verbal reporting, memorization, evaluation, manipulation, etc., would underlie the subjective experience of consciousness (Dehaene & Naccache, 2001).



*Figure 7.* Global neuronal workspace theory of consciousness. Information is consciously accessible if it is broadcast through long-distance connections to disseminated cerebral areas. Two main factors modulate conscious access: strength of sensory inputs and availability of attentional resources. When a stimulus is too weak to be perceived even when attended, it is subliminal, while when its strength is sufficient but it lacks attention to access the global neuronal workspace, it is preconscious (Dehaene et al., 2006).

As mentioned above, the global neuronal workspace theory is supported by empirical data, showing that conscious processing is associated with intense and diffuse activity involving sensory and higher level associative cortices that code for one piece of information at a time (Dehaene, Naccache, et al., 2001; Del Cul et al., 2007; Fisch et al., 2009; Gaillard et al., 2009; Marti et al., 2012, 2015; Sergent et al., 2005). At a cellular level, the global neuronal workspace is supposed to be composed of pyramidal cells that are particularly abundant in the prefrontal regions and have long axons and a lot of spines, allowing intense and long-distance communication (Elston, 2000). At a molecular level, computer simulations and empirical data suggested that bottom-up connections were underpinned by fast glutamate AMPA receptors while top-down ones relied on slow glutamate NMDA receptors (Herrero et al., 2013; Moran et al., 2015; Self et al., 2012; van Loon et al., 2016). GABAergic interneurons would inhibit competing neurons to prevent sustained activity to be destabilized by another simultaneous ignition (Dehaene et al., 2011; Joglekar et al., 2018).

In addition, Dehaene and Changeux introduced two important ideas. First, ignition would not need external stimulus to start and could be triggered endogenously (Dehaene et al., 2011). Indeed, during mind-wandering or resting-state, a wide default-mode network is activated while it is deactivated in goal-oriented task (Greicius et al., 2003; Raichle et al., 2001). The “stream of consciousness”, coined by William James (1890), could therefore correspond to a succession of ignitions sometimes externally driven and sometimes spontaneously generated. Interestingly, this idea was supported by recent empirical data, suggesting that conscious representations are regularly updated contrary to unconscious ones (Salti et al., 2015, 2018). Second, ongoing spontaneous cerebral activity seems to play an important role in conscious access (Dehaene et al., 2005, 2011). When it is very low or nil during sleep or vegetative state, ignition is difficult or even impossible to obtain, i.e. stimuli, even intense, cannot access consciousness (Massimini et al., 2005; Vanhaudenhuyse et al., 2010). On the contrary, when spontaneous activity level is very high, the process of external stimulus is blocked or reduced. This is the case when endogenous ignition is important, e.g. during mind-wandering (Schooler et al., 2011; Smallwood et al., 2008), or when exogenous ignition induced by the processing of another stimulus occupies the workspace, e.g. in inattention blindness or attentional blink (Marti et al., 2012, 2015; Sergent et al., 2005). Cholinergic system probably contributes to the regulation of ongoing spontaneous activity, in particular to the generation of ultraslow fluctuations ( $< 0.1$  Hz) and their synchronicity (Koukoulis et al., 2016).

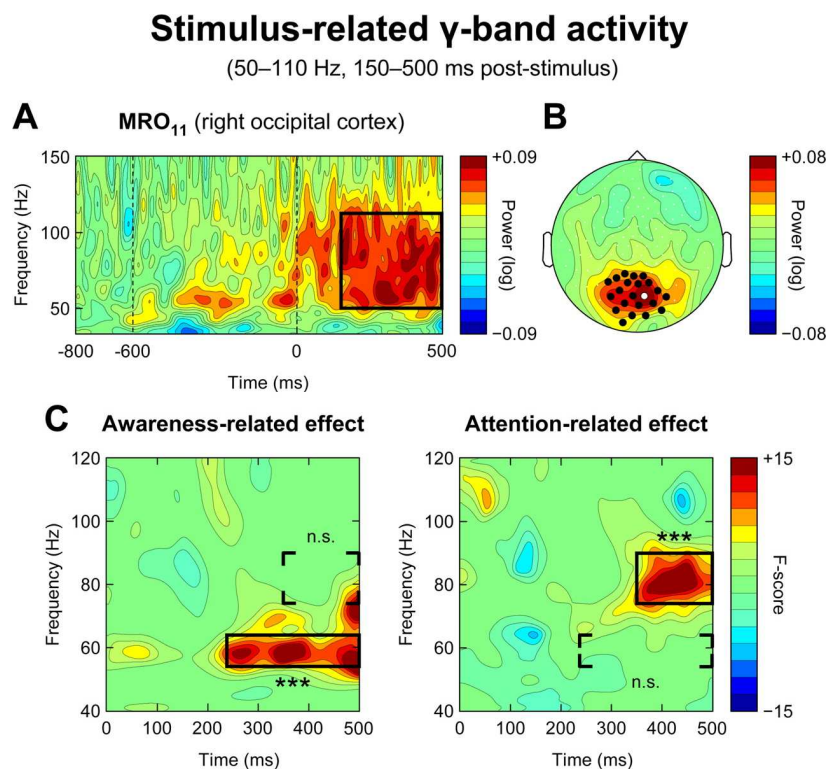
## **Old and new challenges regarding consciousness**

### **The contested role of attention**

The global neuronal workspace model distinguished between two types of non-conscious processing: subliminal condition in which bottom-up stimulus strength is too weak to induce ignition and preconscious condition in which stimulus is sufficiently intense to be consciously perceived but remains unconscious because attentional resources are not available (Dehaene et al., 2006) (Figure 7). Accordingly, masking renders stimuli subliminal while in attentional blink paradigms, invisible stimuli are preconscious: they would have been perceived if they were attended.

Attention amplifies information (Posner et al., 1994) and thus facilitates its access to consciousness. Still, some authors suggested that it was not required for conscious access (Boxtel et al., 2010; Koch et al., 2007; Shafto et al., 2015; Tallon-Baudry, 2012; but Cohen et

al., 2012). Conversely, attention can be exogenously attracted to stimuli that will not access consciousness, during blindsight, inattention blindness or masking (Bressan et al., 2008; Giattino et al., 2018; McCormick, 1997). Therefore, a double dissociation between consciousness and attention can be obtained, to disentangle the two phenomena (Koch et al., 2007; Tallon-Baudry, 2012). On the one hand, an unattended stimulus can be consciously accessed and consciousness enhances brain activity for both attended and unattended stimuli (Koivisto et al., 2006, 2007, 2008; Wyart et al., 2008) (Figure 8). On the other hand, attention amplifies conscious and subliminal processing. In particular, spatial attention modulates high-frequency gamma-band activity (Wyart et al., 2008) (Figure 8) and increases early cerebral activity for both seen and unseen stimuli (Koivisto et al., 2006; Wyart et al., 2012). Subliminal processing is also facilitated by attention. Indeed, without temporal attention, subliminal priming decreased or even totally vanished (Kiefer et al., 2006; Naccache et al., 2002a)



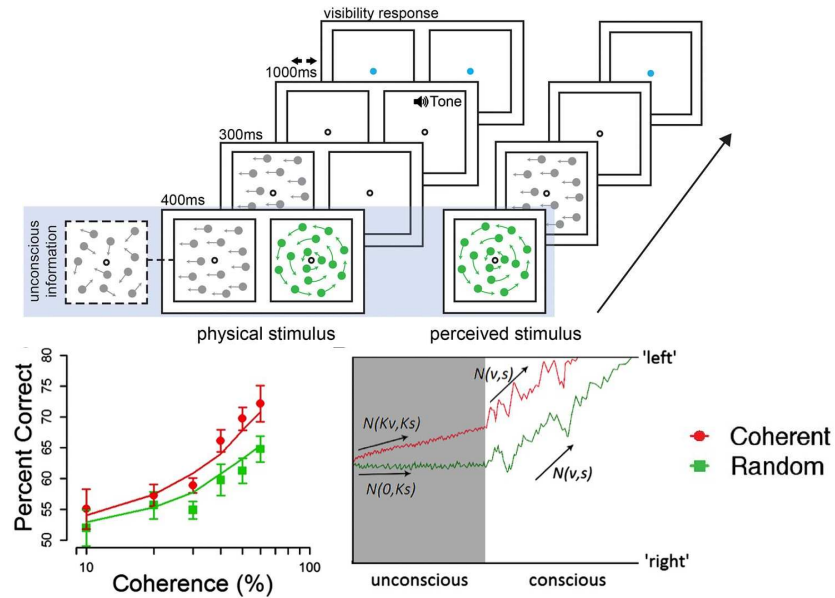
*Figure 8.* Factorial analysis of the gamma-band response in the time–frequency domain disentangling awareness and attention related components (Wyart et al., 2008).

To sum up, attention appears to be related to conscious access since it amplifies preceding unconscious processes, which may facilitate ignition and pro, but the two phenomena are dissociable.

### **Is consciousness a decision?**

In Treisman's experiments (1980), reaction times correlated with stimulus complexity: the more complex the percept was, the longer it was to be reported. Dehaene (2014) also underlined that conscious processing was delayed in regards to events. Indeed, cerebral activity associated with consciousness, e.g. ignition or the P300 component – as its name implies – occurs around 300 ms after the triggering stimulus.

This delay of processing which is a function of complexity suggests that decisional processes may be involved in conscious access. In this sense, consciousness could be considered as a perceptual decision (Dehaene, 2011; Dehaene et al., 2014; Kang et al., 2017; King et al., 2014a; Lafuente et al., 2006; Lau, 2008; Ploran et al., 2007; Shadlen et al., 2011). Indeed, sensory inputs are intrinsically ambiguous, while the content of consciousness corresponds to a unique interpretation of the reality. Conscious representations could therefore result from a probabilistic decision based on sensory evidence accumulation. Given sensory evidence, the stimulus that is the most likely to have been presented is selected among several possible interpretations. Furthermore, the diffusion model (Ratcliff, 1978) states that decisions are made through a noisy process that accumulates information over time until sufficient information is obtained to initiate a response (Gold et al., 2007; O'Connell et al., 2012; Twomey et al., 2015). Interestingly, an accumulation of sensory evidence was shown to occur unconsciously (de Lange et al., 2011; Vlassova et al., 2014; Vorberg et al., 2003) (Figure 9). However, conscious access allows a dramatic increase in the amount of integrated information per unit of time, also called "drift rate" (de Lange et al., 2011; Vlassova et al., 2014). In this sense, conscious perception could coincide with a specific threshold crossing in evidence accumulation, enabling a particularly amplified and broadcast processing of a single piece of information (Dehaene, 2011; Kang et al., 2017; King et al., 2014a; Ploran et al., 2007; Shadlen et al., 2011). In this model, the incompressible delay before conscious perception would therefore correspond to the preceding unconscious accumulation of evidence.



*Figure 9.* In a dichoptic suppression paradigm, participants were presented with an unconscious dot motion stimulus having a variable amount of coherence or containing fully random motion. Then, they had to identify the direction of a visible dot motion stimulus. They were more accurate at identifying the orientation of the stimulus when it was preceded by a masked coherent stimulus than by a random dot motion stimulus and modelling indicated that an accumulation of evidence occurred unconsciously with a reduced but significant drift rate (Vlassova et al., 2014).

In addition, the probability to cross the consciousness threshold is modulated by bottom-up and top-down factors. Obviously, in masking paradigms, the longer the stimulus is presented before being disrupted by a mask, the more likely the threshold will be crossed (Del Cul et al., 2007). Furthermore, the drift rate depends on the stimulus intensity and more generally on the signal-to-noise ratio of sensory inputs (Eger et al., 2007; Esterman et al., 2010; Melloni et al., 2011).

Strikingly, with the exact same amount of sensory evidence, consciousness threshold can vary according to the task and the attentional resources (e.g. Sergent et al., 2005). Attention could amplify information by increasing the drift rate thereby modulating the probability that representations reach awareness (Asplund et al., 2014). Even after a stimulus disappears, post cueing favours conscious access (Sergent et al., 2013; Thibault et al., 2016), suggesting that the drift rate is not fixed by the initial conditions of perception.

As mentioned above, conscious access may reflect a selective process in which multiple possible interpretations of an ambiguous sensory input are reduced to a single interpretation, following a probabilistic inferential model. In order to assign a probability to each plausible interpretation, previous knowledge and internal representations play a crucial role. Influence of priors on consciousness threshold can be formalized by the signal detection theory and Bayesian inferences (King et al., 2014a). Signal detection theory (Green et al., 1966) reckons that perception is the ability to extract a signal among noise. The threshold for detecting a signal therefore corresponds to a cut-off between sensitivity, i.e. the ability not to miss a signal, and specificity, i.e. the ability not to take noise for a signal. Depending on the context, and the importance not to miss a stimulus or to exceedingly detect it, consciousness threshold would be low (sensitivity > specificity) or high (specificity > sensibility). For instance, it was shown that words with a negative emotional valence (e.g. danger) had lower consciousness threshold than neutral words (Gaillard et al., 2006). Following the signal detection theory, this may be explained by an increased sensitivity to negative emotional content because threat signal detection is crucial for survival.

Bayesian inferences theories posit that perception is a probabilistic combination of sensory inputs and prior knowledge. This idea goes back to Helmholtz (von Helmholtz, 1867), but a vast literature had more recently mathematically formalized these computations between fed forward sensory signals and fed back predictions using a hierarchical model (Friston, 2005; Kersten et al., 2004; Mumford, 1992; Rao et al., 1999; for a review, see: Spratling, 2017). Combining sensory inputs and prior knowledge is of considerable help to select the most probable interpretation of an ambiguous sensory input. Interestingly these probabilistic inferences were shown to be optimal in simple tasks. When presented with a more or less ambiguous stimulus, participants' perception reproduces the distribution of probability corresponding to the amount of ambiguity intrinsic to the stimulus. Put simply, if two interpretations are equiprobable, participants choose half of the time the first one and half of the time the second one, whereas if the stimulus is biased towards one interpretation, this one is as much more frequently perceived (Vul et al., 2014). By contrast, in complex tasks, participants' perception is not based on the whole distribution of probabilities but only on samples of it. This can be evidenced by asking participants to make more than one attempt in their responses. The more attempts they make, the better their global sampling (and therefore accuracy) is (Moreno-Bote et al., 2011; Vul et al., 2009).

Consciousness therefore synthesizes and congregates a big amount of unconscious information into a unique conscious representation that is constantly updated to constitute a stream of sequential thoughts (Dehaene, 2014; Salti et al., 2018).

In any case, according to the Bayesian inference model, if the expectations or the prior knowledge about a stimulus are strong, consciousness threshold should be easier to reach. Up to now, many empirical findings confirmed this hypothesis (Aru et al., 2016; Denison et al., 2011; Eger et al., 2007; Meijjs et al., 2018; Melloni et al., 2011; Stein et al., 2011). Finally, not only conscious but also subliminal expectations may to a lesser extent facilitate conscious access. Indeed, conscious and subliminal priming were shown to reduce response times to process a subsequent stimulus (for a review, see: Kouider, Dehaene, et al., 2007). Response times may be shorter because accumulation of evidence to complete the task on the target has already started unconsciously, i.e. conscious accumulation of evidence for decision-making may start at a higher starting point (Vlassova et al., 2014; Vorberg et al., 2003) (Figures 9 and 10). Moreover, if we consider accumulation of evidence as a continuous process beyond and across consciousness threshold, in which conscious perception corresponds to the given point in accumulation, conscious perception of the target may also occur sooner thanks to preceding unconscious accumulation of evidence.

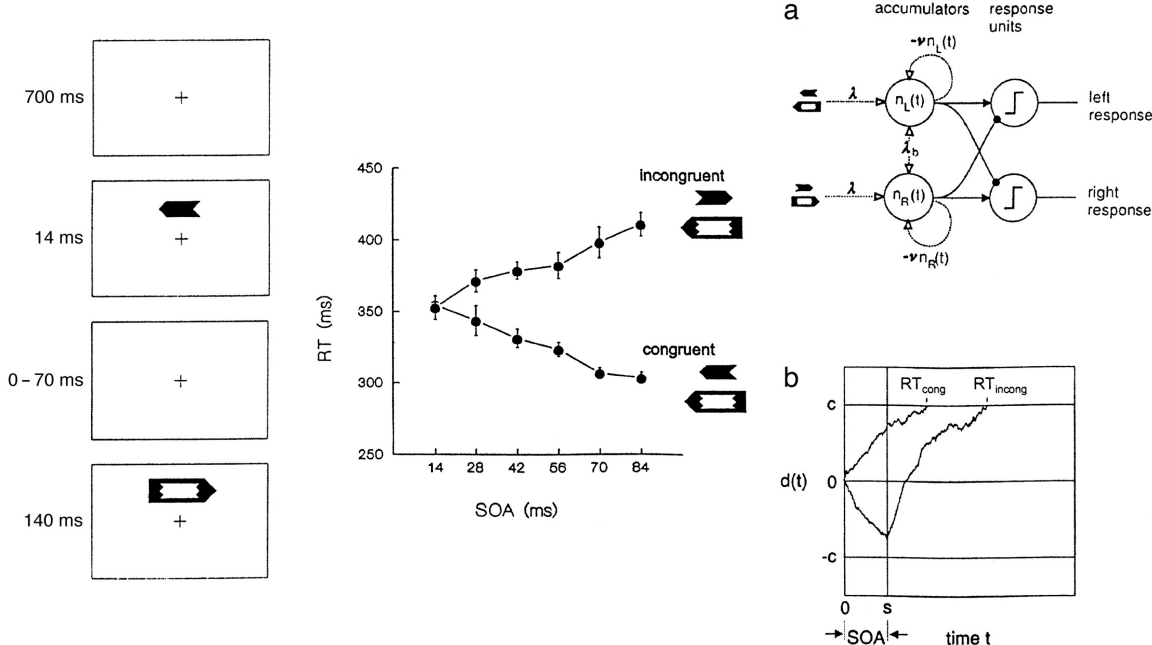


Figure 10. In this priming experiment, the longer the SOA is, the stronger the congruency effect is. Vorberg (2003) proposes a model in which primes and targets feed orientation-specific accumulators.



A response is initiated when the accumulator difference  $d(t)$  crosses the threshold  $c$  or  $-c$ , leading to a longer response time when the accumulation starts on the wrong direction because of the incongruent prime.

To sum up, consciousness can be viewed as a threshold in a decision process that 1) accumulates unconscious sensory evidence according to the physical properties of an incoming stimulus and its relevancy, 2) combines it with priors, and 3) samples the obtained distribution to provide an unequivocal conscious percept (Dehaene, 2014).

### **Can we trust conscious perception?**

In her feature-integration theory, Treisman (1980) noticed that one may make binding errors in attributing the feature of one object to another because of inattention, interference or working memory decay. For instance, in her experiment, when two coloured letters were briefly presented, the colours of two letters could be perceived as interchanged. According to Treisman, this reveals that our perception relies on bound information, completed by “illusory conjunctions” that can be either correct or not. Indeed, we never perceive objects with some but not all features (e.g. a shape without any colour or location), empty spaces in unattended areas, or float free features. She proposed that illusory conjunctions played an important part in the richness of phenomenal consciousness. They would be inferred from the previous knowledge and contextual information in order to complete our perception as well as possible bringing a feeling of fullness when looking at a complex visual scene.

This proposal provides a unified framework for access-consciousness and phenomenal-consciousness (Block, 1995). Indeed, empirical findings suggested that phenomenal-consciousness was an a posteriori reconstruction rather than a vivid experience that cannot be fully reported (de Gardelle et al., 2009). In a replication of Sperling’s partial-report paradigm (Sperling, 1960) (see Figure 5), participants were presented with a matrix of letters that included unexpected items, such as symbols and flipped letters (de Gardelle et al., 2009). Like in the original study, they were able to report some letters of the matrix and could be cued after the matrix disappeared to report a given row of the matrix. They had the same impression as in the original study to have seen all the matrix even if they could neither memorize nor report all its components. However, this study showed that they did not notice the pseudo-letters and tended to report them as real letters while they were perfectly able to detect the symbols. The authors concluded that the feeling to have access to a rich environment that cannot be memorized or

reported is an illusion: that part of our subjective experience is inferred and reconstructed (de Gardelle et al., 2009). In other words, within the access-consciousness taxonomy, such information could be either considered as unconscious when it is not reportable or conscious when participant express the feeling of having perceived something (Naccache, 2018)

Kouider and colleagues (2010a) further proposed that conscious access rested upon a hierarchical model of representations, from lower-level features to higher-level abstractions. Each level would be independently consciously accessible. In this model, the illusion of phenomenal awareness is imputed to an ability to access some but not all levels of representation. For instance, one can apprehend the gist of a visual scene without having detected some of its details (high levels are accessed while low levels are not). Change blindness or inattentional blindness would correspond to this situation: participants have the feeling to have seen every detail while in fact, they missed a change or a surprising stimulus. On the contrary, consciousness of low but not high levels would give the impression to have detected a stimulus without being able to describe it properly. Authors proposed that access to some but not all levels of consciousness would account for the so-called overflow of verbal report by phenomenal consciousness (Block, 1995). A second assumption of the authors is that at each level, sensory inputs are combined with priors. When stimuli are weak, the awareness, if any, is partial and the perception is thereby mostly driven by priors, which can give rise to perceptual illusions particularly in case of strong priors that do not fit external stimuli. Importantly, we would not be aware that such computations take place and rather attribute our perception to external inputs alone. A partial awareness would therefore lead to the wrong impression that we indeed access a rich external world while the perception is actually merely driven by priors (Kouider et al., 2010). Consistently, empirically perceptual illusions have been observed when participants had strong priors on degraded stimuli (de Gardelle et al., 2009; Kouider et al., 2004).

In short, two factors seem to be involved in perceptual illusions: 1) weak or missing sensory inputs that are superseded by contradicting strong priors, 2) unawareness that perception is mostly driven by priors.

### **Controversy about the neural correlates of consciousness**

According to the global neuronal workspace, consciousness is associated with an ignition involving fronto-parietal area, a long-distance synchrony and a sustained cerebral

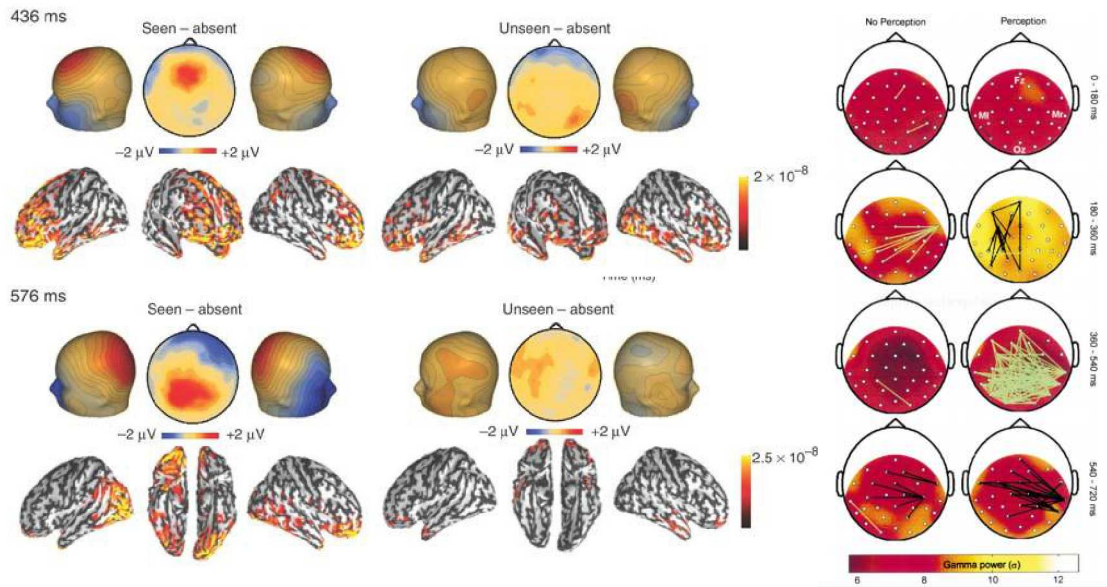
activity (Dehaene et al., 2006, 2011; Dehaene & Naccache, 2001). Reproducible empirical results corroborating these predictions were obtained in verbal-report paradigms (for a review, see: Dehaene et al., 2011). Nevertheless, it is challenging to isolate neural correlates of consciousness – defined as the neural mechanisms jointly sufficient for any one specific conscious experience (Crick et al., 1990; Koch et al., 2016) – because they can be confounded with two other kinds of processes: prerequisites and consequences of conscious access (Aru et al., 2012; de Graaf et al., 2012; Koch et al., 2016). Prerequisites of conscious access precede conscious access, and are required for it. Nevertheless, they can be unsuccessful in inducing consciousness and therefore occur without being followed by consciousness. Conversely, consequences of conscious experience occur after consciousness and necessitate conscious access, so they cannot be observed under unconscious conditions, but their presence is not systematic under conscious conditions and depends on experimental settings (type of stimulus, task...). Methods to assess consciousness and to find its neural correlates were therefore highly discussed. In particular, measures that required conscious stimuli to be verbally reported, to be relevant for the task or those inducing different kinds of processing for conscious and unconscious stimuli were criticized (Aru et al., 2012; Block, 2005; de Graaf et al., 2012; Sandberg et al., 2016; Tsuchiya et al., 2015). We will go over the main cerebral signatures of consciousness and the discussions regarding their genuine implication in conscious access.

Frontal areas are supposed to be activated during conscious processes, but they are also known to be involved in decision-making (Ridderinkhof et al., 2004). Accordingly, experimental results showing that the frontal cortex played a role in consciousness were contested when the objective performance on seen and unseen stimuli was different (e.g. in Del Cul et al., 2007). This point was addressed by studies restricting the statistical comparison between seen and unseen stimuli to correct trials. They found that conscious perception was tightly associated with a widespread brain activity in frontal and parietal region even when the performance was equalized in conscious and unconscious conditions (Lamy et al., 2008; Lau et al., 2006; Persaud et al., 2011; Salti et al., 2015; but Morales et al., 2015). This proposal was again corroborated by a recent study, suggesting that the prefrontal cortex is required to initiate ignition (van Vugt et al., 2018). Nevertheless, there is still an active debate on whether neural correlates of consciousness are located in the front of the brain (Mashour, 2018). Some authors argued that other ways of exploring consciousness, with the study of cerebral lesions, the comparison between dreaming and non-dreaming sleep or the use of cerebral stimulations, did not provide convergent evidence that frontal regions were critical for conscious access (for a

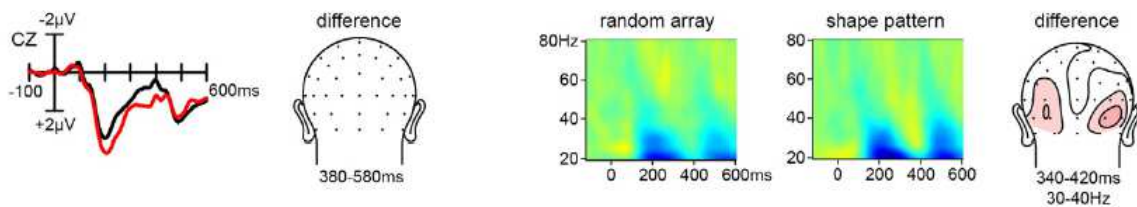
review, see: Boly et al., 2017) but according to other authors, these null-findings are not sufficient to falsify previous positive results (Odegaard et al., 2017).

The transient synchronization of neuronal activity in distributed areas has been proposed to be a neural correlate of consciousness (Crick et al., 1990; Engel et al., 2001; Ward, 2003). Many empirical studies showed that subjective perception was associated with phase synchronization (Doesburg et al., 2005; Gaillard et al., 2009; Gross et al., 2004; Melloni et al., 2007; Rodriguez et al., 1999; Tononi, Srinivasan, et al., 1998; Wyart et al., 2008). However, gamma-band synchrony was also observed in response to masked emotional faces (Luo et al., 2009) and was found to be absent for conscious but irrelevant visual information (Pitts, Padwal, et al., 2014) (Figure 11).

In the vast majority of studies on consciousness, P3 component was observed under conscious conditions (Babiloni et al., 2006; Del Cul et al., 2007; Fernandez-Duque et al., 2003; Lamy et al., 2008; Melloni et al., 2007; Pins et al., 2003; Sergent et al., 2005). Nevertheless, the proposal that P3 was a neural correlate of consciousness was recently questioned (Koch et al., 2016). Indeed, a P3 has also been observed on unconscious trials (Batterink et al., 2012; Silverstein et al., 2015; Brázdil et al., 2001) and was found to be absent on conscious trials when the stimuli were not relevant for the task (Pitts et al., 2011; Pitts, Padwal, et al., 2014; Shafto et al., 2015), suggesting that it may be a post-perceptual process rather than a neural correlate of consciousness (Figure 11, next page).



shapes task-irrelevant



shapes task-relevant

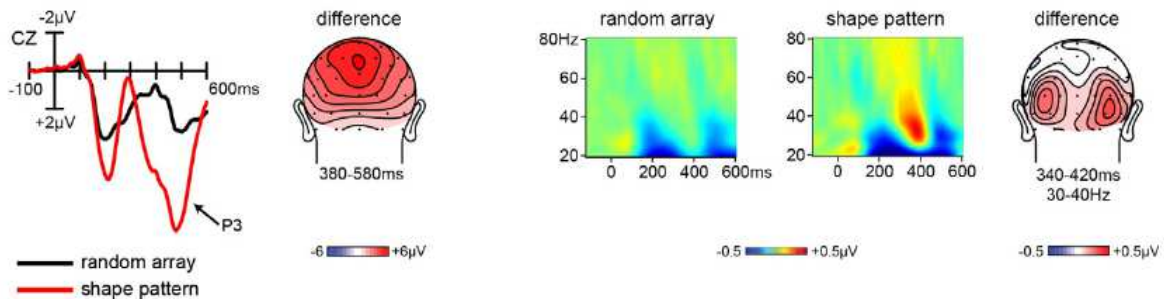


Figure 11. Top left: P3a and P3b components exclusively observed on seen trials in an attentional blink paradigm (Sergent et al., 2005). Top right: Face perception induces a long-distance pattern of synchronization (represented by the lines), corresponding to the moment of perception (Rodriguez et al., 1999). Bottom: Gamma activity and the P3 are not observed for consciously perceived but task-irrelevant stimuli and appeared only when these stimuli become directly relevant to the task (Pitts, Padwal, et al., 2014).

Several authors further proposed that another component, the visual awareness negativity (VAN) was a better correlate of consciousness for visual stimuli because it was observed even for irrelevant and not immediately reported conscious stimulus (Giattino et al.,

2018; Pitts, Metzler, et al., 2014; Railo et al., 2011; Shafto et al., 2015; for a review, see: Koivisto et al., 2010). However, its amplitude increased when the stimulus became relevant to the task, therefore it could also reflect object based-attention (Pitts, Metzler, et al., 2014; Shafto et al., 2015).

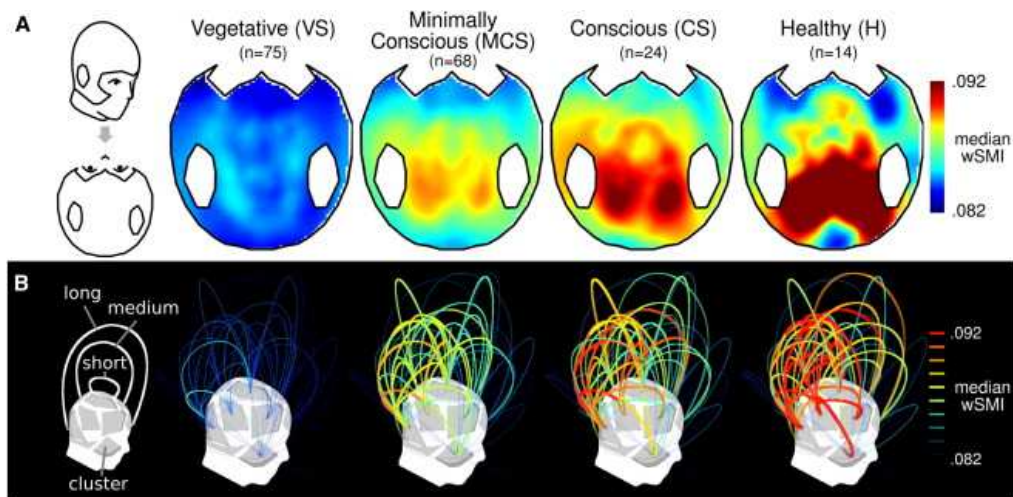
Overall, the mechanisms underlying conscious access are still difficult to delineate, which is not surprising given the upheaval induced by conscious access, rendering information available to many cognitive processes including introspection.

## **Schizophrenia: a pathology of consciousness?**

### **Cerebral lesions may affect consciousness**

Advances in neuroscience were frequently driven by observations in neurology and psychiatry. As regards to consciousness, some neurological lesions directly impact consciousness. Severe cerebral injuries can provoke a coma, which is a durable state of unwakefulness. In some cases, it is followed by a vegetative state, in which awareness is abolished while wakefulness is preserved: vegetative patients are no more responsive to their environment but they are awakened, with an unaffected sleep-wake cycle (Giacino et al., 2002). While wakefulness and awareness are tightly correlated in healthy subjects, these pathological states demonstrate that they can be dissociated (Laureys, 2005). Vegetative patients can progressively regain an ability to communicate, in a minimally conscious state, and finally recover. In these situations, it is possible to detect signs of awareness that predict the subsequent recovery (Daltrozzo et al., 2007).

On the other hand, distinguishing between the patients who are conscious and those who are not but unable to communicate is crucial to take medical decisions. Accordingly, cerebral measures of consciousness constitute promising tools to complement clinical assessment (Faugeras et al., 2012; King, Faugeras, et al., 2013; King, Sitt, et al., 2013; Monti et al., 2010; Owen et al., 2006; Sitt et al., 2014) (Figure 12).



*Figure 12.* The weighted symbolic mutual information (wSMI) evaluates the extent to which two EEG signals present nonrandom joint fluctuations, suggesting that they share information. It was applied it to EEG recordings of awake patients recovering from coma and diagnosed in various states of consciousness and was shown to increase with consciousness, primarily over centroposterior regions (King, Sitt, et al., 2013)

More focused lesions sometimes selectively impair specific aspects of conscious processing. We previously mentioned blindsight patients, who, after occipital lesions, were able to correctly locate a target they did not see (Pöppel et al., 1973; Weiskrantz et al., 1974). After right cerebral strokes, patients may be affected by hemianopia associated with left side neglect (Bisiach et al., 1978, 1979) and hemiasomatognosia, i.e. the loss of awareness of the left part of the body (Feinberg et al., 2010). These patients do not have any awareness of their left side, but exhibit blindsight of the whole left visual hemifield: when they are presented with two drawings of a house, one of each including a fire in the left side, they are able to choose the house that is not burning but not able to explain why (Marshall et al., 1988). On another note, after occipital or temporal lesions, some patients lose the ability to recognize faces. However, their electrodermal skin conductance is larger for familiar than for unfamiliar faces, suggesting that they are able to unconsciously distinguish between the two (Bauer, 1984; Damasio et al., 1982; Tranel et al., 1985).

### **Conscious access disorders and the emergence of mental fictions**

We previously saw that conscious representations were supplemented by inferred information in case of weak or missing sensory information. Importantly, even in healthy

controls, this process probably occurs automatically, unconsciously can sometimes give rise to illusions (Kouider et al., 2010b). Moreover, in many neurological syndromes, patients suffer from anosognosia: they are unaware of their deficit. Accordingly, patients with a conscious access disorder and an anosognosia are confronted to incomprehensible situations promoting illusions or mental fictions, in an attempt to find plausible explanations to their trouble.

An enlightening example of mental fiction was observed in split-brain patients by Gazzaniga. As a reminder, when a stimulus is presented in their left visual hemifield, they are able to semantically process it with their right cerebral hemisphere but not to verbally report it, since their left hemisphere does not access the information. Their verbal report, coming from their left hemisphere, thus tries to provide an explanation to their right hemisphere actions. In a study, they were shown with a picture of a chicken claw in the right side and a snow scene in the left side. They had to choose an associated card with their right hand so they picked a snow shovel picture to match the snow scene. When they were asked why, they justified this choice by saying that a shovel was a good tool to clean a chicken shed! That is, they created a mental fiction to explain why they picked this card, while the left hemisphere only had access to the chicken picture (Gazzaniga, 2000). Similarly, in Korsakoff syndrome, patients have an anterograde amnesia and confabulations: they invent memories that they take as true, which can be understood as mental fictions that fill memory gaps (Burgess, 1996; Moscovitch, 1995).

Patients affected by an asomatognosia usually have a sensory-motor deficit of the body part they neglect. They sometimes develop a somatoparaphrenia, a delusion where they are convinced that this body part belongs to someone else and confabulate about how it ended up on their body (Feinberg et al., 2010; Vallar et al., 2009). This delusion accounts for both the sensory-motor deficit and the unawareness of this deficit: patients observe a limb that does not respond anymore and do not feel that they miss anything, so they logically conclude that this limb is not theirs.

The Capgras syndrome is a misidentification delusion where patients are convinced that their relatives have been replaced by doubles, generally malevolent (Capgras et al., 1994). Contrary to patients suffering from a prosopagnosia, patients affected by a Capgras delusion do not perceive faces familiarity even if they normally recognize their identity (Ellis et al., 1997, 2001; Hirstein et al., 1997). In a sense, the idea that people have been replaced by doubles therefore provides a possible explanation to the inconsistency between the relatives' normal appearance and the absence of feeling of familiarity.



In all these cases, the anosognosia plays a crucial part in the need for explanations that culminate in delusional ideas. Indeed, if patients were aware of their disability they would not need supplementary, and sometimes less plausible, explanations. Importantly, even if delusional beliefs may look weird, bizarre, or obviously contradicted by evidence, they can be regarded as “legitimate abductive inferences” since they appear in reaction to an at least as strange and improbable subjective feeling (Coltheart et al., 2011).

However, delusions are defined as firmly held beliefs despite contradictory evidence. Indeed delusional ideas remain stable in spite of a usually challenging environment composed of relatives and doctors. From a Bayesian perspective, conscious access can be modelled as a perceptual decision that integrates sensory evidence and priors. In all the sub-cited examples, delusional ideas arise after an important and quite sudden change in the sensory inputs processing. Some sensory information is inaccessible, missing, immediately forgotten or incoherent. This change is not consciously perceived and not compatible with previous knowledge. According to the predictive-coding framework (Friston, 2005; Rao et al., 1999; Spratling, 2017), the computation between sensory inputs and priors will therefore update internal representations to minimize prediction-error signals explaining that beliefs evolve to fit the change in sensory inputs. These new and possibly delusional priors will in turn bias the subsequent computations and the resulting perception.. Therefore, delusional beliefs and abnormal perceptions may sustain one another (Fletcher et al., 2009).

Even if the patient’s relatives or clinicians argue against delusional ideas or provide contradictory evidence, patients generally favour their delusion because they trust their sensory processing. Considering that both the estimation of the source information reliability and the message plausibility play a role in adopting someone else’s views (Collins et al., 2018), in such situations, patients would tend to distrust contradictors rather than revising their beliefs and feel persecuted.

### **Abnormal conscious access may account for schizophrenic symptoms**

Schizophrenia is a severe psychiatric disease that affects 1% of the general population worldwide (McGrath et al., 2008). Patients affected by schizophrenia show positive symptoms, such as delusions and hallucinations, negative symptoms, including withdrawal from social interactions and daily life activities, cognitive impairments, and disorganization syndrome.

Many studies revealed that conscious access was impaired in schizophrenia. Patients affected with schizophrenia exhibit an elevated conscious threshold and abnormal conscious processes compared to healthy controls while their subliminal processing is preserved (Butler et al., 2003; Charles et al., 2017; Danion et al., 2001; Dehaene, Artiges, et al., 2003; Del Cul et al., 2006; Green et al., 2011; Hanslmayr et al., 2013; Herzog et al., 2015; Huddy et al., 2009; Mathis et al., 2012; Plomp et al., 2013).

If sensory evidence is correctly processed unconsciously but does not cross consciousness threshold, patients could be unable to consciously explain some aspects of their behaviour, emotions, or intuitions that arise implicitly, guided by unconscious processing. Disorganization syndrome is characterized by incoherence between emotions, thoughts, and behaviour and could therefore directly emerge from this dissociation between conscious and unconscious processing. Disorganization and delusions could thus be the two sides of the same coin. Indeed, like in the sub-cited examples, patients may build mental fictions in order to justify their behaviour, like split-brain patients, or to explain their feelings, like patients with Capgras syndrome.

A phenomenological description of the emergence of delusion was provided by the “aberrant salience” model (Kapur, 2003). It posits that during psychotic transition, patients abnormally assign salience to external stimuli and internal representations. Random stimuli therefore become meaningful and need to be explained. Delusions would secondly arise to make sense of these phenomenological experiences. Hallucinations, which are defined as perception without object, would “reflect a direct experience of the aberrant salience of internal representations” (Kapur, 2003). Such aberrant salience experiences may be accounted by a global diminution in conscious access with occasional burst of few representations into consciousness whose provenance (external versus internal) is confused. Again, the inability to link this new information to current conscious representations because of a wider gap between conscious and unconscious processing may favour its assignation to an external cause. Indeed, hallucinations and delusions of control, in which patients have the feeling that they are guided or constrained by external forces, were described as failure to compensate for the sensory consequences of inner speech or actions (Allen et al., 2007; Daprati et al., 1997; Feinberg, 1978; Lindner et al., 2005; Shergill et al., 2005).

Finally, cognitive impairments observed in schizophrenia mostly concern explicit processing while implicit cognitive processing is preserved (Danion et al., 2001, 2005; Huron

et al., 1995; Linden et al., 2010; van 't Wout et al., 2007). Therefore these cognitive impairments could be a consequence of conscious access disruption. On the other hand, cognitive skills that are important for conscious access, such as attention, decision-making, probabilistic inferences, are impaired in schizophrenia (Averbeck et al., 2011; Fuller et al., 2006; Luck et al., 2006; Schaefer et al., 2013) and may therefore precede and/or contribute to a disruption of conscious access.

### **Predictive-coding and consciousness threshold**

We previously saw that conscious representations may correspond to discrete samples of probabilistic inferences coming from unconscious processing (Dehaene, 2014). Patients with schizophrenia have abnormal conscious probabilistic inferences: they tend to jump to conclusions (Fine et al., 2007; Huq et al., 1988), have a bias against disconfirmatory evidence (Woodward et al., 2008), probably because they overweight evidence-hypothesis matches (Broyd et al., 2017; Speechley et al., 2010).

More broadly, a vast literature suggests that psychosis could arise from an abnormal predictive coding, in particular from a decreased precision (i.e. confidence) in the encoding of prior beliefs relative to the sensory data (for reviews, see: Adams et al., 2013; Friston et al., 2016; Sterzer, Adams, et al., 2018). The failure to attenuate sensory precision according to predictions would lead to the impression that the world is surprising and uncertain, and would foster delusional explanations (Corlett et al., 2007; Fletcher et al., 2009), like in the aberrant salience model (Kapur, 2003). Moreover, it could favour hallucinations in patients since their own thoughts and actions would not be predicted, therefore not recognized as self-generated and attributed to an external cause (Allen et al., 2007; Feinberg, 1978; Lindner et al., 2005; Shergill et al., 2005). This hypothesis is supported by empirical data showing that patients with schizophrenia do not perceive visual illusions which rely on priors (Notredame et al., 2014), have better performance than controls in following the motion of an unpredicted target (Adams et al., 2012, 2016) and have more perceptual instability when they are presented with ambiguous stimuli (Schmack et al., 2015). However, the persistence of delusional ideas and hallucinations that do not involve agency rather suggest an opposite pattern in which the precision of priors is increased compared to the precision of sensory evidence (Powers et al., 2016). Indeed, several studies also suggested that an overweighting of priors expectations was present in early psychosis (Teufel et al., 2015) and correlated with hallucinations (Cassidy et al., 2018; Powers, Mathys, et al., 2017).

Interestingly, Sterzer et al. (2018) proposed that priors weights could be different at low and high levels of a hierarchical organization of representations. According to the authors, delusions would be related to weak low-level priors whereas hallucinations would rely on strong high-level priors. We further suggest that consciousness threshold constitutes a limit above which representations may be mostly influenced by priors while unconscious processing may be preferentially driven by sensory evidence or at least spared from inappropriate biases due to overweight priors. Indeed, sensory inputs may be first processed unconsciously at the lower levels of the hierarchy and propagate up to the higher conscious levels. If sensory evidence does not access consciousness, conscious representation might not be updated according to sensory evidence driving conscious representations towards priors. By contrast, priors are likely to come from the top of the hierarchy and to propagate down to the lower levels, thus a gap between conscious and unconscious processing could hinder prior inclusion in the combination with sensory inputs at unconscious low levels. So far, it is not clear whether an elevated consciousness threshold would be associated with abnormal unconscious probabilistic inferences or only an abnormal sampling of normally processed unconscious information. More tentatively, if conscious priors and expectations facilitate conscious access (Aru et al., 2012; Denison et al., 2011; Eger et al., 2007; Meijs et al., 2018; Melloni et al., 2011; Stein et al., 2011), confirmatory evidence would be more prone to cross the consciousness threshold and to confirm delusional ideas. Still, since unconscious processing normally or excessively takes into account sensory evidence in schizophrenia, disconfirmatory evidence could randomly burst into consciousness, appealing for additional explanations and thus fostering delusions.

### **What does the study of schizophrenia bring to the study of consciousness?**

The dissociation between altered conscious and preserved subliminal processing in schizophrenia allows to explore which aspects of a given cognitive function require conscious access. Indeed, unconscious processing is more limited than conscious processing, therefore, if patients have better performances in the subliminal than in the conscious condition for a given task, it indicates that this cognitive processing does not require conscious processing or that two distinct systems are implied for its conscious and unconscious parts. For instance, the comparison between patients and controls suggested that conflict monitoring could occur unconsciously without involving the anterior cingulate cortex, but that it was, however, needed for conscious conflict monitoring that was impaired in patients (Dehaene, Artiges, et al., 2003).

Likewise, patients' data supports that error detection is underpinned by distinct brain mechanisms in the conscious and the subliminal condition (Charles et al., 2013, 2017).

Furthermore, the knowledge about the pathophysiology of schizophrenia and about consciousness may fuel each other. For example, schizophrenic patients exhibit long-range connectivity and synchrony abnormalities (Lee et al., 2003; Pettersson-Yeo et al., 2011; Spencer et al., 2004; Stephan et al., 2009; Uhlhaas et al., 2010, 2014; Zhou et al., 2018), that are compatible with the predictions of theoretical models according to which conscious access relies on a coherent long-distance brain activity (Dehaene et al., 2011; Engel et al., 2001; Melloni et al., 2010; Treisman, 1996; Ward, 2003). Furthermore, current pharmacological models of schizophrenia target NMDA or cholinergic transmission (Corlett et al., 2011; Koukouli et al., 2017; Krystal et al., 1994; Lahti et al., 2001) which are assigned to important functions in conscious access. Indeed, NMDA is thought to be central for top-down amplification, long-distant communication and synchrony, whilst cholinergic transmission may support ongoing spontaneous cerebral activity (Dehaene et al., 2005, 2011; Koukouli et al., 2016; Self et al., 2012).

Finally, schizophrenia provides an opportunity to discover factors that have a causal effect on consciousness, since a medical intervention may improve conscious access in this population. Until now, there is no evidence that drugs currently used to treat schizophrenia have any effect on consciousness threshold. In addition, the previous studies which evidenced that patients with schizophrenia had a conscious access impairment were conducted on treated patients. The fact that antipsychotics do not enhance conscious access is not surprising since their main pharmacological mechanisms is to block D2 receptors of dopamine (Kapur et al., 2000; Seeman et al., 1976), while dopamine is not known to be directly involved in conscious access. More recently, stimulation techniques and glutamatergic drugs were proposed as innovating treatments for schizophrenia and may have an effect on consciousness threshold. Transcranial direct current stimulation (tDCS) is a non-invasive technique that can stimulate or inhibit the local cerebral activity. Studies suggested that stimulation by tDCS improved consciousness in patients in minimally conscious state (Thibaut et al., 2014) and could dampen schizophrenic symptoms when applied to the left dorsolateral prefrontal cortex (Palm et al., 2016; but Fitzgerald et al., 2014).

Finally, an NMDA hypofunction probably contributes to the pathophysiology of schizophrenia (Coyle, 1996; Olney et al., 1995). Accordingly, a therapeutic approach could be

to compensate this hypofunction by enhancing NMDA neurotransmission. Glycine is an allosteric agonist that promotes the glutamatergic transmission through NMDA receptors (Johnson et al., 1987; Kleckner et al., 1988). It was therefore a promising target to improve schizophrenic symptoms (Coyle et al., 2004; Deutsch et al., 1989). Glycine agonists and glycine transporter inhibitors were developed, but results were contrasted (Bugarski-Kirola et al., 2014; Goff, 2014; Heresco-Levy et al., 1999; Tsai et al., 2004; Umbricht et al., 2014; for reviews, see: Howes et al., 2015a; Beck et al., 2016).

While the study of consciousness in patients with schizophrenia sheds light on aspects of pathophysiology and paves the way for new therapeutics, schizophrenia also provides an example of an elective impairment of conscious access with preserved subliminal processing that is an opportunity to better understand the specificities and the mechanisms of conscious access.

## **Overview of the thesis**

In the present thesis, we will study conscious and non-conscious processing in schizophrenia and healthy controls and examine which factors are required or favour conscious access.

In the first part of the thesis, we will focus on abnormalities of conscious processing in schizophrenia starting with a literature review and following with empirical findings.

In the first chapter, we will present a literature review on disruption of conscious access in schizophrenia that draws several work hypotheses.

Among other hypotheses, dysconnectivity may prevent the broadcasting of conscious information within the global workspace. In the second chapter, we will explore the link between cerebral connectivity, consciousness threshold and psychotic symptoms using tractography imaging on healthy controls, patients with bipolar disorder with and without psychotic features and patients with schizophrenia.

In the third chapter, we will turn to the effects of interactions between bottom-up and top-down factors on conscious access, and focus on the role of attention. Using electroencephalography we will explore the modulation of evidence accumulation by attention

in healthy controls and patients with schizophrenia to see whether an impairment in top-down attentional amplification may account for the abnormal conscious access observed in patients.

The second part of the thesis is devoted to the study of conscious access and subliminal processing in healthy controls, but aim to explore some aspects of conscious processing that could be impaired in schizophrenia.

Following the idea of chapter 3, the fourth chapter presents a pilot study preceding a wider investigation of ketamine effects on conscious access. We manipulate bottom-up and top-down processing using metacontrast backward masking and attentional blink in order to disentangle potential effects of ketamine on consciousness.

In the fifth chapter, we will tackle the role of prediction in conscious access, since patients with schizophrenia have both abnormal inferences and an elevated consciousness threshold. The purpose of this study is to see whether healthy controls have a different consciousness threshold when put into a predictable versus an unpredictable environment and whether confirmation or violations of their predictions modify their ability to consciously perceive or categorize an incoming stimulus.

The sixth chapter is devoted to quite a distinct work on conscious and subliminal processing of syntactic features, showing notably that they could be extracted from masked words, and induce different levels of priming on a subsequent word.

In the annex, a supplementary article and a commentary are attached. The article deals with conscious and unconscious memory suppression effects and the commentary concerns an article on neural correlates of consciousness.







## **Part I.**

### **Impairments of conscious access in schizophrenia**



# **Chapter 1. Disruption of conscious access in schizophrenia**

## **Introduction of the article**

We first conducted a literature review about conscious access in schizophrenia, in which we report many studies showing that patients with schizophrenia have an elevated consciousness threshold and impaired conscious processing while non-conscious processing is not affected. In addition, our review draws a link between experimental studies on patients with schizophrenia, the extensive literature on the neural basis of consciousness and the NMDA role in the pathophysiology of schizophrenia.

## **Article**

Berkovitch, L., Dehaene, S., & Gaillard, R. (2017). Disruption of Conscious Access in Schizophrenia. *Trends in Cognitive Sciences*, 21(11), 878–892.

<http://doi.org/10.1016/j.tics.2017.08.006>

## Review

Disruption of Conscious  
Access in SchizophreniaLucie Berkovitch,<sup>1,2,\*</sup> Stanislas Dehaene,<sup>1,3</sup> and  
Raphaël Gaillard<sup>4,5,6,7</sup>

Schizophrenia is a severe and complex psychiatric disorder resulting in delusions, hallucinations, and cognitive impairments. Across a variety of paradigms, an elevated threshold for conscious perception has been repeatedly observed in persons with schizophrenia. Remarkably, even subtle measures of subliminal processing appear to be preserved. We argue here that the dissociation between impaired conscious access and intact unconscious processing may be due to a specific disruption of top-down attentional amplification. This proposal is compatible with the neurophysiological disturbances observed in schizophrenia, including dysconnectivity, abnormal neural oscillations, and glutamatergic and cholinergic dysregulation. Therefore, placing impaired conscious access as a central feature of schizophrenia can help researchers develop a coherent and parsimonious pathophysiological framework of the disease.

## A Neuroscientific Approach to Consciousness in Schizophrenia

**Schizophrenia** (see [Glossary](#)) is a severe disease that affects approximately 0.6–1% of the general population around the world [1]. Since the first descriptions of schizophrenia [2,3] it has been observed that patients are unaware of their symptoms, disconnected from reality, and exhibit negative symptoms that affect both high-level and basic cognitive functions. However, only more recently has it become clear that patients with schizophrenia exhibit specific deficits in conscious processing that could underpin most of these symptoms. Although consciousness has long been an important research topic in psychology and philosophy, its definition has been operationalized with the rise of cognitive neuroscience [4]: information is considered conscious if subjects are able to report it. By experimentally manipulating whether information is presented consciously or unconsciously to participants, neuroscientists have been able to compare how the two different information types are processed and to identify the neurophysiological signatures of consciousness [5,6].

Capitalizing on this growing science of consciousness, here we review recent results showing that persons with schizophrenia exhibit a dissociated profile of impaired conscious access and preserved unconscious processing. We discuss the plausible mechanisms of such a dissociation in light of the **global neuronal workspace** (GNW) theory of consciousness and disentangle the role of bottom-up and top-down deficits in this specific disruption of conscious access. We then confront those experimental results with recently proposed Bayesian models of schizophrenia. Finally, in line with the GNW model and the pivotal role of glutamatergic and cholinergic transmissions in conscious access, we examine the neurophysiological and molecular mechanisms that may underlie the dissociation between impaired conscious access and preserved unconscious processing in schizophrenia.

## Trends

Patients with schizophrenia exhibit impairments of conscious processing and an elevated threshold for conscious perception, while subliminal processing is preserved.

The sensory impairments in schizophrenia could be explained by a disorder of conscious top-down attentional amplification rather than by bottom-up processing deficits.

Bayesian models account for the emergence of delusions through inappropriate updating of conscious representations according to sensory evidence.

Brain-imaging and neurophysiological studies of schizophrenia reveal anomalies in long-distance connectivity and synchrony between distant brain areas that may have a pivotal role in the disruption of conscious access.

NMDA receptors may have an important role in the pathophysiology of schizophrenia: there is growing evidence that NMDA receptors are dysregulated in this affection, that they have a prominent role in long-distance top-down connectivity, and that their disruption may induce psychosis and disorders of consciousness in subjects without schizophrenia.

<sup>1</sup>Cognitive Neuroimaging Unit, CEA DSV/I2BM, INSERM, Université Paris-Sud, Université Paris-Saclay, NeuroSpin Center, 91191 Gif/Yvette, France

<sup>2</sup>Sorbonne Universités, UPMC Université Paris 06, IFD, 4 Place Jussieu, 75252 Paris cedex 05, France

<sup>3</sup>Collège de France, 11 Place Marcelin Berthelot, 75005 Paris, France

## Dissociations between Conscious Access and Unconscious Processing in Schizophrenia

### Explicit versus Implicit Behavior

Many high-level cognitive functions, such as memory, attention, processing speed and executive functions, are broadly impaired in schizophrenia. It was proposed that, in some domains, schizophrenia specifically affects explicit cognitive processing, while implicit abilities remain preserved [7–9]. Indeed, persons with schizophrenia were found to exhibit a selective deficit in explicit recollection, but no impairment in implicit memory as measured by familiarity [7]. Implicit grammar learning was also preserved [8]. Patients also showed preserved implicit emotion processing while they were impaired in explicit emotion classification [10,11].

### Conscious versus Subliminal Processing

The dissociation between explicit and implicit processing has been further explored by comparing conscious versus **subliminal** processing. Studies of visual masking revealed an elevated threshold for conscious perception in schizophrenia [12–18]. For instance, when a digit was presented for a fixed duration and then, after a variable delay, followed by a mask made of several letters, persons with schizophrenia needed a longer delay than controls to consciously perceive the digit (Figure 1A,B). Similarly, patients are less likely to report that they perceive an unexpected event during **inattentive blindness** [19] and showed an exaggerated attentional blink effect compared to controls, associated with a decreased P300 [20]. Patients' nonaffected first-degree relatives may also exhibit an elevated masking threshold, suggesting that this finding is independent of medication and is an endophenotype of schizophrenia [21].

Remarkably, however, patients appear to process subliminal stimuli normally, resulting in a dissociation between impaired conscious processing and preserved subliminal processing. For instance, in number processing, conscious visual masking is impaired in schizophrenia while subliminal **priming** is preserved [14] (Figure 1C). Controls and patients were asked to compare a target number to five. This number was preceded by a fast presentation of another number that served as a prime and could be rendered invisible by masking. In the control group, performance in comparing the target number to five was affected by the congruency between the prime and the target under conscious (i.e., unmasked) and subliminal (masked) conditions: subjects were faster to answer when the prime and the target were congruent (both more or both less than five) than when they were incongruent (one more than and the other less than). However, in the patient group, the priming effect was observed only with subliminal primes but not with visible primes (Figure 1C).

Normal subliminal processing in patients with schizophrenia has also been observed in studies involving inhibitory processing [22] and emotional face or gaze direction processing under **continuous flash suppression** [23,24]. Some studies even suggest that masked emotional priming [25] and unconscious semantic priming [26] are enhanced in patients compared with healthy controls. Similarly, in a **change blindness** paradigm, patients moved their eyes toward the changes faster than did controls, suggesting normal or even enhanced unconscious processing, while their capacity to explicitly detect and report the changes was reduced [27]. Indeed, in the same studies, as soon as the threshold for conscious perception was crossed, conscious processing was impaired in schizophrenia, including inhibitory processing [22], number comparison [15], conscious priming [15], and conflict detection [14,28].

### Impaired Metacognition and Conscious Error Detection

Metacognition, the ability to represent and monitor one's own mental state, is also subject to this dissociation between altered conscious processing and preserved unconscious processing. For instance, a recent study assessed conscious and unconscious error monitoring, using subjective reports and an electrophysiological measure of error detection, in controls and

<sup>4</sup>INSERM, Laboratoire de 'Physiopathologie des maladies Psychiatriques', Centre de Psychiatrie et Neurosciences, CPN U894, Institut de Psychiatrie (GDR 3557), 75014 Paris, France

<sup>5</sup>Human Histopathology and Animal Models, Infection and Epidemiology Department, Institut Pasteur, 75015 Paris, France

<sup>6</sup>Université Paris Descartes, Sorbonne Paris Cité, Faculté de Médecine Paris Descartes, 75006 Paris, France

<sup>7</sup>Centre Hospitalier Sainte-Anne, Service Hospitalo Universitaire, 75014 Paris, France

\*Correspondence:  
lucie.berko@hotmail.com  
(L. Berkovitch).

persons with schizophrenia while they performed a number comparison task on masked stimuli [13]. Persons with schizophrenia presented a decreased ability to monitor their own errors on conscious trials, accompanied by a severely reduced **error-related negativity** (ERN), as also reported in other studies (Figure 2A,B) [28,29] (reviewed in [30]). Remarkably, however, the patients' performance in unconsciously evaluating the likelihood of having made an error was preserved on masked trials (Figure 2D). This study also showed that the ERN was present exclusively on trials when subjects reported seeing the target number: when the same stimulus was presented at threshold, an ERN was seen only on seen trials, not on unseen trials (Figure 2D) [13]. Thus, this study demonstrates that schizophrenia affects conscious error detection, while leaving subliminal error monitoring essentially intact.

### Self-Monitoring and Sense of Agency

In the phenomenological approach to perception, schizophrenia is described as a disorder of the sense of self, in which aspects of oneself are experienced as akin to external objects, with a weakened sense of existing as a vital and self-coinciding source of awareness and action (reviewed in [31]). Indeed, rigorous experiments have revealed deficits in conscious self-monitoring and agency. Persons with schizophrenia are impaired in discriminating their own hand from an alien hand [32]. Delusions of control can be conceptualized as a deficient representation of the links between conscious intention and action [33]. In a recent study [34], participants' sense of agency over subsequent action outcomes was manipulated by subliminal priming. Persons with schizophrenia showed a normal influence of subliminal priming on motor performance, but a reduced or even reversed influence of subliminal primes on the sense of agency, suggesting a dissociation between actual motor performance and the subjective feeling of control over action outcomes. This result again fits with the idea that, while automatic motor operations appear to be preserved, conscious aspects of motor behavior, such as sense of agency, are affected in schizophrenia.

## A Framework for Anomalies of Consciousness in Schizophrenia

### The Global Neuronal Workspace Theory of Consciousness

The above review shows that many cognitive impairments are demonstrated in schizophrenia. We posit that most, if not all, of them reflect a disruption in the ability to consciously access and manipulate information, with preserved unconscious processing. The GNW theory provides a theoretical framework that may account for this dissociation in schizophrenia. In turn, schizophrenia is a clinical condition that might be considered as a model disease to study which mechanisms are specific to conscious processing.

According to GNW theory [4,35–38], derived from Baars' seminal theory [39], conscious access rests upon the transient stabilization of neuronal activity encoding a specific piece of information. This occurs in a network of high-level brain regions interconnected by long-range connections, with the prefrontal cortex (PFC) acting as a key node. Conscious access starts when top-down attention signals amplify a relevant piece of information. On conscious trials, a wave of self-sustaining activity reaches the PFC, where information is stabilized and broadcasted to other areas. Global broadcasting is thought to render the information accessible to introspection and reportable to others (Figure 3). During access to a specific piece of information, other surrounding workspace neurons are inhibited and unavailable for processing other stimuli which remain **preconscious**, thus resulting in the attentional blink and other similar dual-task limitations. The transient dedication of central cognitive resources to a given stimulus is subjectively experienced as conscious perception [4,35–38].

Experimental tests of GNW theory have confirmed that a late and sudden nonlinear transition toward a metastable state of globally distributed brain activity, termed '**ignition**', characterizes conscious access [40,41]. Whether a given stimulus will induce global ignition and, therefore,

## Glossary

**Aberrant salience:** abnormal attribution of relevance to a stimulus that should normally be considered as neutral.

**Attentional amplification:** neurophysiological process through which a weak neural signal is strengthened by becoming the focus of attention, therefore increasing its chances of crossing the consciousness threshold.

**Bayesian predictive-coding framework:** theoretical model in which the brain continuously predicts upcoming events and uses Bayesian statistics to update posterior beliefs with sensory evidence to minimize prediction errors.

**Beta-band:** neural activity emitted in a frequency band between 13 and 30 Hz.

**Change blindness:** inability to detect a change in an image that flickers or changes very slowly.

**Cholinergic neurons:** nerve cells that use acetylcholine as a neurotransmitter. They are mostly located in the basal forebrain and are involved in wakefulness and rapid eye movement sleep.

**Continuous flash suppression:** psychophysical technique in which a stimulus is made invisible by being presented to one eye while other potent images are quickly flashed to the other eye.

**Disorganization syndrome:** incoherence between emotions, thoughts, and behavior, observed in persons with schizophrenia.

**Error-related negativity:** negative electroencephalographic component observed immediately after the subject makes an erroneous response.

**Gamma-band:** neural activity emitted in a frequency band between 30 Hz and approximately 100 Hz.

**Global neuronal workspace (GNW):** theoretical model according to which conscious access involves a large-scale neuronal network involving parietofrontal reverberant states and allowing the global sharing of information.

**Ignition:** sudden nonlinear transition toward a metastable state of globally distributed brain activity, characteristic of conscious access.

**Inattentive blindness:** inability to perceive an unexpected stimulus due to a lack of attention.

conscious perception, depends on both the initial amount of sensory evidence [40] and the availability of **attentional amplification** [41]. The GNW model predicts that two different mechanisms may affect conscious processing. At the sensory level, information may be too weak to be amplified. In this case, a bottom-up sensory deficit can lead to an elevated threshold of consciousness. Alternatively, sensory stimulation may be adequate but insufficiently amplified by top-down processes and/or maintained through self-sustained activity [42].

### Bottom-Up versus Top-Down Impairment

Which of these mechanisms best explains the deficit of conscious access in schizophrenia? Based on neurophysiological data, several authors have defended the view that the elevated threshold for conscious access in schizophrenia arises from a low-level deficit (reviewed in [16]). The reasoning rests on the observation of anomalies in steady-state responses [43] and early ERPs, such as the auditory P50 in a variety of paradigms, including prepulse inhibition of startle responses by a weaker preceding tone, inhibitory gating in response to paired sensory stimuli, or mismatch negativity (MMN) [44,45] (reviewed in [46]). An anomalous visual P1 response to low spatial frequency stimuli is also present in schizophrenia and has been attributed to a specific bottom-up dysfunction of the **magnocellular visual pathway**, while the **parvocellular pathway** is preserved (reviewed in [47]). According to the bottom-up hypothesis, the increased visual masking in schizophrenia thus stems from this magnocellular dysfunction.

However, this bottom-up hypothesis was recently contested since there is no clear evidence for whether the magnocellular pathway is hyper or hypoactive in schizophrenia, which casts doubt upon its role in the elevated consciousness threshold observed in schizophrenia [17]. Moreover, perceptual visual deficits in schizophrenia could be related to impaired communication between dorsal and ventral visual pathways rather than to an impairment of a specific pathway [48]. A bottom-up impairment also appears to be incompatible with the full preservation of subtle measures of unconscious processing, such as subliminal priming [14,15]. Therefore, it was proposed that magnocellular channels contribute primarily to conscious object vision via a top-down modulation of re-entrant activity in the ventral object-recognition stream, and that the preserved unconscious priming involves intact parvocellular channels [49]. There is indeed ample evidence that, in healthy controls, information amplification depends on a combination of bottom-up and top-down factors, with attention and expectation having a major role [40,41,50–53]. Even early brain responses, such as the MMN [54,55], the visual P1 [56–58], or the auditory P50, in healthy controls [59] and persons with schizophrenia [60], are sensitive to attentional allocation and top-down signaling. For instance, a reduced MMN is observed in schizophrenia both when a surprising sound arises within a regular sequence and when a predicted sound is omitted, suggesting a top-down prediction impairment [61]. Moreover, most early processing impairments in schizophrenia are magnified under conditions of top-down amplification [18,62–65].

To provide a pure test of the existence of a bottom-up impairment in schizophrenia, differences between patients and controls should be re-examined under inattention conditions that minimize top-down amplification. A recent study [66] dissociated bottom-up and top-down components by flashing numbers at various levels of masking to healthy controls and to persons with schizophrenia, in two maximally different conditions: focused attention versus distraction by a difficult concurrent task. Under unattended conditions, ERP were indistinguishable between persons with schizophrenia and healthy controls. In particular, the amplitude of N1 and N2 events increased linearly with target-masked SOA, identically in both groups, suggesting that the linear accumulation of evidence, which constitutes the first stage of bottom-up processing of masked stimuli [40,67], was unimpaired. By contrast, a major impairment was observed in the focused-attention condition: the N1 component was insufficiently amplified, and the late nonlinear ignition component associated with the P3 component was drastically reduced (Figure 1D), consistent

**Ketamine:** noncompetitive NMDA receptor antagonist drug that is used as an anesthetic agent at high doses but can induce psychosis-like symptoms at lower doses.

**Magnocellular visual pathway:** dorsal visual stream that provides spatial, depth, and motion information.

**Mismatch negativity (MMN):** event-related potential elicited when the brain detects a violation in an established pattern of sensory input.

**NMDA receptors:** glutamatergic receptors activated by the neurotransmitter glutamate. They are thought to be involved in the formation of slow attractor states and in synaptic plasticity, learning, and memory.

**Ongoing spontaneous activity:** brain activity that unfolds in the absence of sensory input (i.e., during resting state).

**Parvocellular pathway:** ventral visual stream that provides identity, detail, or color information.

**Phase synchrony:** systematic temporal relation between oscillatory neuronal responses.

**Preconscious:** information that remains unconscious due to a lack of top-down attention, possibly due to distraction by a concurrent task.

**Prediction error:** difference between the actual outcome and the predicted outcome.

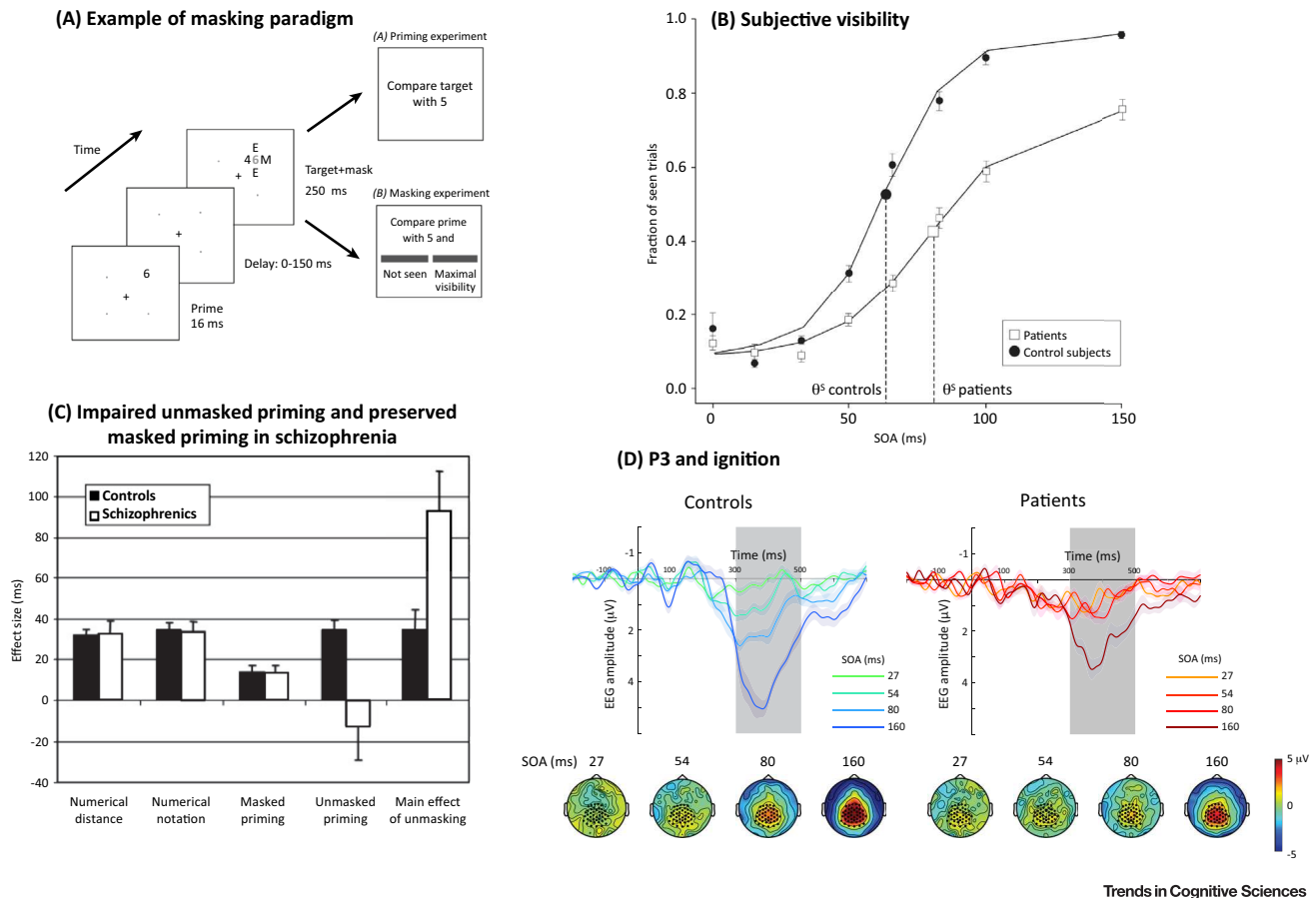
**Priming:** modulation of task performance on a stimulus due to pre-exposure to a related stimulus.

**Prior:** probability distribution representing a belief before it is updated by sensory evidence.

**Schizophrenia:** psychiatric disease characterized by positive symptoms, such as delusions (firmly held beliefs despite contradictory evidence) and hallucinations (perception without object), as well as negative symptoms, including withdrawal from social interactions and daily life activities, cognitive impairments, and disorganization syndrome.

**Subliminal:** information that is too short or too weak to be consciously perceived.





Trends in Cognitive Sciences

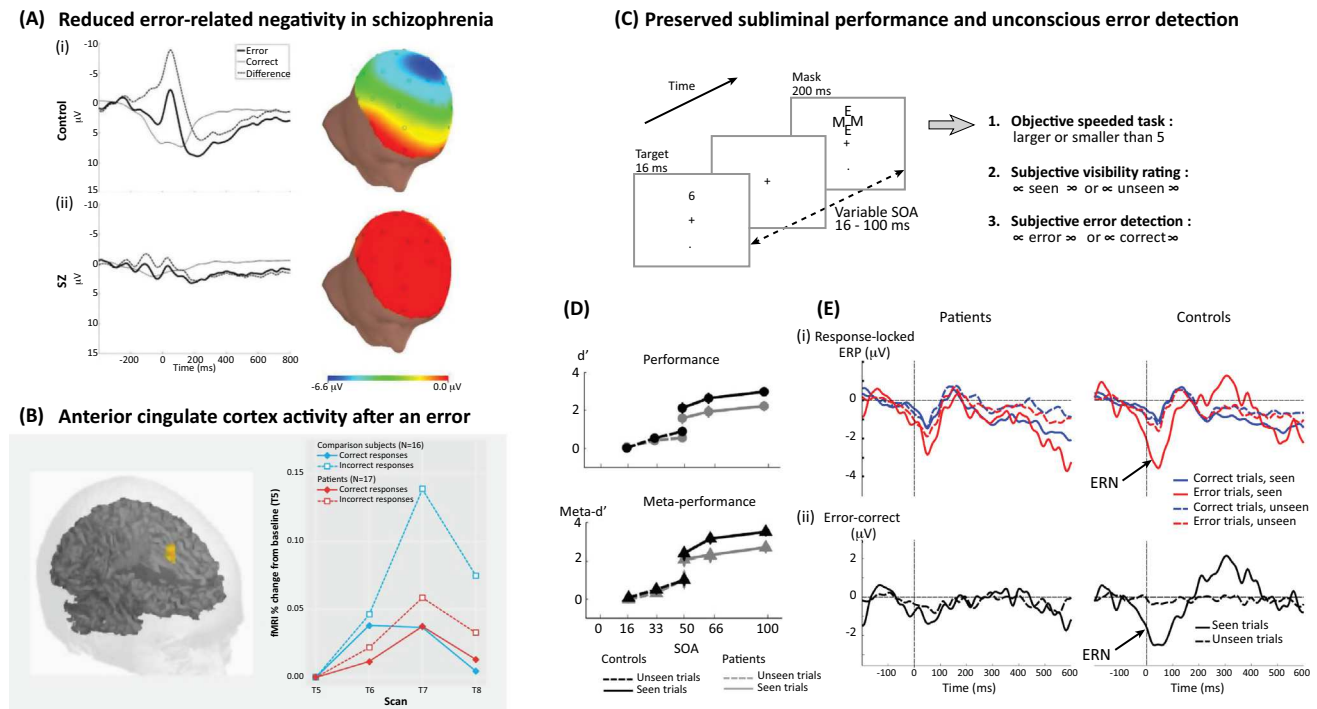
**Figure 1. Conscious Access Is Impaired in Schizophrenia.** (A) Example of masking paradigm by which conscious access can be parametrically manipulated. A digit (called the prime) is flashed for 16 ms. After a variable delay, it is surrounded by a mask comprising three letters and a target digit. The longer the delay between the prime and the mask (SOA), the higher the probability of seeing the prime. Participants can be asked various tasks: compare the target with five (priming), compare the prime with five (objective visibility), or report whether they saw it, using seen/not-seen labels or a continuous scale (subjective visibility). (B) Elevated subjective consciousness threshold in schizophrenia. Proportion of trials subjectively rated as 'seen' as a function of SOA. Subjective consciousness thresholds ( $\theta^s$ ) are defined in each group as the SOA for which the sigmoid curve reached its inflexion point. Error bars represent the standard error. (C) Both groups showed identical effects of numerical distance, number notation, and subliminal priming. However, they differed in the unmasked priming effect, which requires conscious control of interference. Patients were also severely slowed in the unmasked condition compared with the masked condition. (D) P300 and ignition are reduced in schizophrenia. Time courses of event-related potentials (ERPs) in P300 electrodes as a function of SOAs. Topographies show cerebral activity during the P300 time window. The cluster of electrodes is represented by the black dots in the topographies and the P300 time window by the gray rectangle in the time courses. Reproduced from [14,15,66].

with previous results [13,20,68,69]. Interestingly, patients showed an essentially normal attentional amplification of the P1 and N2 components, suggesting that only some but not all top-down attentional amplification processes are impaired in schizophrenia.

In summary, the time course of stimulus processing, as assessed by electrophysiological measures, suggests that most subliminal and preconscious stimuli are processed normally in schizophrenia. However, some stimuli that would have been conscious in healthy controls fail to cross the threshold for conscious perception and, thus, remain preconscious in patients with schizophrenia due to either a failure of top-down amplification or an inappropriately biased top-down amplification originating from the GNW (Figure 3).

### Relation to Bayesian Models of Top-Down Predictive Coding

In the **Bayesian predictive-coding framework**, perception is considered a statistical inference that combines bottom-up incoming sensory evidence with top-down predictions based

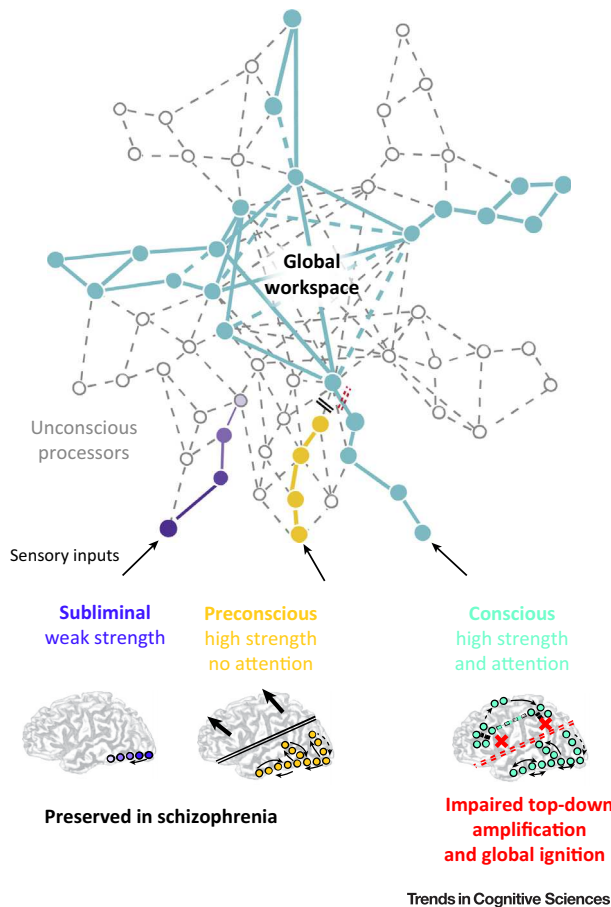


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**Figure 2. Dissociation between Preserved Unconscious Confidence and Impaired Conscious Error Detection in Schizophrenia.** (A) Error-related negativity (ERN) for control participants (i) and participants with schizophrenia (ii) during an arrow flankers task. Waveforms show channel Cz, and head maps show the difference between error and correct trials from 0 to 100 ms. (B) Persons with schizophrenia had a reduced error-related activity in the anterior cingulate cortex compared with normal subjects while performing a continuous performance task [press a target button whenever an 'A' (cue) was followed by an 'X' (probe), otherwise press another nontarget button]. (C) Experimental paradigm exploring error detection on seen and unseen trials. (D) Performance ( $d'$ , circles) corresponds to the participants' ability to compare the target digit with five. Meta-performance (meta- $d'$ , triangles) corresponds to the subjective ability to determine whether this comparison performance was correct or erroneous. Patients (gray lines) and controls (black lines) exhibit identical above-chance performance for unseen trials (broken line) but not for seen trials (solid line). Thus, unconscious metacognition is preserved while conscious error detection is impaired. (E) Time courses of ERPs as a function of objective performance and visibility for controls and patients. (i) Grand-average ERPs recorded from a cluster of central electrodes (FC1, FC2, C1, Cz, and C2) for patients (left) no ERN is observed between erroneous (red lines) and correct (blue lines) trials, whereas a strong ERN is observed for controls (right). (ii) Difference waveforms for error minus correct trials show a strong ERN only for controls and only on seen (solid lines), not on unseen (broken lines) trials. Reproduced from [13,28,29].

on learned or innate **priors** [70]. In case of a mismatch, a **prediction error** signal is sent in the bottom-up direction to update the internal model and, therefore, minimize later surprise. This framework was recognized early on as having the potential to explain psychotic symptoms: hallucinations could be understood as an imbalance between priors and sensory inputs, whereas delusion would result from a failure to update beliefs according to incoming prediction-error signals [71,72].

Empirical data have provided support for the general notion of impaired inference in schizophrenia, making the world less predictable, more bizarre, and prone to delusions [73,74]. For instance, in a task of perceiving black-and-white Mooney pictures, a shift toward prior knowledge was observed in a clinical group of individuals with early psychosis, and was associated with proneness towards psychosis in the general population [75]. Conversely, many studies suggest that patients' perception is sometimes excessively biased toward sensory inputs. Patients can be remarkably less susceptible than control subjects to visual illusions that arise from a strong effect of prior knowledge on sensory interpretation [76]. Moreover, they have a weaker tendency towards perceptual stabilization during intermittent viewing of ambiguous stimuli [77] and are impaired in tracking predicted target trajectories during a smooth pursuit of



**Figure 3. A Hypothesis of Impaired Top-Down Amplification and Conscious Access in Schizophrenia.** Dehaene *et al.* [37] distinguished three forms of processing in relation to conscious experience (i) subliminal processing, where incoming information is too weak to enter the global neuronal workspace (GNW) even if attended (purple color); (ii) preconscious processing, where information fails to be amplified by top-down attention and, therefore, is blocked from entering the GNW (yellow); and (iii) conscious processing, where information enters the GNW thanks to its strength and top-down amplification (light blue). Both subliminal and preconscious information are unconscious (i.e., not subjectively perceived and not reportable). Persons with schizophrenia show preserved subliminal [13–15,22] and preconscious processing [27], while conscious processing and conscious access are impaired [13–15,22]. In accordance with GNW theory, we postulate that the main mechanism of this impairment is an abnormal top-down amplification, which precludes information from crossing the threshold for access to consciousness. Thus, information that would have been consciously perceived by a normal subject remains preconscious, resulting in an elevated consciousness threshold.

occluded visual targets, but are better than controls in following unpredicted target deviations, suggesting that their perceptual predictions have reduced precision [78].

A related but distinct theoretical proposal builds upon the hypothesis of a disrupted balance of excitation and inhibition at the cellular level. It was suggested that, in psychosis, this imbalance brings forth a pathological form of causal inference called ‘circular belief propagation’ [79]. Instead of precisely cancelling each other through a perfect match, bottom-up sensory information and top-down predictions would reverberate and, thus, prior beliefs would be misinterpreted as sensory observations, and vice versa. Experimental evidence [80] suggests that schizophrenia is associated with an overestimation of sensory evidence through ascending inference loops, leading the patients to overestimated sensory evidence by erroneously combining it with itself and the prior multiple times: the patients ‘expect what they see’. In a computational model used to fit patients’ behavior, the free parameter that characterizes

these excessive ascending loops correlated with positive symptoms, while another parameter allowing for increased descending loops ('see what you expect') correlated with negative symptoms. Finally, both circular loops jointly predict a clinical measure of thought disorganization [80].

While these Bayesian models are built on a hierarchical view of brain function, they typically do not consider the specific role that conscious access may have in this hierarchy. The present review leads to the suggestion that bottom-up unconscious evidence accumulation is preserved or even enhanced in schizophrenia [27,78], and that the Bayesian inference deficit arises at the moment where conscious conclusions are drawn, through a discrete, sudden, nonlinear sampling of the unconscious distributions computed by unconscious processors [3]. The reduced GNW ignition, associated with a reduced P3 event-related potential, would then be a direct reflection of the failure to update conscious beliefs according to incoming evidence, as postulated by Bayesian theories.

Going further, the increase in the consciousness threshold and the presence of false inferences may mutually reinforce each other in schizophrenia. On the one hand, since expectations are known to facilitate conscious access [50,52,53], any impairment in the ability to draw inferences and to use them to develop expectations would result in an increase in the consciousness threshold. On the other hand, the gap between conscious representations and unconsciously processed incoming stimuli could give rise to inadequate inferences and, therefore, contribute to the **disorganization syndrome** observed in schizophrenia. Patients may not be able to consciously explain the aspects of their behavior, emotions, or intuitions that arise implicitly, guided by unconscious processing, and that occasionally burst into consciousness. Such unstable experiences would promote the invention of fictive interpretations and delusional beliefs, as also observed in patients with split-brains [81]. This hypothesis is in line with the phenomenological approach, which conceptualizes dysfunctions in schizophrenia as a deficit in the ability to combine components of self-experience into a coherent narrative [82].

Using computational modeling, it was recently demonstrated that, in an unstable environment, confidence is lowered. This leads to a reduction in the speed of reinforcement learning parameters, a metacognitive mechanism that is specifically disrupted in a **ketamine** model of psychosis [83]. Those effects are underpinned by altered neural activity in a frontoparietal network, including dorsomedial PFC and dorsal anterior cingulate. Interestingly, electrical stimulation of the dorsal anterior cingulate in humans elicits the subjective expectation of an imminent challenge coupled with a determined attitude to overcome it [84]. Dorsal anterior cingulate cortex is known to be activated during conflict monitoring [85]. Experiments indicate that overloading subjects with conflicting information induces a feeling of lack of control and leads normal subjects to endorse conspiracy theories or superstitions [86]. Therefore, we speculate that a similar effect may trigger, in persons with schizophrenia, the urge to search for an explanation and, thus, ultimately forge delusional beliefs.

### Neurophysiological and Molecular Basis of Impaired Consciousness in Schizophrenia

Can the proposed dissociation shed light on the physiopathology of schizophrenia? The GNW model makes precise predictions about the neurophysiological impairments that may disrupt conscious access without impacting on unconscious processing. Since conscious broadcasting relies on a fast interconnection of distant brain regions, dysconnectivity or abnormal interareal synchrony could specifically disrupt conscious processing. Moreover, considering the pivotal role of **NMDA receptor**-mediated glutamatergic transmission in top-down attentional amplification, an anomaly of this receptor pathway may also account for schizophrenia symptoms. In this section, we discuss both hypotheses in turn.

### Evidence for Dysconnectivity and Abnormal Oscillations

A key hypothesis of GNW theory [35–38,88,89], which is also mentioned in other theories of consciousness [87], is that conscious processing relies on long-range connectivity and synchrony to broadcast information to distant cerebral areas [35–38,88,89]. **Phase synchrony** is considered a basic mechanism through which information can be integrated across neuronal populations at multiple timescales [90,91]. Empirically, conscious perception in healthy controls is characterized by an increase in distributed **gamma-band** activity [92–94] and long-range **beta-band** communication [88,89,95].

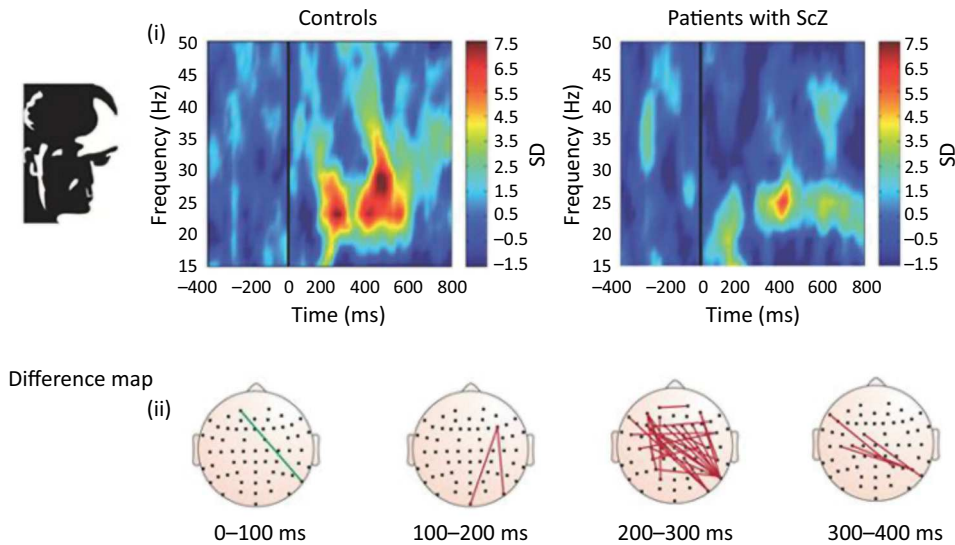
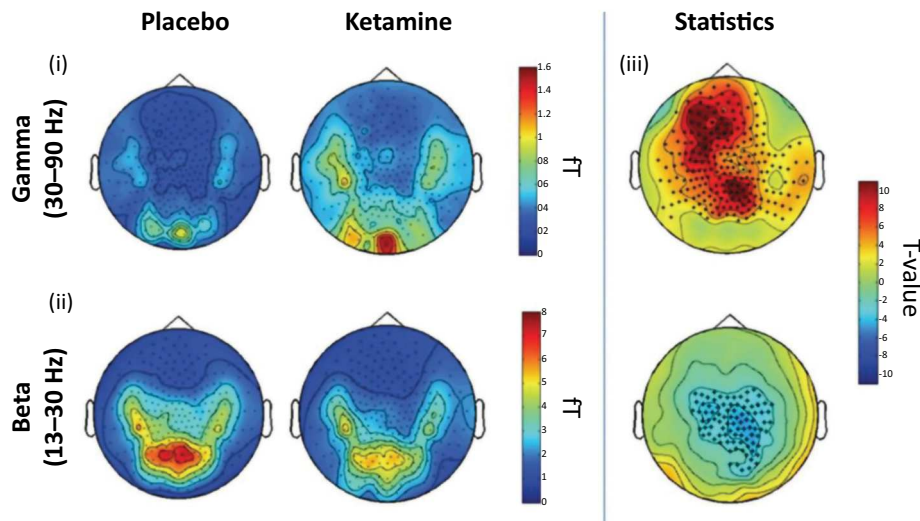
Therefore, it is of interest that these mechanisms appear to be strongly anomalous in patients with schizophrenia (Figure 4A), and could explain their disrupted conscious perception. The long-range synchrony of gamma and beta-band oscillations is disturbed in schizophrenia [96–98]. Persons with schizophrenia have long been known to exhibit abnormal anatomical and functional long-distance corticocortical connectivity (reviewed in [99]). Those findings fit with the dysconnectivity hypothesis, which postulates that the main symptoms of schizophrenia are better explained by abnormal connectivity and, therefore, impaired integration between distant brain regions [48,100,101] than by the isolated disruption of any localized brain process.

### The NMDA Receptor Dysregulation Hypothesis

Early computer simulations of the GNW model hypothesized that bottom-up propagation is primarily supported by fast glutamatergic AMPA receptors, whereas top-down amplification is supported by slower glutamatergic NMDA receptors [36,102]. NMDA receptors are ubiquitous, but electrophysiological studies using NMDA receptor antagonists confirm that they are particularly involved in top-down signaling [103–106]. NMDA receptors also appear to be critical for attention-induced reductions in variance and noise correlations [103].

Remarkably, an abnormal regulation of NMDA receptors has been suggested to be the core pathology in schizophrenia [101,107–109]. Indeed, schizophrenia-like psychotic symptoms have been observed in patients with autoimmune anti-NMDA receptor encephalitis [110]. Similar symptoms can be induced in healthy controls by NMDA receptors antagonists, such as ketamine and phencyclidine [111–114]. It was demonstrated that subjects with remitted schizophrenia were sensitive to the psychotomimetic effects of infused ketamine and that it brought forward symptoms that were similar to their own symptoms [113], suggesting that glutamatergic hypofunction is close to the pathophysiology of psychotic symptoms in schizophrenia. The subtle alterations that are observed in schizophrenia, for instance in perceptual learning, reasoning, or in ERPs, such as the mismatch negativity, can also be mimicked in normal subjects by administration of low doses of ketamine [83,115,116]. At higher doses, ketamine induces anesthesia, probably when the disruption of long-distance prefrontal-parietal connectivity exceeds a threshold value [117]. Put simply, large-scale NMDA blockade can have a direct and massive impact on consciousness.

Therefore, a core dysfunction of NMDA-based corticocortical circuitry in schizophrenia appears as a plausible, although not necessarily unique, mechanism for the deficits in top-down attention, conscious access, and conscious processing. Such an hypothesis fits with the finding that NMDA receptor antagonists affect gamma-band activity and reduce alpha- and beta-band activity thought to be involved in long-distance communication and the mediation of feedback to lower sensory areas (Figure 4B) [103,118–121]. Depressed delta and theta frequency range power is also observed after administration of NMDA antagonists in nonhuman mammals and linked to a reduction in top-down connectivity [103,104]. In addition to disrupting brain rhythms, NMDA blockade could disturb conscious access by disorganizing neural assemblies through a decreased signal:noise ratio [122]. For instance, low-dose ketamine administration can be associated with an enhanced functional connectivity in healthy

**(A) Long-distance phase synchrony is impaired in schizophrenia****(B) Ketamine increases gamma- and decreases beta-band activity**

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**Figure 4. Abnormal Neural Oscillations in Schizophrenia (ScZ) and under Ketamine Could Result in Impaired Conscious Access and Conscious Processing.** (A) Mooney faces were presented in an upright and inverted orientation and participants indicated whether a face was perceived. (i) The average phase synchrony (indicated by the colored scale) over time for all electrodes. In patients with schizophrenia, phase synchrony between 200 ms and 300 ms was significantly reduced relative to controls. In addition, patients with schizophrenia showed a desynchronization in the gamma band (30–55 Hz) in the 200–280 ms interval. (ii) Differences in the topography of phase synchrony in the 20–30 Hz frequency range between groups. Red lines indicate reduced synchrony between two electrodes in patients with schizophrenia compared to controls. Green lines indicate greater synchrony for patients with schizophrenia. (B) Topographic plots represent the average power spectra (fT) of gamma (i) and beta (ii) frequency ranges recorded during the resting state by magnetoencephalography (MEG) after administration of placebo (left) or ketamine (right). (iii) Results of the nonparametric cluster-based statistic highlighting sensors showing a statistically significant effect for gamma (i) and beta (ii) frequencies (red ketamine > placebo; blue: placebo > ketamine) ( $P < 0.001$ ). Abbreviation: SD, standard deviation. Reproduced from [98,119].

controls [123–125]. In particular, a PFC hyperconnectivity correlating with the psychotomimetic effects was observed after ketamine administration in healthy volunteers. This effect mimicked similar observations in individuals at high risk for schizophrenia as well as in patients with recently diagnosed schizophrenia, but not in patients with chronic schizophrenia [123]. Such increased connectivity could result in a consciousness impairment either by fractioning the GNW into overactive subparts or by saturating the GNW with endogenous spontaneous activity and, therefore, preventing external stimuli from entering its bottleneck [126]. In the first case, rapid transitions between spontaneously activated GNW states could result in a disorganization syndrome [127] and hallucinations [128]. The second hypothesis, saturation, would be similar to what can be observed during the loss of consciousness in temporal lobe seizures, in which an excessive synchronization overloads the brain networks involved in conscious processing [129]. In both hypotheses, a few signals would be abnormally amplified, and would block conscious access to others, resulting in the subjective feeling that these amplified signals are particularly salient [130].

#### Other Molecular Alterations

NMDA receptor alterations are by no means the only molecular markers of schizophrenia. Psychotic symptoms could also result from anomalies in  $\gamma$ -aminobutyric acid-mediated (GABAergic), dopaminergic, and cholinergic circuits, which are frequently reported and which may interact with each other. Note, however, that an NMDA receptor dysfunction could be linked to such impairments [131]. For instance, reduced prefrontal NMDA input to the ventral tegmental area has two consequences: (i) reduce the activity of GABAergic interneurons in ventral tegmental area, which in turn increases or disinhibits the activity of dopaminergic cells projecting to the striatum via D2 receptors resulting in aberrant dopamine bursts; or (ii) decrease the activity of dopaminergic neurons projecting back to the PFC via D1 receptors [101,132,133]. In turn, dopamine bursts could reinforce the abnormal coupling of cortical networks resulting from NMDA receptor dysfunction, similarly to the demonstration of an increased cortical coupling in proportion to striatal prediction errors in healthy controls [134].

Serotonin and acetylcholine also act as potent modulators of NMDA-dependent cortical circuits, such that their dysregulation may disrupt NMDA receptor conductance properties, trafficking or subunit composition [101]. Indeed, the MMN and P50 suppression and dysconnectivity observed in persons with schizophrenia or in healthy controls after ketamine administration may be reversed by nicotine administration [135,136] (reviewed in [46]).

Crucially, serotonin and acetylcholine are also involved in the transition between the awake and asleep states. **Cholinergic neurons** contribute to cortical arousal and increase their firing prior to awakening through nicotinic and muscarinic effects in both thalamus and cortex [137]. Moreover, the cholinergic system has a crucial role in regulating **ongoing spontaneous activity**, in particular the generation of ultraslow fluctuations (<0.1 Hz) and their synchronicity [138]. Remarkably, a single-nucleotide polymorphism on the gene encoding nicotinic acetylcholine receptor subunit alpha-5 increases the probability of schizophrenia in humans and leads to impaired prefrontal-dependent behaviors and ultraslow activity, which can be rescued by nicotine administration [139].

Simulations of the GNW and experimental results indicate that low levels of arousal and vigilance (e.g., during sleep or vegetative state) can prevent conscious access [102,140,141]: the removal of a brainstem drive to GNW neurons may lead to a failure of global ignition by external stimuli, even if they are long and intense. A moderate level of spontaneous activity is needed to facilitate conscious access, particularly for weak stimuli, because it brings GNW neurons closer to firing threshold. Conversely, simulations also show that exceedingly high spontaneous activity, by inducing spontaneous endogenous ignition of

GNW neurons irrespective of external stimulation, has a blocking role and prevents access to other external stimuli [102]. Thus, consciousness deficits could arise from both upwards and downwards shifts in the level of spontaneous neuronal activity.

### Concluding Remarks

Persons with schizophrenia exhibit an elevated consciousness threshold. In this paper, we argue that this anomaly is mostly due to attentional top-down deficits rather than to bottom-up impairments, since no deficit is observed under subliminal or inattention conditions. At a functional level, the disruption of consciousness appears to be underpinned by dysconnectivity among higher cortical areas participating in the GNW, a condition that can be triggered by impairments to NMDA-receptor mediated pathways and possibly to other systems such as cholinergic circuits.

Our proposal is that the conscious–unconscious dissociation is a fundamental distinction that must be taken into account to understand the core symptoms of psychosis. According to the present view, delusions constitute a set of conscious beliefs that remain stable even when they are contradicted by sensory evidence correctly processed at a lower subliminal level. The ensuing prediction errors, in turn, fuel a ceaseless search for these inadequate conscious explanations that we call delusions. This framework raises novel questions for Bayesian models of psychosis (see Outstanding Questions), and calls more generally for the use of experimental paradigms that dissociate cognition below and above the conscious threshold in schizophrenia. It also promotes interventions that would attempt to restore connectivity or synchrony in the GNW, possibly through glutamatergic or cholinergic modulation or brain stimulation.

### Disclaimer Statement

R.G. has received compensation as a member of the scientific advisory board of Janssen, Lundbeck, Roche, and Takeda. He has served as consultant and/or speaker for Astra Zeneca, Boehringer-Ingelheim, Pierre Fabre, Lilly, Otsuka, Recordati, SANOFI, Servier and received compensation, and he has received research support from Lilly and Servier.

### Acknowledgments

This research was supported by the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), the Institut National de la Santé et de la Recherche Médicale (INSERM), Collège de France, Fondation pour la Recherche Médicale (FRM), the Bettencourt-Schueller Foundation, and the Canadian Institute for Advanced Research (CIFAR).

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### Outstanding Questions

Can we design additional, more direct experimental tests of the hypothesis that unconscious probabilistic computations are preserved in schizophrenia while conscious sequential sampling from this distribution is impaired?

Does the administration of ketamine in healthy participants provide a proper model of schizophrenia? Would we observe abnormal conscious processing, elevated consciousness threshold, and preserved subliminal processing with ketamine, similar to what is observed for patients with schizophrenia?

Would psychotropic agents that affect the glutamatergic, dopaminergic, or nicotinic pathways correct the symptoms of impaired access to consciousness in schizophrenia?

What is the link between predictive coding and access to consciousness? Do valid predictions facilitate conscious perception, or by contrast, do violations and other surprising events gain easier access to consciousness, as is the case for unexpected emotional words?



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## **Chapter 2. Perturbations of conscious access and long-distance connectivity in psychosis**

### **Introduction of the article**

In the above presented review, we saw that patients with schizophrenia exhibited dissociation between impaired conscious access and preserved subliminal processing. The global neuronal workspace (GNW) theory of consciousness predicts that an abnormal connectivity within the neuronal network should disrupt conscious access without impacting subliminal processing.

In this chapter we explore whether connectivity, as measured by MRI-based tractography, correlates with consciousness threshold in three different populations: patients with schizophrenia who are known to have dysconnectivity and elevated consciousness threshold, patients with bipolar disorder who have dysconnectivity and for whom an elevated consciousness has sometimes been reported, and healthy controls. First, we show patients with bipolar disorder having psychotic features have an elevated consciousness threshold like patients with schizophrenia. Second, global fractional anisotropy correlates with consciousness threshold across subjects. A causal mediation analysis suggests that elevated consciousness threshold probably mediates the link between abnormal connectivity and psychotic symptoms.

### **Abstract**

According to the global neuronal workspace (GNW) theory, the long-distance connectivity of higher cortical areas, particularly prefrontal cortex, plays an essential role in conscious access by permitting a global ignition and broadcasting of distributed cell assemblies coding for the selected piece of information. Moreover, an elevated consciousness threshold has been repeatedly observed in patients with schizophrenia, and to a lesser extent, in patients with bipolar disorder. Here, we explored the link between cerebral connectivity and the threshold for conscious perception in patients with schizophrenia, bipolar disorder and controls. In a visual masking paradigm, participants were asked to report the identity and subjective visibility of a masked digit. The target-mask delay varied according to a staircase procedure and progressively converged towards the participant's threshold. Cerebral connectivity was measured using tractography based on diffusion MRI. Patients with bipolar disorder having

psychotic features and patients with schizophrenia had an elevated masking threshold compared to controls and to patients with bipolar disorder without psychotic features. Furthermore, the threshold correlated negatively with the mean fraction anisotropy of the left and right inferior frontal-occipital fasciculus, left and right cingulum, and corpus callosum. No correlation was observed with the occipito-temporal inferior longitudinal fasciculus, confirming that this correlation was specific to the network supposedly involved in the GNW. Causal mediation analysis further suggested that alterations in connectivity observed in patients led to an increase masking threshold which, in turn, favoured the occurrence of psychotic symptoms. These results support the hypothesis that long-distance cortical connectivity is crucial in conscious access and altered in psychosis.

## **Introduction**

During the last decades, much progress has been made in the understanding of the mechanisms of consciousness, thanks to an ongoing dialogue between experimental data and theoretical frameworks. The global neuronal workspace theory (Dehaene et al., 2011; Dehaene, Kerszberg, et al., 1998) assumes that information becomes consciously accessible when it is amplified by attention and triggers sustained activity in a large network of interconnected neurons (see Figure 1, left panel). This hypothesis is supported by experimental studies showing that conscious access is associated with a late and sudden non-linear transition toward a metastable state of globally distributed brain activity, termed “ignition” (Del Cul et al., 2007; Fisch et al., 2009; Lamy et al., 2008; Lau et al., 2006; Persaud et al., 2011; Salti et al., 2015; Sergent et al., 2005; van Vugt et al., 2018). The global neuronal workspace (GNW) theory predicts that an abnormal attentional amplification or connectivity within the postero-anterior long-distance cortical network should hinder conscious access. Interestingly, it turns out that anaesthetic agents, such as ketamine, induce a reversible loss of consciousness through the disruption of long-distance prefrontal-parietal connectivity (Blain-Moraes et al., 2014; Bonhomme et al., 2016; Lee et al., 2013; Uhrig et al., 2016; Vlisides et al., 2017; for a review, see: Mashour et al., 2018)

Neurological lesions have been previously studied to test some cerebral areas involvement in consciousness. For instance, lesions in the prefrontal cortex were shown to elevate masking threshold suggesting that it plays a crucial role in conscious access (Del Cul et al., 2009). Similarly, alterations of long-distance postero-anterior fibres may cause spatial

neglect, i.e. a state of partial unawareness of the environment (Thiebaut de Schotten et al., 2005; Urbanski et al., 2008). Importantly, some neurological and psychiatric diseases, such as multiple sclerosis and schizophrenia, are associated with diffuse anatomical and functional cerebral dysconnectivity (Au Duong et al., 2005; Cader et al., 2006; Lowe et al., 2002; Pettersson-Yeo et al., 2011; Stephan et al., 2009; Vinckier et al., 2014). Using diffusion MRI, alterations in fractional anisotropy, indicating disorganized and/or insufficient myelinated fibre tracts, were found in patients with schizophrenia (Kelly et al., 2018), particularly in prefrontal cortex (Buchsbaum et al., 1998), cingulum (Sun et al., 2003; Voineskos et al., 2010). Importantly, such a reduction of anisotropy was observed even in drug-naïve patients (Gasparotti et al., 2009) and was correlated with positive and negative symptoms (Skelly et al., 2008; Wolkin et al., 2003). These clinical populations are therefore of considerable interest to explore the link between cortical connectivity and conscious access.

Crucially, an elevated threshold for conscious perception had been repeatedly observed in schizophrenic patients using backward masking (Berkovitch et al., 2018; Butler et al., 2003; Charles et al., 2017; Del Cul et al., 2006; Green et al., 2011; Herzog et al., 2013), inattentional blindness (Hanslmayr et al., 2013) and attentional blink (Mathis et al., 2012) paradigms. We recently proposed that such a disruption in conscious access could increase the liability to delusions and hallucinations: partial access to information would make patients more interpretative and prone to develop false inferences that fuel delusional ideas (Berkovitch et al., 2017). Several mechanisms were put forward to explain this conscious access impairment (for a review, see: Berkovitch et al., 2017), in particular a disruption of top-down attentional amplification (Berkovitch et al., 2018) and an abnormal connectivity of long-range fibre tracts that bring sensory information into the high-level brain areas collectively forming the proposed global neuronal workspace, particularly prefrontal cortex (Carmel et al., 2006; Dehaene, Naccache, et al., 2001; Del Cul et al., 2007, 2009; Gaillard et al., 2009; Lafuente et al., 2006; Lamy et al., 2008; Lau et al., 2006; Persaud et al., 2011; Salti et al., 2015; Sergent et al., 2005; van Vugt et al., 2018). Nevertheless, the existence of a direct link between cerebral connectivity and the threshold for conscious perception has never been explored in schizophrenia.

In multiple sclerosis, patients also exhibit an elevated masking threshold: on average, they need a longer delay between a digit and a backward mask in order to consciously perceive the digit compared to controls (Reuter et al., 2007). The transition between non-conscious and conscious perception of the digit is non-linear and the “non-linear transition threshold” is



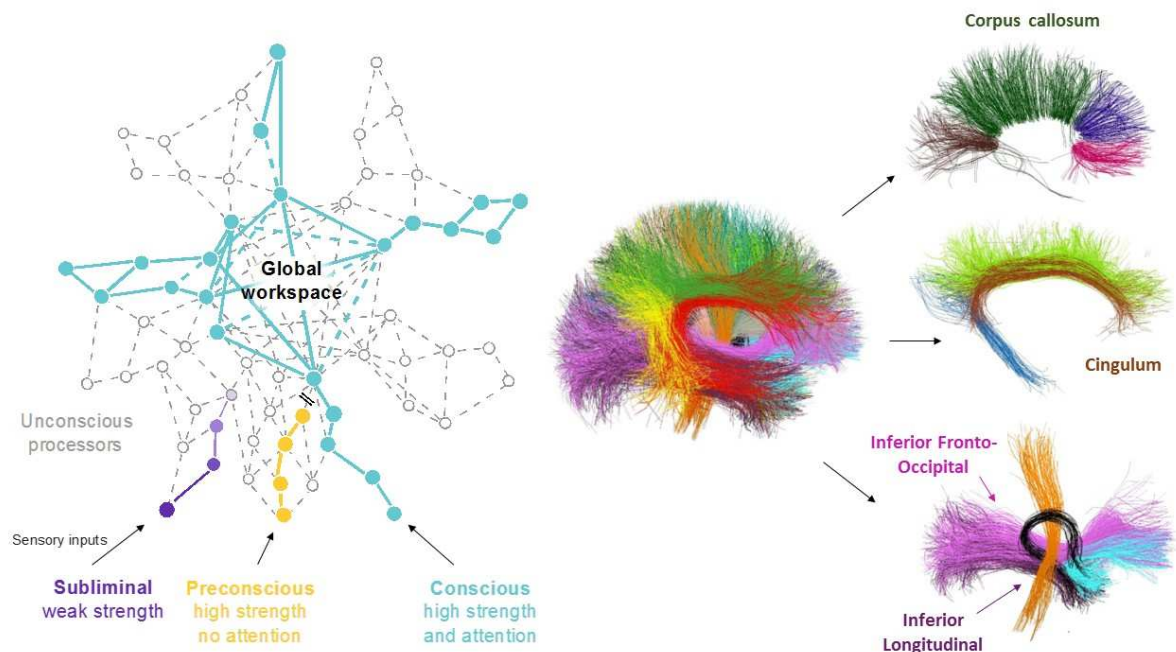
inversely correlated with a measure of fibre tract integrity (magnetization transfer ratio) in the right dorsolateral prefrontal white matter, the right occipito-frontal fasciculus and the left cerebellum (Reuter et al., 2009). This study provides a first indication that conscious access relates to the integrity of large long-distance white matter bundles.

Bipolar disorder and schizophrenia are sometimes considered as belonging to the same spectrum, with shared symptoms, risk factors and pathophysiology (Lichtenstein et al., 2009). Interestingly, dysconnectivity and reduction of white matter tracts have been observed in bipolar patients as well (Benedetti et al., 2011; Lin et al., 2011), particularly those with psychotic features (Anticevic et al., 2013; Sarrazin et al., 2014). Therefore, here we formulated and tested the hypothesis that dysconnectivity would be present in both schizophrenic and bipolar patients with psychotic symptoms and may cause an elevation in the threshold for conscious perception that would in turn favour psychotic symptoms in these populations (Berkovitch et al., 2017; Friston et al., 1995; McIntosh et al., 2008; Skelly et al., 2008; Stephan et al., 2009).

Up to now, few studies explored the threshold for conscious access in bipolar patients, with mixed results. Most of them found that bipolar patients had an elevated threshold during backward masking (Chkonia et al., 2012; Fleming et al., 1995; MacQueen et al., 2004; McClure, 1999), but one of them found that backward masking was unaffected (Goghari et al., 2008). The first goal of the present study is to measure the masking threshold in patients affected by bipolar disorder, particularly those with psychotic features, in order to probe the link between psychotic symptoms and an elevated threshold.

Another goal of this study is to explore whether long-range postero-anterior structural connectivity, as measured by diffusion MRI-based tractography, correlates with a behavioural estimation of consciousness threshold in patients with schizophrenia, and to extend these results to other populations, namely patients with bipolar disorder and healthy controls. Following the predictions of global neuronal workspace theory (Dehaene et al., 2011; Dehaene, Kerszberg, et al., 1998), we assume that slight fluctuations of connectivity in the general population would correlate with variations in threshold for conscious perception. We therefore aimed to assess whether the correlation between cerebral connectivity and conscious access is specific to a pathological state or observable in general population, and to study effects of clinical symptoms on cerebral connectivity and consciousness threshold.

In patients with schizophrenia ( $n = 26$ ), bipolar disorders with or without psychotic symptoms ( $n = 10$  and  $17$  respectively) and controls ( $n = 46$ ), we assessed the consciousness threshold using a backward visual masking paradigm, while cerebral connectivity was measured using diffusion imaging based tractography and generalized fractional anisotropy (gFA). We conducted analyses on seven cortical fibre bundles. Five of them are supposed to play a critical role in conscious access according to the global neuronal workspace theory (Dehaene et al., 2011). Left and right inferior-fronto-occipital fasciculus (IFOF) and left and right cingulum long fibres (CLF) correspond to long distance postero-anterior fibres (Forkel et al., 2014; Guevara et al., 2012; Sarubbo et al., 2013), while the body of corpus callosum underlies interhemispheric communication and the formation of a single bi-hemispheric state of ignition (Hesselmann et al., 2013). Two additional bundles (left and right inferior longitudinal fasciculi ILF) were included in the analysis as a control, to check whether correlation between masking threshold and cerebral connectivity was restricted to fibres involved in the global neuronal workspace (Figure 1, right panel). Indeed, the ILF connects occipital and inferior temporal areas primarily involved in early vision, and a study investigating spatial awareness suggested that damage to IFOF contributed to spatial neglect but this was not the case for the ILF (Urbanski et al., 2008).



*Figure 1.* Representation of the global neuronal workspace and detailed view of the bundles of interest. Left panel. The global neuronal workspace theory assumes that an information becomes consciously accessible when it is amplified by attention and triggers sustained activity in a large network

of interconnected neurons. The long-distance connectivity of higher cortical areas, particularly prefrontal cortex, therefore plays an essential role in conscious access. Right panel. We restricted the imaging analysis to bundles supposedly involved in the global workspace. Left and right inferior-fronto-occipital fasciculi (IFOF, pink) and left and right cingulum long fibres (CLF, brown) correspond to long distance postero-anterior, the body of corpus callosum (green) underlies interhemispheric communication and the formation of a single bi-hemispheric state of ignition. Two additional bundles (left and right occipito-temporal inferior longitudinal fasciculi ILF, purple) were included in the analysis as a control, to check whether a correlation between masking threshold and cerebral connectivity was restricted to fibres involved in the global neuronal workspace.

We predicted that (1) an elevated masking threshold would be observed in patients with schizophrenia and to a lesser extent in patients with bipolar disorder, (2) this elevated masking threshold would be correlated with psychotic features, and (3) long-distance postero-anterior cerebral connectivity would correlate with threshold for conscious perception in both patients and healthy controls.

## **Material and methods**

### **Participants**

We included 99 participants: 27 patients with bipolar disorder (10 without psychotic features and 17 with psychotic features), 26 patients with schizophrenia and 46 controls. All subjects underwent consciousness threshold and MRI assessments. Controls were recruited through advertisements and sampled from the general population. They were free of any past or present psychiatric disorder and first-degree family history of bipolar disorder, schizophrenia or schizoaffective disorder. Patients were recruited from two psychiatry departments of university-affiliated hospitals (APHP, Henri Mondor Hospitals Créteil and Fernand Widal – Lariboisière, Paris, France) and were included if suffering from DSM-IV bipolar disorder type 1 or 2, schizophrenia or schizoaffective disorder. History of psychotic features for patients with bipolar disorder was defined as at least 1 manic or 1 depressive episode with delusions or hallucinations (DSM-IV-R). Inclusion criteria for all participants were age between 18 and 60, no history of alcohol or drug abuse/dependence, no previous head trauma with a loss of consciousness, no current or past cardiac or neurological disease, no contraindications for magnetic resonance imaging (MRI). Participants' characteristics are reported in table 1. The

study was approved by the local institutional review board (CPP Mondor University Hospital, Créteil, France). Written informed consent was obtained for all subjects after a complete description of the study. Chlorpromazine equivalents were calculated following international, expert consensus based recommendations (Gardner et al., 2010), information was missing for one patient with bipolar disorder. Current psychotic symptoms were rated using the Positive and Negative Symptom Scale (PANSS, Kay et al., 1987); this information was missing for 5 subjects (1 patient with bipolar disorder and 4 patients with schizophrenia). Participants' characteristics are summarized in Table 1.

**Table 1 – Behavioural measures**

	<i>Control</i> <i>mean</i> <i>(± s.d.)</i>	<i>Bipolar disorder without psychotic features</i> <i>mean</i> <i>(± s.d.)</i>	<i>Bipolar disorder with psychotic features</i> <i>mean</i> <i>(± s.d.)</i>	<i>Schizophrenia</i> <i>mean (± s.d.)</i>	<i>Statistical test</i> <i>(test value, p-value)</i>
Sample size	46	9	17	25	—
Age (years old)	35.6 (±11.4)	31.6 (±8.4)	34.9 (±12.4)	29.5 (±8.5)	F <sub>3,93</sub> = 1.96 p = 0.13
Gender (M/F)	21/25	8/1	9/8	17/8	χ <sub>3</sub> = 7.5 p = 0.058
PANSS* score	—	38.0 (±5.2)	39.1 (±14.4) (1 missing)	72.4 (±21.4) (4 missing)	F <sub>2,43</sub> = 22.26 p < 0.001
Chlorpromazine equivalence dose (mg/day)	—	146.3 (±252.8)	186.3 (±339.4) (1 missing)	864.2 (±735.3)	F <sub>2,47</sub> = 9.11 p < 0.001
Consciousness threshold (ms)	54 (±10)	49 (±10)	64 (±12)	62 (±14)	F <sub>3,93</sub> = 6.52 p < 0.001

\*Positive and negative syndrome scale

### Consciousness threshold measure

Stimuli and procedure were similar to Del Cul et al. (2009) which used a variant of the masking paradigm used in previous studies with normal and clinical populations (Berkovitch et al., 2018; Charles et al., 2017; Del Cul et al., 2006, 2007; Reuter et al., 2007, 2009) (see Figure 2). A target digit (0–9) was presented for a fixed duration of ~17 ms at a randomly

chosen position among four (1.4 degrees above or below and 1.4 degrees right or left of the fixation cross). After a variable delay (stimulus onset asynchrony or SOA), a metacontrast mask appeared at the target location for 250 ms. The mask was composed of four letters (two horizontally aligned M and two vertically aligned E) surrounding the target stimulus location without superimposing or touching it.

On each trial, subjects were first asked to report subjective visibility (“Did you see the digit?”) and then to name the masked digit under forced-choice instructions (“Whether or not you saw a digit, please attempt to name it”). Responses were made verbally in French and were recorded manually by the experimenter.

Target-mask SOA varied on a trial-by-trial basis according to target visibility using a ‘double staircase’ algorithm (Del Cul et al., 2009), in order to maintain subjective visibility at the threshold. Each trial was randomly assigned to one of the two staircases, one starting with the shortest SOA (17 ms) and the other with the highest SOA (133 ms). Independently for each staircase, the stimulus-mask SOA was decreased by one frame (17 ms) whenever the subject reported seeing the stimulus on the previous trial and was correct in the objective discrimination task. Otherwise, the SOA was increased by one frame. Once SOA reached the approximate value of the subject’s conscious perception threshold, the SOA variations often reversed from one trial to the next. The algorithm stopped the experimental block once the number of reversals reached an arbitrary value ( $n = 18$ ). As in Del Cul and colleagues’ experiment. (2009), the masking threshold was estimated as the mean SOA over the trials 15-50.

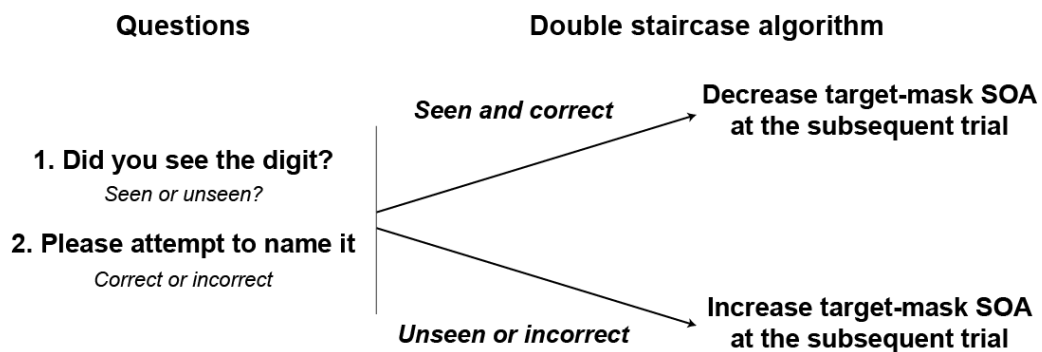
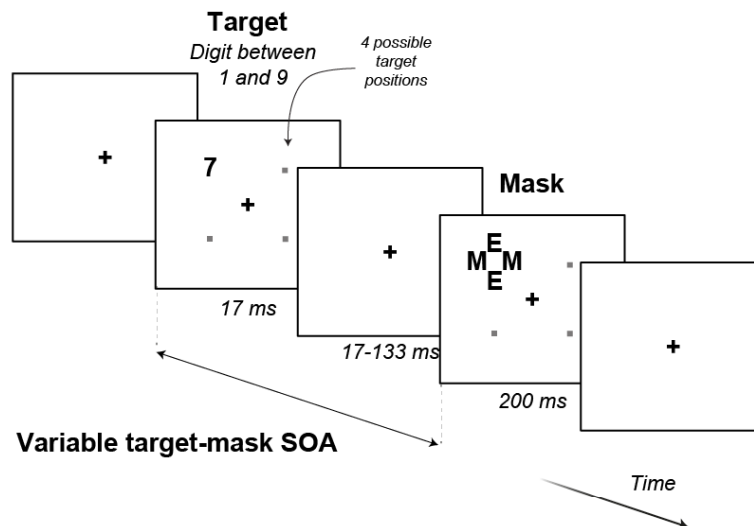


Figure 2. Experimental paradigm. To determine the masking threshold, a double staircase algorithm was used. A digit target was presented for 17 ms and masked after a variable delay (SOA) by a metacontrast mask composed of four letters. Participants had to say whether they saw the digit or not and to name it. If the target was both seen and correctly named, the target-mask SOA was decreased in the subsequent trial, making the target more difficult to consciously perceive. Otherwise (unseen and/or incorrect answers), the target-mask SOA was increased.

## MRI acquisition

We scanned all participants at Neurospin neuroimaging centre on the 3T Magnetom TrioTim syngo MR B17 with 12-channel head coil (Siemens Medical Solutions). The MRI protocol included a high-resolution T1-weighted acquisition (TE, 2.98 milliseconds; TR, 2300 milliseconds; 160 sections; voxel size, 1.0 × 1.0 × 1.1 mm) and a DW sequence along 60 directions (voxel size, 2.0×2.0×2.0 mm; b = 1400 s/mm<sup>2</sup> plus 1 image in which b = 0; TE 92 ms; TR 12 s; 60 axial sections). Data were assessed for movement, susceptibility, and noise artifacts with the operators blinded to the diagnosis.

## **DWI data processing**

We here briefly describe the processing of diffusion-weighted images (DWI) as the present protocol is similar to the one we used in previous studies (i.e. Sarrazin et al., 2014; and Souza-Queiroz et al., 2016). We used Connectomist 2.0 and BrainVisa 4.2 software to process DW MRI data (<http://www.brainvisa.info>). The DW images were corrected for noise/spikes with q-space interpolation correction. We then computed an orientation distribution function at each voxel included in this mask using an analytical QBI model (spherical harmonic order, 6; regularization factor  $\lambda=0.006$ ) (Descoteaux et al., 2007). As an equivalent to fractional anisotropy, we evaluated the generalized FA (gFA) from all the computed orientation distribution functions (Tuch, 2004). A decreased gFA value is thought to indicate the loss of integrity or loss of coherence of WM (Le Bihan et al., 2012).

The definition of the 3-dimensional space within which the fibres are tracked is necessary for tractography algorithms. To compute a more robust mask, we used a T1-based propagation tractography mask (Guevara et al., 2012). We performed whole-brain tractography in each subject native space using a regularized streamline deterministic algorithm (one seed per voxel, forward step 0.5 mm, bilateral propagation). Algorithm propagation was interrupted if the tract length exceeded 300 mm, if the tract streamline propagated outside the mask or if the curvature between two steps exceeded 30°. No between-subject registration was performed.

Whole-brain tractography volumes were then segmented using an automatic segmentation pipeline based on a clustering technique relying on the definition of a pairwise distance between fibres and described in depth elsewhere (Guevara et al., 2012; Sarrazin et al., 2014). This process leads to the segmentation of the tractography datasets into 22 known deep WM bundles, allowing a whole-brain exploration of WM connectivity. We then extracted the mean gFA along the bundles for each subject using Brain VISA software.

## **Statistical analysis**

Welch two sample t-tests, analyses of variance (ANOVAs) and Pearson's correlation were conducted on masking threshold, with clinical and imaging characteristics as within-subject factors. Regarding clinical characteristics, factors were diagnosis (bipolar disorder versus schizophrenia), history of psychotic symptoms for bipolar disorder (presence versus absence), chlorpromazine equivalent daily doses and PANSS scores. Their effects were

analysed separately because they were expected to strongly interact. We conducted Pearson correlations between masking threshold and mean gFA separately for each bundle with, and then ANOVAs on masking threshold with mean gFA and clinical characteristics as within-subject factors. Statistical results were adjusted for multiple comparisons using the `p.adjust` function in the R software, with the Bonferroni method.

Finally, we examined the link between connectivity, masking threshold and psychotic symptoms across subjects with causal mediation analysis, inspired from Baron and Kenny (1986; see also: Shrout et al., 2002). Mean gFA was explored as a predictor variable of masking threshold with a first linear model. Then, in a second linear model, presence of psychotic features was studied as an outcome variable, explained by mean gFA (predictor variable) and consciousness threshold (moderator variable). The two linear models were entered in a causal mediation analysis with 10.000 simulations, using the `mediate` function included in the R software mediation package (Tingley et al., 2014, <https://www.r-project.org>). Results are expressed with p-values (significant under 0.05), Welch *t*-value, Pearson *r*-value, *F*-value, and quasi-Bayesian 95% confidence intervals.

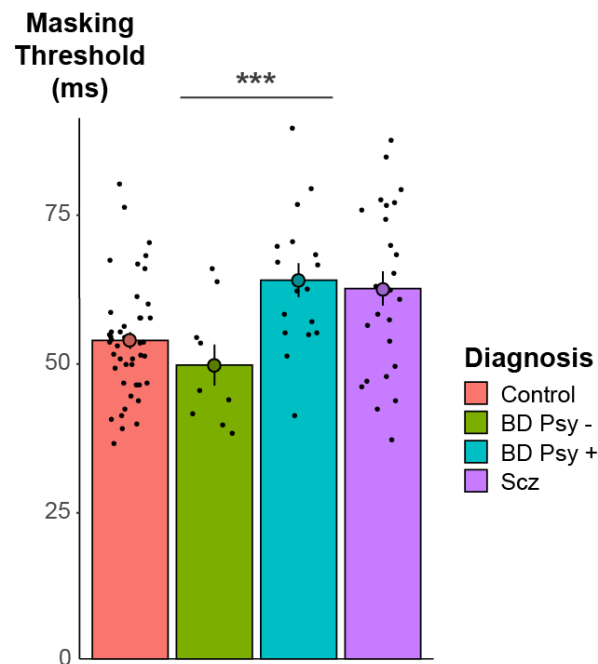
## Results

### **Behavioural results: the masking threshold is elevated in patients with psychotic features**

We first examined whether the masking threshold was significantly influenced by clinical characteristics. Two participants (one patient with bipolar disorder, one with schizophrenia) were excluded because their consciousness thresholds were more than 3 standard deviations above the group mean (134 ms and 97 ms respectively). Behavioural data and participants' characteristics are summarized in Table 1, behavioural results are shown in Figure 3. An ANOVA revealed a significant interaction between masking threshold and diagnosis ( $F_{2,94} = 4.72$ ,  $p = 0.011$ ). We conducted Welch *t*-tests to compare the groups two by two. Patients with schizophrenia had a significantly higher masking threshold than controls (62 ms versus 54 ms,  $t_{35.7} = 2.75$ ,  $p = 0.009$ ). By contrast, in a two-tailed test, patients with bipolar disorder did not significantly differ in consciousness threshold from healthy controls (59 ms versus 54 ms,  $t_{40.2} = 1.79$ ,  $p = 0.081$ ). No significant difference was observed between the two patient groups ( $t_{48.1} = -0.92$ ,  $p = 0.36$ ). Among patients, there was no significant relation between the chlorpromazine equivalent daily doses and the masking threshold (Pearson  $r =$



0.22,  $t_{48} = 1.58$ ,  $p = 0.12$ ) but symptomatology as assessed by the PANSS exhibited a significant positive correlation ( $r = 0.31$ ,  $t_{44} = 2.14$ ,  $p = 0.038$ ).



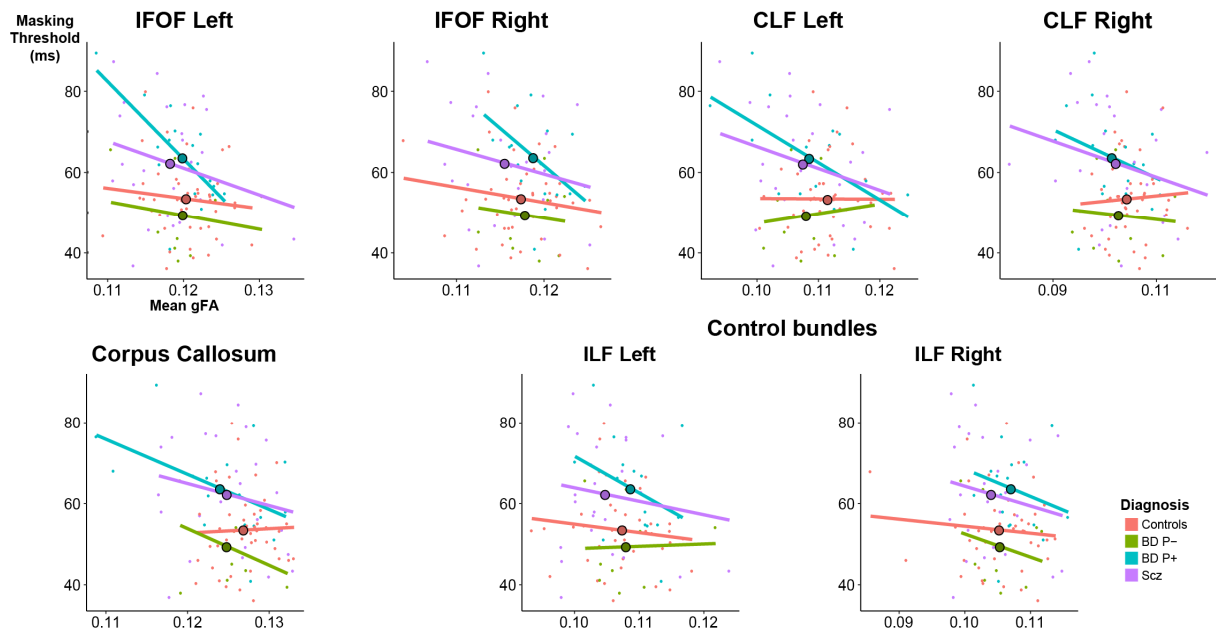
*Figure 3.* Behavioural results. The masking threshold was significantly increased in patients with psychosis, i.e. with bipolar disorder associated with psychotic features (BD Psy+, blue) and with schizophrenia (Scz, purple) compared to controls (pink) and patients with bipolar disorder without psychotic features (BD Psy-, green). \*\*\* =  $p < 0.001$ . Error bars represent one standard error of the mean.

To further explore the masking threshold in patients with bipolar disorder according to their symptoms, we split the group into two subgroups according to the presence or absence of psychotic features. Across subjects, a significant difference was observed between participants with and without psychotic symptoms (i.e. controls and patients with bipolar disorder without psychotic features, versus patients with schizophrenia and with bipolar disorder and psychotic features (63 vs. 53 ms,  $t_{72.1} = -4.14$ ,  $p < 0.001$ ). Patients with bipolar disorder without psychotic features did not differ from controls regarding their consciousness threshold (49 ms vs. 54 ms,  $t_{10.8} = 1.11$ ,  $p = 0.29$ ). However, patients with bipolar disorder with psychotic features had a significantly higher masking threshold than healthy controls (64 ms vs. 54 ms,  $t_{24.2} = -3.21$ ,  $p = 0.004$ ), and did not differ from patients with schizophrenia ( $t_{38.6} = -0.35$ ,  $p = 0.73$ ).

## Anatomical connectivity correlates with masking threshold

Across subjects, the masking threshold was significantly and negatively correlated with the mean gFA of the left IFOF (Pearson  $r = -0.29$ ,  $t_{95} = -2.95$ ,  $p = 0.004$ ), right IFOF ( $r = -0.22$ ,  $t_{95} = -2.19$ ,  $p = 0.031$ ), left CLF ( $r = -0.28$ ,  $t_{95} = -2.80$ ,  $p = 0.006$ ), right CLF ( $r = -0.21$ ,  $t_{95} = -2.05$ ,  $p = 0.043$ ) and body of corpus callosum ( $r = -0.27$ ,  $t_{95} = -2.77$ ,  $p = 0.007$ ) (Figure 4). A negative correlation implies that a greater anisotropy leads to an improved conscious perception and therefore a lower threshold, as predicted by the GNW hypothesis. Note that three of these correlations remain significant after Bonferroni adjustments, correcting for the seven bundles tested (left IFOF:  $p_{\text{adjusted}} = 0.028$ , right IFOF:  $p_{\text{adjusted}} = 0.22$ , left CLF  $p_{\text{adjusted}} = 0.042$ , right CLF:  $p_{\text{adjusted}} = 0.30$ , corpus callosum:  $p_{\text{adjusted}} = 0.049$ ).

Correlations did not significantly differ between the three groups (healthy controls, patients with bipolar disorder and with schizophrenia) when compared two by two (all  $F < 2.8$ , all  $p > 0.09$ ). Crucially, for control bundles (i.e. left and right ILF), mean gFA did not significantly correlate with masking threshold (all  $|t_{95}| < 1.7$ , all  $p > 0.1$ ).



*Figure 4.* Masking threshold as a function of mean of generalized fraction anisotropy (gFA) in each subgroup of participants. Each participant is represented in the point cloud (pink: controls, green: patients with bipolar disorder without psychotic features, blue: patients with bipolar disorder and psychotic features, purple: patients with schizophrenia). Mean of the masking threshold and the mean gFA in each group is represented by the dots with black outlines on the regression lines. A significant negative correlation between masking threshold and mean gFA was observed across subjects for the left

and right inferior frontal-occipital fasciculi, left and right cingulums, and the corpus callosum. By contrast, no such correlation was evidenced for the left and right inferior longitudinal fasciculi, confirming that this correlation was specific to the network supposedly involved in the GNW.

We then examined whether the effect of mean gFA on masking threshold was influenced by medication (chlorpromazine equivalent daily doses). Effect of mean gFA remained significant for left IFOF ( $F_{1,45} = 6.01$ ,  $p = 0.018$ ), left CLF ( $F_{1,45} = 4.54$ ,  $p = 0.039$ ) and corpus callosum ( $F_{1,45} = 4.67$ ,  $p = 0.036$ ) but failed to reach significance for right IFOF and CLF (all  $F_{1,45} < 3$ , all  $p > 0.09$ ) when medication was taken into account as an additive fixed effect.

Then we explored whether clinical characteristics influenced the correlation between the mean gFA and the masking threshold. PANSS interaction with mean gFA had no significant effect on masking threshold within patients (gFA  $\times$  PANSS: all  $F_{1,42} < 1$ , all  $p > 0.3$ ). By contrast, interaction between psychotic features and mean gFA across subjects had a significant effect on masking threshold for left CLF (gFA  $\times$  psychotic features:  $F_{1,93} = 4.77$ ,  $p = 0.032$ ) but it was not the case for other bundles (all  $F_{1,93} < 2.5$ , all  $p > 0.1$ ). When splitting participants into two groups according to psychotic features, correlation between mean gFA of left CFL and masking threshold was significant for patients with psychotic features but not for participants without psychotic features (with:  $r = -0.38$ ,  $t_{40} = -2.62$ ,  $p = 0.012$ , without:  $r = 0.06$ ,  $t_{53} = 0.42$ ,  $p = 0.68$ ).

Finally, we conducted a mediation analysis to tentatively investigate the link between connectivity, consciousness threshold and psychotic symptoms. We assumed that dysconnectivity would elevate the consciousness threshold, which would in turn favour psychotic symptoms. We entered the presence of psychotic features as an outcome variable, mean gFA as a predictor variable and masking threshold as a moderator variable in two linear models that were next combined to perform mediation analysis. Results are presented in Figure 5. They indicated that the correlation between altered mean gFA and psychotic features was mediated by elevated masking threshold for all bundles (left IFOF: effect mediated by the consciousness threshold (ACME): CI = [-24.01 -3.45],  $p = 0.003$ ; right IFOF: ACME: CI = [-21.79 -1.12],  $p = 0.026$ ; left CLF: ACME: CI = [-16.03 -1.95],  $p = 0.006$ ; right CLF: ACME: CI = [-14.60 -0.35],  $p = 0.038$ , corpus callosum: ACME: CI = [-22.33 -2.68],  $p = 0.007$ ). No direct effect yielded a significant result (all  $p > 0.1$ ). Those results tentatively suggest that a reduced gFA does not induce psychotic symptoms directly, but only through its effect on the consciousness threshold.

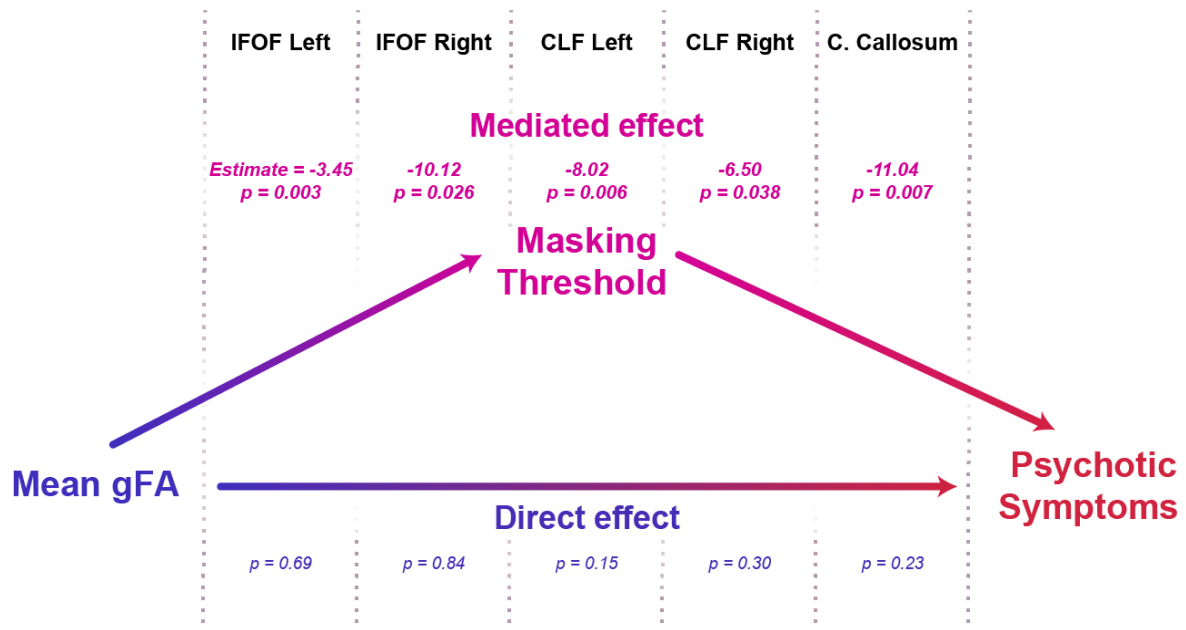


Figure 5. Causal mediation analysis. To examine the link between connectivity (mean gFA), masking threshold and psychotic features, we conducted a causal mediation analysis across subjects with mean gFA as a predictor variable, psychotic symptoms as an outcome variable, and masking threshold as a moderator variable. In this figure, we report estimates and p-values of mediated and direct effects for each bundle (in columns). Mediated effects (pink) were significant for all bundles while direct effects (in blue) were not. These results tentatively suggest that a reduced gFA does not induce psychotic symptoms directly, but only through its effect on the masking threshold.

## Discussion

Using a visual backward masking paradigm, we estimated the consciousness threshold with a double staircase algorithm (Del Cul et al., 2009), and explored whether it was correlated with structural connectivity in diffusion imaging based tractography. Overall, we found that patients with schizophrenia and bipolar disorder had an elevated masking threshold compared to healthy controls. Presence of psychotic features was a critical factor: in patients with bipolar disorder without psychotic features, the masking threshold was indistinguishable from controls, while that of patients with bipolar disorder and psychotic features was comparable to that of patients with schizophrenia. Furthermore, the increase in masking threshold was correlated with clinical scores but not with medication.

Our results confirm previous behavioural findings, indicating that patients with schizophrenia have an elevated consciousness threshold (for a review, see: Berkovitch et al., 2017). Furthermore, the distinct profile of patients with bipolar disorder according to the

presence or absence of psychotic features may account for the contrasted results that were previously obtained (Chkonia et al., 2012; Fleming et al., 1995; Goghari et al., 2008; MacQueen et al., 2004; McClure, 1999). In previous studies, an elevated threshold was also observed in patients with schizophrenia or bipolar disorder outside acute episodes (Fleming et al., 1995; Green et al., 1999). To a lesser extent, their unaffected siblings also exhibited deficits in visual masking (Green et al., 1997; MacQueen et al., 2004). Therefore, a disruption in conscious access may constitute a trait marker or an indicator of vulnerability to schizophrenia or bipolar disorder (Saccuzzo et al., 1986).

Our study was also designed to probe the correlation between consciousness threshold and long-distance cortical connectivity. Measures of mean gFA in left and right inferior-fronto-occipital fasciculus (IFOF) left and right cingulum long fibres (CLF) and corpus callosum were significantly correlated with the masking threshold. This result fits with global neuronal workspace theory, which assumes that conscious perception arises from an ignition of neuronal cell assemblies disseminated in multiple cerebral regions and interconnected by long-distance fibre tracts, thus permitting brain-scale information broadcasting (Dehaene et al., 2011; Dehaene, Kerszberg, et al., 1998). On the one hand, IFOF connects the occipital and frontal lobes and is involved in the propagation of brain activation from perceptual occipital areas to associative prefrontal cortices (Forkel et al., 2014; Sarubbo et al., 2013). In addition, IFOF organization was previously shown to significantly correlate with the masking threshold in patients with multiple sclerosis (Reuter et al., 2009). Finally, IFOF lesions may induce spatial neglect (Thiebaut de Schotten et al., 2005; Urbanski et al., 2008). On the other hand, cingulum long fibres are likely to be involved in the neural network sustaining conscious information processing. In particular, posterior cingulate cortex is usually considered as a hub in the global neuronal workspace since it was shown to exhibit a major deactivation during a loss of consciousness, notably during anaesthesia (Alkire et al., 2008), sleep (Horovitz et al., 2009) or in vegetative state patients (Norton et al., 2012). Furthermore, a recent study showed that disrupting posterior cingulate connectivity directly disconnected consciousness from the external environment (Herbet et al., 2014). Finally, corpus callosum is the structure that links the two cerebral hemispheres and its disruption may cause a lack of awareness of stimuli processed by the right hemisphere (Gazzaniga, 1967, 2000).

In our study, correlation between mean gFA and masking threshold was independent of diagnosis, and was observed for left IFOF, left CLF and corpus callosum independently of

medication. This observation is compatible with the GNW's prediction that connectivity should influence conscious perception in both controls and patients. Crucially, the mean gFA of the ILF, a bundle that does not belong to the global workspace and is involved in the local propagation of information among specialized and largely unconscious processors of the occipital and ventral temporal lobes, was not correlated with the consciousness threshold. This result confirms previous findings in spatial neglect (Urbanski et al., 2008) and supports the idea that conscious access relies on a specific long-distance network.

Interestingly, the correlation between mean gFA and masking threshold was stronger for patients with psychosis (schizophrenia or bipolar disorder with psychotic features) suggesting a link between these three variables. We previously suggested that dissociation between preserved subliminal processing and altered conscious access could favour the advent of psychotic symptoms (Berkovitch et al., 2017).

Effects of ketamine exemplify the potential link between dysconnectivity, consciousness threshold and psychotic symptoms. Indeed, ketamine is a noncompetitive *N*-methyl-D-aspartate receptor antagonist that is used in medicine as an anaesthetic agent. These effects on consciousness were shown to rest upon a disruption of long-distance prefrontal-parietal connectivity (Blain-Moraes et al., 2014; Bonhomme et al., 2016; Lee et al., 2013; Uhrig et al., 2016; Vlisides et al., 2017; for a review, see: Mashour et al., 2018). Moreover, when administered at low doses, ketamine can also induce reversible psychotic-like symptoms such as delusional ideas (Krystal et al., 1994; Lahti et al., 2001; Pomarol-Clotet et al., 2006). These psychotomimetic effects may be related to an elevated consciousness threshold that could be underpinned by disruption of cerebral connectivity.

We therefore tentatively propose a causal model of psychotic symptoms in which: (1) dysconnectivity disrupts conscious access and elevate consciousness threshold, and (2) abnormal conscious access ultimately translates into psychotic symptoms. The gap between conscious representations and unconsciously processed incoming stimuli may promote psychotic symptoms through several routes. An elevated consciousness threshold would severely decrease the amount of information entering consciousness, and the few random sensory information bursting into consciousness may thus be overweight, creating a subjective feeling of aberrant salience (Kapur, 2003). Moreover, as unconscious processing is preserved, it would continue to implicitly guide behaviour, and fuel intuitions that the patient cannot consciously explain. This strange overall situation would urge the patient to forge explanations

that may culminate in delusional ideas (Berkovitch et al., 2017). Since those conscious constructions would be partly disconnected from the external environment (because of the deficit in conscious access), delusional beliefs would remain stable in the face of contradictory evidence. Even when crossing the threshold of consciousness, disconfirmatory evidence would mainly appear as bizarre and may foster further delusions rather than question internal representations.

This proposal is closely related to the extensive literature on hierarchical predictive-coding brain mechanisms and its possible anomalies in psychosis. According to this model, the brain predicts sensory inputs at varying levels of abstraction and hallucination and delusions could respectively result from an imbalance between priors and sensory inputs, and a failure to update beliefs according to incoming prediction-error signals (Adams et al., 2013; Fletcher et al., 2009; Powers, Mathys, et al., 2017; Sterzer, Voss, et al., 2018).. Interestingly, the model of circular inferences proposed by Jardri and colleagues also provides a computational account for the relative overweight of the few sensory evidence crossing consciousness threshold, that could be reverberated in the GNW (Jardri et al., 2013, 2017).

This model, although tentative, is corroborated by the causal mediation analysis conducted in the present study, which suggested that the elevated masking threshold act as a mediating factor between reduced gFA and psychotic features.

Finally, our finding that both patients with schizophrenia and patients with bipolar disorder and psychotic features exhibit an elevated masking threshold supports the hypothesis of a continuum between the two diseases (Hill et al., 2013; Lichtenstein et al., 2009; McIntosh et al., 2008; Möller, 2003). Patients with bipolar disorder and psychotic features may constitute a homogenous subtype of bipolar disorder, as suggested by clinical (Marneros et al., 2009), genetic (Goes et al., 2008), and imaging studies (Anticevic et al., 2013; Sarrazin et al., 2014). In this sense, psychotic features in bipolar disorder would be a symptomatic dimension per se, underpinned by a specific pathophysiology that may involve elevation of consciousness threshold (Allardyce et al., 2007; Henry et al., 2010).

In our study, however, an important caveat is that the small sample size within each subgroup of patients with bipolar disorder did not allow us to adjudicate between the hypotheses of a continuum or of distinct subgroups of patients with bipolar disorder. More broadly, we lacked power to explore difference of connectivity between the groups and to evidence

differences in the correlation between masking threshold and connectivity when comparing the groups two by two. Indeed, we only observed a significant difference between patients with psychosis and controls for the left cingulum. Such a difference might have been evidenced in other bundles with a larger sample size. Similarly, the fact that right IFOF and CLF did not survive adjustments for multiple comparisons might also be partly related to the small sample size.

To sum up, our results suggest that interhemispheric and long-range postero-anterior connectivity plays a crucial role in conscious access, as predicted by the global neuronal workspace theory of consciousness. Patients with psychotic features exhibited an elevated consciousness threshold that correlated with an abnormal organization of long-distance cortical fibre tracts, particularly those bringing visual information to the prefrontal cortex and broadcasting it to both hemispheres. Such impairments were observed both in patients with schizophrenia and in patients with bipolar disorder and psychotic features, suggesting that psychosis and impaired conscious access may be intimately related phenomena.

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# **Chapter 3. Impaired conscious access and abnormal attentional amplification in schizophrenia**

## **Introduction of the article**

According to the global neuronal workspace (GNW) theory of consciousness, conscious access starts when a relevant piece of information is amplified by attention and triggers sustained cerebral activity in disseminated cerebral regions interconnected by long-range neurons. The GNW model therefore predicts that abnormal attentional amplification should disrupt conscious access but spare subliminal processing.

In this study, we explore whether an impaired attentional amplification could account for the dissociation between conscious and subliminal processing in schizophrenia. Using electroencephalography, we manipulated a bottom-up factor (the delay between a mask and a target) and a top-down factor (whether the target is attended or not) and compared behavioural measures and cerebral activity between patients with schizophrenia and controls. Importantly, this paradigm also allowed to study how attention modulated accumulation of evidence in healthy controls. Our results suggest that top-down attention enables a specific mode of amplification and integration in which sensory evidence triggers a series of successive stages of increasingly amplified activation, which ultimately translates into a global ignition. Some but not all these top-down attentional amplification processes are impaired in schizophrenia, while bottom-up processing seems to be preserved.

## **Article**

Berkovitch, L., Del Cul, A., Maheu, M., & Dehaene, S. (2018). Impaired conscious access and abnormal attentional amplification in schizophrenia. *NeuroImage: Clinical*, 18, 835–848. <http://doi.org/10.1016/j.nicl.2018.03.010>



# Impaired conscious access and abnormal attentional amplification in schizophrenia

Berkovitch L.<sup>a,b,\*,1</sup>, Del Cul A.<sup>c,d,1</sup>, Maheu M.<sup>a,e</sup>, Dehaene S.<sup>a,f</sup>

<sup>a</sup> Cognitive Neuroimaging Unit, CEA DSV/12BM, INSERM, Université Paris-Sud, Université Paris-Saclay, NeuroSpin Center, 91191 Gif-sur-Yvette, France

<sup>b</sup> Sorbonne Universités, UPMC Univ Paris 06, IFD, 4 place Jussieu, 75252 Paris Cedex 05, France

<sup>c</sup> AP-HP, Groupe Hospitalier Pitié-Salpêtrière, Service de Psychiatrie d'Adultes, 75013 Paris, France

<sup>d</sup> Inserm, CNRS, APHP, Institut du Cerveau et de la Moelle (ICM), Hôpital Pitié-Salpêtrière, Sorbonne Universités, UPMC Univ Paris 06, 75013 Paris, France

<sup>e</sup> Université Paris Descartes, Sorbonne Paris Cité, 75006 Paris, France

<sup>f</sup> Collège de France, 11 Place Marcelin Berthelot, 75005 Paris, France

## ARTICLE INFO

### Keywords:

Attention  
Psychosis  
Visual awareness  
Masking  
Top-down  
Bottom-up

## ABSTRACT

Previous research suggests that the conscious perception of a masked stimulus is impaired in schizophrenia, while unconscious bottom-up processing of the same stimulus, as assessed by subliminal priming, can be preserved. Here, we test this postulated dissociation between intact bottom-up and impaired top-down processing and evaluate its brain mechanisms using high-density recordings of event-related potentials. Sixteen patients with schizophrenia and sixteen controls were exposed to peripheral digits with various degrees of visibility, under conditions of either focused attention or distraction by another task. In the distraction condition, the brain activity evoked by masked digits was drastically reduced in both groups, but early bottom-up visual activation could still be detected and did not differ between patients and controls. By contrast, under focused top-down attention, a major impairment was observed: in patients, contrary to controls, the late non-linear ignition associated with the P3 component was reduced. Interestingly, the patients showed an essentially normal attentional amplification of the P1 and N2 components. These results suggest that some but not all top-down attentional amplification processes are impaired in schizophrenia, while bottom-up processing seems to be preserved.

## 1. Introduction

Schizophrenia is a serious psychiatric disorder that affects approximately ~1% of the population worldwide and causes positive symptoms, such as delusions and hallucinations, negative symptoms, including withdrawal from social interactions and daily life activities, cognitive impairments, and disorganization syndrome. Experimental studies of visual masking have reproducibly revealed an elevated threshold for the perception of masked visual stimuli in schizophrenia (Butler et al. 2003; Charles et al. 2017; Dehaene et al. 2003a; Del Cul et al. 2006; Green et al. 1999, 2011; Herzog et al. 2004; Herzog and Brand 2015; Plomp et al. 2013). For instance, in classical masking experiments in which the target-mask duration is manipulated, patients with schizophrenia typically need a longer delay between the two, compared to controls, to consciously perceive the target (Charles et al. 2017; Del Cul et al. 2006). Similarly, patients are less likely to report

that they perceived an unexpected event during inattentive blindness (Hanslmayr et al. 2013) and show an exaggerated attentional blink effect compared to controls, associated with a decreased P300 (Mathis et al. 2012).

Theoretical models of conscious processing suggest that the conscious perception of a stimulus involves the bottom-up propagation of sensory signals through the visual hierarchy, as well as top-down amplification by late and higher-level integrative processes (Dehaene et al. 2003b; Dehaene and Changeux 2011). Many brain areas and networks continuously process sensory information in an unconscious manner, but conscious access is thought to start when top-down attention amplifies a given piece of information, allowing it to access a network of high-level brain regions broadly interconnected by long-range connections (Baars 1993; Dehaene 2011; Dehaene and Changeux 2011; de Lafuente and Romo, 2006). This so-called global neuronal workspace integrates the new incoming piece of evidence into the current

\* Corresponding author at: Cognitive Neuroimaging Unit CEA DRF/JOLIOT, INSERM, Université Paris-Sud, Université Paris-Saclay, DRF/JOLIOT/NEUROSPIN/UNICOG, Bât. 145 – Point Courrier 156, F-91191 Gif-sur-Yvette Cedex, France.

E-mail address: [luacie.berko@hotmail.com](mailto:luacie.berko@hotmail.com) (L. Berkovitch).

<sup>1</sup> Denotes co-first authorship.

conscious context, makes it available to multiple others brain processors and verbally reportable.

Conscious access, in the face of incoming sensory evidence, has been likened to a “decision to engage” the global workspace (Dehaene 2008; Shadlen and Kiani 2011). Borrowing from the diffusion model (Ratcliff 1978) according to which decisions are made through a noisy process that accumulates information over time until sufficient information is obtained to initiate a response, it has been proposed that a non-conscious accumulation of sensory evidence precedes conscious access (Vorberg et al. 2003). According to that hypothesis, peripheral perceptual processors would accumulate noisy samples arising from the stimulus, and conscious access would correspond to a perceptual decision based on this accumulation (Dehaene 2011; King and Dehaene 2014). Both the amount of sensory evidence (e.g. the contrast of a stimulus) and the attentional resources would modulate the rate of accumulation of sensory information per unit of time, or drift rate, and thus the likelihood of consciously perceiving the stimulus. According to these theoretical models, an elevated consciousness threshold could thus result from both a bottom-up perceptual impairment and/or an insufficient top-down attentional amplification.

The increased sensibility to visual masking in schizophrenia was initially interpreted as indicating a bottom-up deficit, as other experimental results suggest low-level visual impairments in schizophrenia (Butler et al. 2003; Cadenhead et al. 1998; Green et al. 2011). Indeed, an impaired visual P1 to low spatial frequency stimuli was repeatedly observed in schizophrenic patients and attributed to a specific magnocellular visual pathway dysfunction (Butler et al. 2005, 2007; Javitt 2009; Kim et al. 2006; Martínez et al. 2012). Moreover, schizophrenic patients exhibit deficits in the auditory P50, which is normally reduced for the second paired stimuli compared to the first, but insufficiently so in patients compared to controls (Javitt and Freedman 2015), even if this effect may also be due to a dampened response to the first stimulus (Yee et al. 2010). Finally, patients also suffer from an abnormal pre-pulse inhibition of startle responses, a paradigm in which a weak sensory stimulus (the prepulse) inhibits the elicitation of the startle response caused by a sudden intense stimulus (Bolino et al. 1994; Braff et al. 1992).

However, observing a reduced activity of early ERP components is not sufficient to conclude in favor of a purely bottom-up impairment in schizophrenia. Similar findings could indeed also stem from impaired top-down attentional processes. This latter explanation is worth considering given the widely acknowledge modulatory effect that attention may have on early brain activation including the mismatch negativity (Kasai et al. 1999; Oades et al. 1997; Sauer et al. 2017), the P1 (Feng et al. 2012; Hillyard and Anllo-Vento 1998; Luck and Ford 1998; Wyart et al. 2012), and probably the P50 in healthy controls (Guterman et al., 1992) and schizophrenic patients (Yee et al. 2010). An additional argument suggesting that bottom-up processing may not be responsible for the patients' elevated consciousness threshold in masking experiments comes from the observation that subliminal processing can be fully preserved in schizophrenia patients, as reported in a variety of paradigms with masked words (Dehaene et al. 2003a) or digits (Del Cul et al. 2006), subliminal error detection (Charles et al. 2017) and response inhibition (Huddy et al. 2009; for a review, see: Berkovitch et al. 2017). This argument rests upon the idea that subliminal priming merely reflects the feed-forward propagation of sensory activation (Fahrenfort et al. 2008; Lamme and Roelfsema 2000).

In summary, evidence for early visual processing deficits in schizophrenia is inconclusive and could be due either to an impairment of bottom-up processing, or to a lack of appropriate top-down attentional modulation as suggested by previous work (Dima et al. 2010; Fuller et al. 2006; Gold et al. 2007; Luck et al. 2006; Plomp et al. 2013).

Here we tested the hypothesis that bottom-up information processing is intact while top-down attentional amplification is deficient in schizophrenia by recording high-density electroencephalography (EEG) in a visual masking paradigm. We systematically and orthogonally

manipulated a bottom-up factor (the delay between the mask and the target) and a top-down factor (whether the stimuli were attended or unattended). Our goal was two-fold. First, we probed the brain mechanisms by which attention amplifies the processing of masked stimuli in healthy controls, therefore lowering down their threshold for access to conscious report. Second, we evaluated which of these mechanisms are impaired in schizophrenic patients. The hypothesis of intact bottom-up processing predicts that, once attention is withdrawn, early event related potentials (ERPs) should be equally reduced in both patients and controls, without any difference between these two groups. On the other hand, the difference between attended and unattended conditions, which provides a measure of attentional amplification, should reveal a deficiency of top-down amplification in schizophrenia, eventually resulting in a reduction or suppression of the global cortical ignition typically associated with conscious perception in normal subjects (Del Cul et al. 2007; Sergent et al. 2005).

The present research capitalizes upon a previous study in which we demonstrated that event-related potentials could be used to monitor the successive stages of processing of a masked stimulus (Del Cul et al. 2007). In this previous work, a digit target was presented for a brief fixed duration (14 ms), and followed – after a variable stimulus-onset-asynchrony (SOA) – by a mask consisting of surrounding letters. A fixed amount of sensory evidence was therefore initially injected while a variable amount of time was available to accumulate the evidence before the processing of the mask disrupted it. ERPs were used to monitor the successive stages of visual information processing associated with unconscious processing and conscious vision. Following the subtraction of mask-evoked brain activity, a series of distinct stages were observed. First, the P1 and the N1 components were shown to vary little with SOA, reflecting the unconscious processing of the incoming digits. Second, an intermediate negative waveform component (N2) linearly increased with SOA but stopped at a fixed latency with respect to the mask, suggesting an accumulation of evidence in occipito-temporal cortical areas and its interruption by the mask. Finally, the late P3 component showed a sigmoidal variation with SOA, tightly parallel to subjective reports of target visibility, thus suggesting that the P3 indexes an all-or-none stage of conscious access to perceptual information (see also e.g. Sergent et al. 2005).

In the present study, we aimed at replicating those findings as well as probing which of these stages persist when the very same stimulus (a masked digit) is presented under conditions of inattention (see Fig. 1). By doing so, we intended to explore the interaction between the amount of masking (as modulated by target-mask SOA) and the availability of attentional resources, and to manipulate those variables while comparing schizophrenic patients and controls. In the focused attention condition, subjects were asked to focus their attention to the peripheral masked digits and to report their visibility (as in the original study by Del Cul et al. 2007). In the unattended condition, we maximized the withdrawal of attention from our masked stimuli through the use of a highly demanding concurrent task: subjects were asked to focus on small color changes presented at fixation and to report which color was predominant, while the same masked digits were presented in the periphery of the visual field. Because the digits were entirely task-irrelevant, presented at a parafoveal location and asynchronous with the color changes, all kinds of attention were withdrawn (executive attention, i.e. linked to the task; spatial attention, i.e. linked to the location of the stimulus; and temporal attention, i.e. linked to the timing at which the stimulus appears).

Based on our hypothesis of preserved feedforward and impaired top-down processing in schizophrenia, we predicted that, under inattention, the early sensory components indexed by P1, N1 and even N2 would remain present (though reduced by inattention) and identical in patients and controls. We also expected that attention would amplify these sensory components in order to facilitate the accumulation of sensory evidence from the masked stimulus, and that this amplification would be impaired in schizophrenia patients.

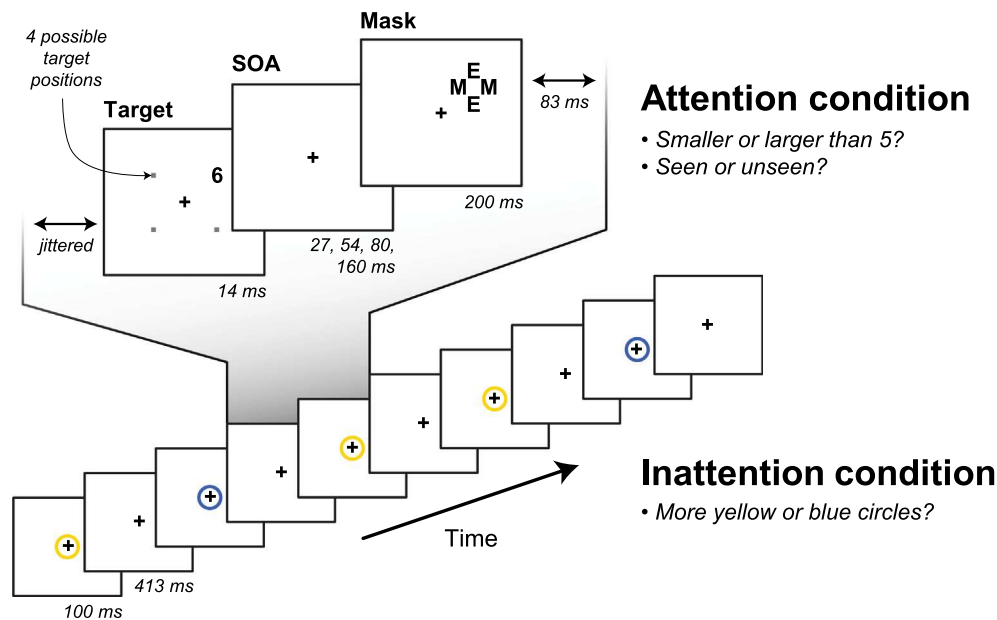


Fig. 1. Experimental design

## 2. Material and methods

### 2.1. Participants

Sixteen patients with schizophrenia (mean age 37 years, range 25–51; 5 women) participated to the study. All were native French speakers. Patients met DSM-IV criteria for schizophrenia or schizo-affective disorders and were recruited from the psychiatric department of Creteil University Hospital (Assistance Publique, Hôpitaux de Paris). They had a chronic course and were stable at the time of the experiment. A French translation of the Signs and Symptoms of Psychotic Illness Scale (SSPI) (Liddle et al. 2002) was used to evaluate their symptomatology, and chlorpromazine equivalents were calculated to assess whether there was significant correlations between symptoms, treatment and behavioural results.

The comparison group consisted of sixteen control subjects (mean age 35.5 years, range 21–51, 4 women). Comparison subjects were excluded for history of any psychotic disorder, bipolar disorder, recurrent depression, schizotypal or paranoid personality disorder. Patients and controls with a history of brain injury, epilepsy, alcohol or substance abuse, or any other neurological or ophthalmologic disorders were also excluded. Patients and controls did not differ significantly in sex, age and level of education (see Table 1). All experiments were approved by the French regional ethical committee for biomedical research (Hôpital de la Pitié Salpêtrière), and subjects gave written informed consent.

### 2.2. Design and procedure

The experimental paradigm is summarized in Fig. 1. We used a variant of the masking paradigm designed in our previous studies in normal and clinical populations (Charles et al. 2017; Del Cul et al. 2006, 2007). A target digit (1, 4, 6 or 9) was presented for a fixed duration of ~14 ms at a randomly chosen position among four (1.4 degrees above or below and 1.4 degrees right or left of the fixation cross). After a variable delay (stimulus onset asynchrony or SOA), a metacontrast mask appeared at the target location for 250 ms. The mask was composed of four letters (two horizontally aligned M and two vertically aligned E) surrounding the target stimulus location without superimposing or touching it. Four visibility levels (SOAs 27, 54, 80 and 160 ms) and a mask-only condition were randomly intermixed across

**Table 1**  
Characteristics of participants.

Characteristics	Schizophrenic mean (± s.d.)	Control mean (± s.d.)	Statistical test (test value, p-value, BF)
Sample size	16	16	–
Age (y.o.)	37.44 (± 7.4)	35.5 (± 10.5)	$t_{26.99} = 0.60$ $p = 0.55$ $BF = 1/2.59$
Gender (M/F)	11/5	12/4	$\chi_1 = 0.16$ $p = 0.69$ $BF = 1/2.75$
Years of education (from first year of high school)	7.9 (± 2)	8.9 (± 3.3)	$t_{24.90} = -1.04$ $p = 0.31$ $BF = 1/1.97$
SSPI <sup>a</sup> scale total score	12.2 (± 6.8)	–	–
Antipsychotic equivalence dose (CPZ-Eq., in mg)	650.2 (± 376.3)	–	–

<sup>a</sup> Sign and Symptom of Psychotic Illness.

trials. In the mask-only condition, the target number was replaced by a blank screen with the same duration (i.e. 14 ms). The fixation cross was surrounded by 5, 6 or 7 successive colored circles which could be either blue or yellow. The presentation of each of these circles lasted for 100 ms, and the inter-stimulus interval between them was 105 ms (SOA = 513 ms).

The same exact sequence of stimuli was presented under two distinct conditions, which differed only in the requested task. Under the attended condition, subjects were asked to pay attention to the masked digits and give two behavioural responses: (1) decide whether the digit was larger or smaller than 5 (which provided an objective measure of target perception) and (2) report the digit visibility using a categorical response “seen” or “not seen” (which provided a subjective measure of conscious access). Under the unattended condition, participants had to estimate the predominant color of the rapid sequence of colored circles surrounding the fixation cross. Note that the peripheral stimuli always appeared between the 2nd and the 3rd colored circles, while participants were still forced to pay attention to the central task because not enough evidence was yet delivered to accurately decide which of the 2 colors was the most frequent (given that the number of circles varied between five and seven). On each trial, feedback informed the subjects

whether their answer was correct or not in order to reinforce their motivation and help them to maintain attention. At the end of the unattended blocks, participants were asked whether they noticed anything in their peripheral visual field.

Instructions for both attended and unattended tasks were given at the beginning of the experiment and were repeated before each block (attended or unattended). Subjects were asked to complete four blocks of trials: two “attended” blocks (A) and two “unattended” blocks (U), in A-U-U-A order for half of the subjects and in U-A-A-U order for the other half. There were 640 trials in total (320 unattended and 320 attended), i.e. 64 trials in each combination of attention (2 levels) and masking (5 levels, i.e. SOA = 27, 54, 80, or 160 ms, plus the mask-only condition).

On each trial, subjects viewed a stream of small circles presented at fixation, with a brief presentation of a masked digit at one of four possible locations in the periphery of the visual field. The same exact sequence of stimuli was presented in two distinct experimental conditions. In the attended condition, subjects were asked to compare the target digit to a fixed reference of 5 (two alternatives forced-choice, objective task), then report whether they could see it or not (subjective visibility task). The delay between the target and the metacontrast mask (SOA) varied between 27 and 160 ms in order to modulate the amount of masking. In the unattended condition, subjects had to estimate the predominant color of small circles surrounding the fixation cross, thus withdrawing attention from the irrelevant peripheral digit.

### 2.3. Behavioural data analysis

For each subject, several behavioural parameters were measured separately in each SOA condition. In the attended condition, we measured the performance in comparing the target against 5 (objective measure of conscious access) and the rate of seen trials (subjective measure of conscious access). In the unattended condition, we measured the performance in estimating which color was more frequent. Analyses of variance (ANOVAs) were conducted on each of those behavioural measures, with SOA as a within-subject factor and group (patients or controls) as a between-subject factor. Within the patient group, Pearson correlation coefficients were computed between behavioural measures and variables such as the clinical scale (*SSPI* scale, measuring the extent of positive, negative, and disorganization symptoms, Liddle et al. 2002) and antipsychotic treatment posology (chlorpromazine equivalent). A measure of sensitivity ( $d'$ ) was computed by confronting subjective visibility (seen versus not seen) against the presence or absence of a target (target versus mask-only trials).

### 2.4. ERP methods

EEG activity was acquired using a 128-electrode geodesic sensor net referenced to the vertex, with an acquisition sampling rate set to 250 Hz. We rejected voltage exceeding  $\pm 200 \mu\text{V}$ , transients exceeding  $\pm 100 \mu\text{V}$ , or electro-oculogram activity exceeding  $\pm 70 \mu\text{V}$ . The remaining trials were averaged in synchrony with mask onset, digitally transformed to an average reference, band-pass filtered (0.5–20 Hz) and corrected for baseline over a 250 ms window during fixation at the beginning of the trial. Contralateral activity is represented conventionally on the left hemisphere and ipsilateral activity on the right one. The activity observed on mask-only trials was subtracted from that on trials in which the target was effectively presented, thus isolating the target-evoked activity.

In order to quantify the modulatory effect of SOA on EEG activity, linear regression models were fitted at the subject-level on the trial-averaged EEG signals, separately at each electrode and each time-point using the values of SOA as a parametric modulator (combined with an offset variable) of the EEG response. Group averaged regression coefficients (beta) corresponding to SOA were estimated, and  $R^2$  values (i.e. proportion of explained variance) are reported as an unbiased and normalized measure of the quality of fit.

ERP components were identified based on latencies, topographical responses (contralateral P1 and N1, bilateral N2 and P3) and previous work (Del Cul et al. 2007). For each subject, under each SOA and attention condition and for each digit-evoked ERP component, the EEG signals were averaged over corresponding clusters of electrodes and time windows (P1: 65–110 ms over parieto-temporal electrodes; N1: 125–200 ms over parieto-temporal electrodes; N2: 200–300 ms over fronto-central electrodes; P3: 300–500 ms over fronto-central electrodes; see Del Cul et al. 2007).

In order to assess effect of experimental variables, we conducted analyses of variance (ANOVAs) separately for each these ERP components on their corresponding averaged amplitude (over electrodes and time points) with SOA (categorically recoded) and attention condition (attended or not) as within-subject factor and group (patients or controls) as a between-subject factor. We also compared the amplitude of each component against zero using a  $t$ -test in order to identify which of these components significantly persisted in the unattended condition.

### 2.5. Source localization

Cortical current density mapping was obtained using a distributed model consisting of 10,000 current dipoles. Dipole locations were constrained to the cortical mantle of a generic brain model built from the standard brain of the Montreal Neurological Institute, and warped to the standard geometry of the EEG sensor net. The warping procedure and all subsequent source analysis and surface visualization were performed using BrainStorm software (<http://neuroimage.usc.edu/brainstorm>) (Tadel et al. 2011). EEG forward modelling was computed with an extension of the overlapping-spheres analytical model (Huang et al. 1999). Cortical current maps were computed from the EEG time series using a linear inverse estimator (weighted minimum-norm current estimate or wMNE; see Baillet et al. 2001, for a review). We localized the sources separately for each subject and computed a group average that was then smoothed at 3 mm FWHM (corresponding to 2.104 edges on average), and thresholded at 40% of the maximum amplitude (cortex smoothed at 30%).

### 2.6. Statistical comparisons

Because many of the hypotheses at stake lie on an absence of difference (e.g. preserved feedforward processing in schizophrenic patients), besides frequentist statistics (values of the statistic, e.g.  $t$ s or  $F$ s, as well as  $p$ -values are reported), we also conducted Bayesian statistics whenever required. Contrary to frequentist statistics, Bayesian statistics symmetrically quantify the evidence in favor of the null ( $H_0$ ) and the alternative ( $H_1$ ) hypotheses, therefore allowing to conclude in favor of an absence of difference (Wagenmakers et al. 2010). To do so, the *BayesFactor* package (<http://bayesfactorpcl.r-forge.r-project.org>) implemented in R (<https://www.r-project.org>) was used. Bayes Factor were estimated using a scale factor of  $r = 0.707$ . For each Bayesian statistical test, the corresponding Bayes factor ( $\text{BF}_{10} = p(\text{data}|H_1)/p(\text{data}|H_0)$ ) is reported. Even though threshold values of Bayes factors have been proposed (e.g. a BF larger than 3 is usually taken as providing substantial evidence), a BF value of  $x$  can directly be interpreted as the observed data being approximately  $x$  times more probable under the alternative compared to the null hypothesis. When BFs favored the null hypotheses (i.e.  $\text{BF}_{10} < 1$ ), we directly reported the inverse Bayes factor (i.e.  $\text{BF}_{01} = 1/\text{BF}_{10}$ ) quantifying the evidence in favor of the null compared to the alternative hypothesis.

## 3. Results

### 3.1. Behaviour

Behavioural results appear in Fig. 2. As concerns the main digit-related task, under the attended condition, a main effect of SOA was

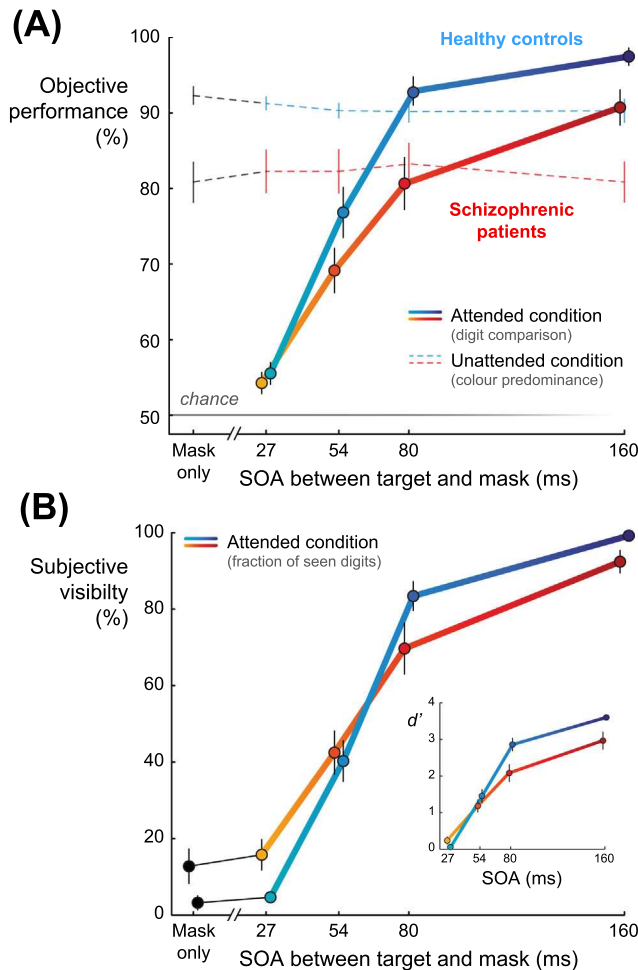


Fig. 2. Behavioural results

(A) Objective performance as a function of SOA in the attended (comparing the masked digit to 5, solid lines) and the unattended conditions (estimating the predominant color of small circles surrounding the fixation cross, dashed lines). Error bars represent one standard error of the mean. Healthy controls (blue lines) performed better than schizophrenic patients (red lines) in both conditions. There was no effect of SOA in the unattended condition. (B) Subjective visibility of the masked digit and  $d'$  measures as a function of SOA in the attended condition. Error bars represent one standard error of the mean. Healthy controls (blue lines) reported higher visibility and had higher  $d'$  than schizophrenic patients (red lines) for long SOAs (i.e. 80 and 160 ms). Schizophrenic patients reported higher visibility than controls in the mask-only and the 27 ms SOA conditions but  $d'$  measures did not significantly differ between the two groups for short SOAs (i.e. 27 and 54 ms).

observed on both objective performance ( $F_{1,30} = 184.02$ ,  $p < 0.001$ ) and subjective visibility ( $F_{1,30} = 287.17$ ,  $p < 0.001$ ).

Objective performance was significantly lower for patients compared to controls (73.7% vs. 80.7%, group effect  $F_{1,30} = 7.44$ ,  $p = 0.011$ ), but a significant group  $\times$  SOA interaction ( $F_{3,90} = 3.14$ ,  $p = 0.029$ ) reflected the fact that this difference was significant only at the longest SOAs, i.e. 80 ms and 160 ms ( $F_{1,30} = 11.21$ ,  $p = 0.002$ ), not at the shortest SOAs 27 ms and 54 ms ( $F_{1,30} = 2.78$ ,  $p = 0.110$ ,  $BF = 1/1.8$ ). Importantly, objective performance remained higher than chance in both groups (controls: 66.2%,  $t_{31} = 6.19$ ,  $p < 0.001$ , patients: 61.7%,  $t_{31} = 5.624$ ,  $p < 0.001$ ).

Subjective visibility was also affected by a group  $\times$  SOA interaction ( $F_{3,90} = 5.83$ ,  $p = 0.001$ ). Indeed, patients reported a significantly lower visibility at SOAs 80 ms and 160 ms (patients: 81.1% vs. controls: 91.3%;  $F_{1,30} = 4.53$ ,  $p = 0.042$ ), and a significantly higher visibility in the mask-only and the 27 ms SOA conditions (14.3% vs. 3.9%,  $F_{1,30} = 5.53$ ,  $p = 0.026$ ) compared to controls. No difference was observed between the two groups at SOA 54 ms ( $F_{1,30} = 0.083$ ,  $p = 0.780$ ,

$BF = 1/2.9$ ). Measures of sensitivity ( $d'$ ) confirmed that patients were less able than controls to detect the target digit when SOAs were long (80 ms:  $t_{27.7} = -2.66$ ,  $p = 0.013$ ; 160 ms:  $t_{17.6} = -2.55$ ,  $p = 0.020$ ), while no significant difference was observed for short SOAs (27 ms:  $t_{27.3} = 1.44$ ,  $p = 0.162$ ,  $BF = 1/1.4$ ; 54 ms:  $t_{29.9} = -1.03$ ,  $p = 0.312$ ,  $BF = 1/2.0$ ).

Objective and subjective visibility were strongly correlated within subjects in both groups, and the strength of this correlation did not significantly differ between the two groups (mean Pearson  $r$  for controls: 0.97 vs. 0.96 for patients,  $t_{29.85} = 0.30$ ,  $p = 0.764$ ,  $BF = 1/2.9$ ). However, the patients' objective performance was neither significantly correlated with the treatment (Pearson  $r = 0.095$ ,  $t_{14} = 0.36$ ,  $p = 0.725$ ,  $BF = 1/5.0$ ), nor with the clinical score (Pearson  $r = -0.28$ ,  $t_{14} = -1.07$ ,  $p = 0.304$ ,  $BF = 1/3.1$ ). Subjective performance showed a weak trend towards a negative correlation with treatment (across all SOAs: Pearson  $r = -0.50$ ,  $t_{14} = -2.18$ ,  $p = 0.046$ ,  $BF = 1.4$ , for SOAs = 80 or 160 ms: Pearson  $r = -0.47$ ,  $t_{14} = -1.99$ ,  $p = 0.066$ ,  $BF = 1.0$ ), but this correlation was strongly driven by one participant's results (chlorpromazine equivalent: 1550 mg per day, subjective visibility across all SOAs: 16.0%; correlation after excluding this participant: Pearson  $r = -0.16$ ,  $t_{13} = -0.59$ ,  $p = 0.567$ ,  $BF = 1/4.4$ ). Finally, the clinical score was not correlated with subjective visibility (all SOAs: Pearson  $r = 0.00$ ,  $t_{14} = 0.00$ ,  $p = 0.997$ ,  $BF = 1/5.3$ ; for SOAs = 80 or 160 ms: Pearson  $r = -0.14$ ,  $t_{14} = -0.54$ ,  $p = 0.596$ ,  $BF = 1/4.6$ ).

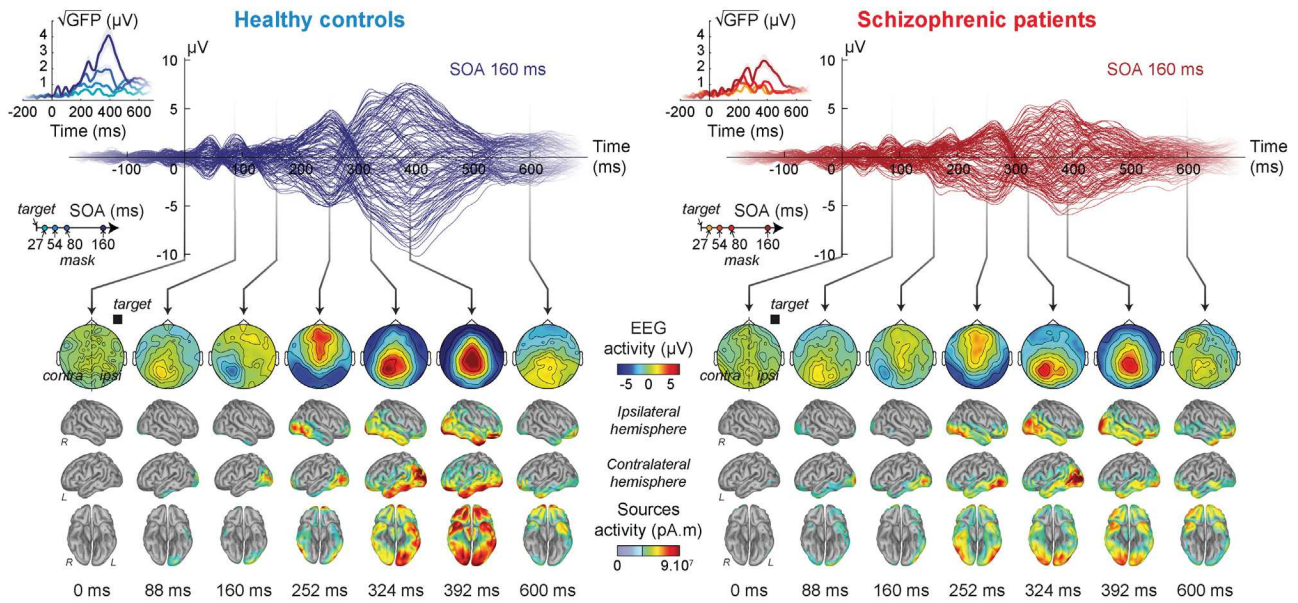
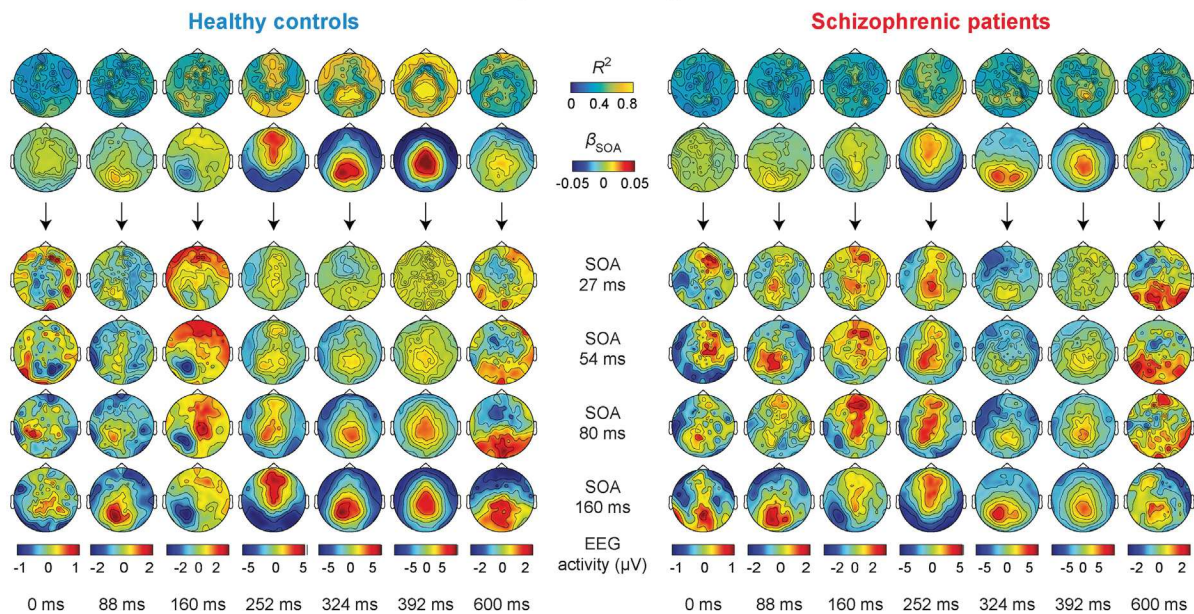
As concerns the distracting task, under the unattended condition, performance in the central color task was lower for patients compared to controls (81.9% vs. 90.9%,  $F_{1,30} = 11.48$ ,  $p = 0.002$ ). There was no main effect of SOA ( $F_{4,120} = 0.39$ ,  $p = 0.817$ ,  $BF = 1/43.0$ ) nor a group  $\times$  SOA interaction ( $F_{4,120} = 1.16$ ,  $p = 0.331$ ,  $BF = 1/13.3$ ). Within the patient group, performance was neither significantly correlated with treatment (Pearson  $r = 0.43$ ,  $t_{14} = 1.791$ ,  $p = 0.095$ ,  $BF = 1/1.3$ ) nor with clinical score (Pearson  $r = -0.45$ ,  $t_{14} = -1.91$ ,  $p = 0.077$ ,  $BF = 1.1$ ).

After the experiment, all subjects reported that they noticed the presence of the peripheral masked stimuli in the unattended condition, but that these stimuli could not be precisely identified and did not prevent them from estimating the dominant color of the central circles.

### 3.2. EEG activity evoked by the target

Target-evoked brain activity is shown in Fig. 3A in the case of the longest SOA (i.e. 160 ms) in the attended condition for both groups. At least five different components specific to conscious EEG visual responses could be identified: contralateral P1 (peaking at 88 ms post-target) and N1 (160 ms) followed by bilateral N2 (252 ms), P3a (324 ms) and P3b (392 ms). Scalp topographies and corresponding sources reconstruction are shown at specific time points (0, 88, 160, 252, 324, 392 and 600 ms).

First, at 88 ms and 160 ms (corresponding respectively to P1 and N1 components), brain activity elicited by the target was restricted to contralateral occipito-temporal regions (conventionally displayed on the left hemisphere) in both groups, reflecting the activation of early visual areas. The activity was slightly more diffuse and ventral in the patient group at 160 ms. At 252 ms (with a topography corresponding to the N2/P3a component), the activity spread to the ipsilateral hemisphere and moved forward in the postero-lateral part of the inferior temporal gyrus, including the visual number form area (Shum et al. 2013), and anterior prefrontal activity was detected. Then, at 324 ms, as a posterior P3b began to emerge in the scalp topography, the source activity spread bilaterally into the ventral stream, though more pronounced in the contralateral hemisphere, as well as in the inferior prefrontal and parietal cortices. Finally, at 392 ms (corresponding to the full-blown P3b component), activity became intense and fully bilateral in both groups, reaching ventral and dorsolateral prefrontal as well as parietal regions, especially in the control group. At 600 ms, in

**(A) Brain activity evoked by the target digits in the attended condition****(B) Parametric modulation of EEG activity according to SOA**

**Fig. 3.** EEG activity evoked by target digits in the attended condition

(A) Time course of brain activity at the longest SOA (i.e. 160 ms) for controls (blue curves on the left) and patients (red curves on the right). Global field potentials are shown in inset as a function of time and SOA. Specific time points were selected below, providing an overview of brain activity evoked by the target as a function of time. Shaded area around the curve represents one standard error of the mean. (B) Topographical maps of both explained variance ( $R^2$ ) and regression coefficient ( $\beta$ ) from a linear regression of EEG signals' amplitude on SOA, performed at each electrode and time point. Below, classical EEG voltage topographies are shown for each time point (horizontally) and for each SOA (vertically).

both groups, activity strongly decreased in the occipital lobes while remaining sustained in anterior frontal and temporal regions.

### 3.2.1. ERP components amplitudes

In order to examine which of the ERP components evoked by a masked stimulus persist under a condition of inattention, we first tested whether the amplitude of each component was significantly different from zero at the longest SOA (160 ms) under attended and unattended conditions. In the control group, under the attended condition (see Fig. 4A), the amplitude of all ERP components was significantly different from zero (P1:  $t_{15} = 3.10$ ,  $p = 0.007$ ; N1:  $t_{15} = -4.95$ ,  $p < 0.001$ ; N2:  $t_{15} = -6.25$ ,  $p < 0.001$ ; P3:  $t_{15} = 10.83$ ,  $p < 0.001$ ),

while under unattended conditions (see Fig. 4B), only the amplitude of the N1 and N2 components was significantly different from zero (N1:  $t_{15} = -3.35$ ,  $p = 0.004$ ; N2:  $t_{15} = -4.54$ ,  $p < 0.001$ ; P1:  $t_{15} = -0.05$ ,  $p = 0.962$ ,  $BF = 1/3.9$ ; P3:  $t_{15} = -0.35$ ,  $p = 0.732$ ,  $BF = 1/3.7$ ). Similar results were observed in the patient group under attended condition (P1:  $t_{15} = 4.31$ ,  $p < 0.001$ ; N1:  $t_{15} = -3.70$ ,  $p = 0.002$ ; N2:  $t_{15} = -3.70$ ,  $p = 0.002$ ; P3:  $t_{15} = 6.31$ ,  $p < 0.001$ ) but only the N2 amplitude was significantly different from zero under unattended condition (N2:  $t_{15} = -3.91$ ,  $p = 0.001$ ; P1:  $t_{15} = -0.09$ ,  $p = 0.930$ ,  $BF = 1/3.9$ ; N1:  $t_{15} = -0.85$ ,  $p = 0.408$ ,  $BF = 1/2.9$ ; P3:  $t_{15} = -0.49$ ,  $p = 0.635$ ,  $BF = 1/3.5$ ). For both groups, the P3 component totally vanished under unattended conditions. The results



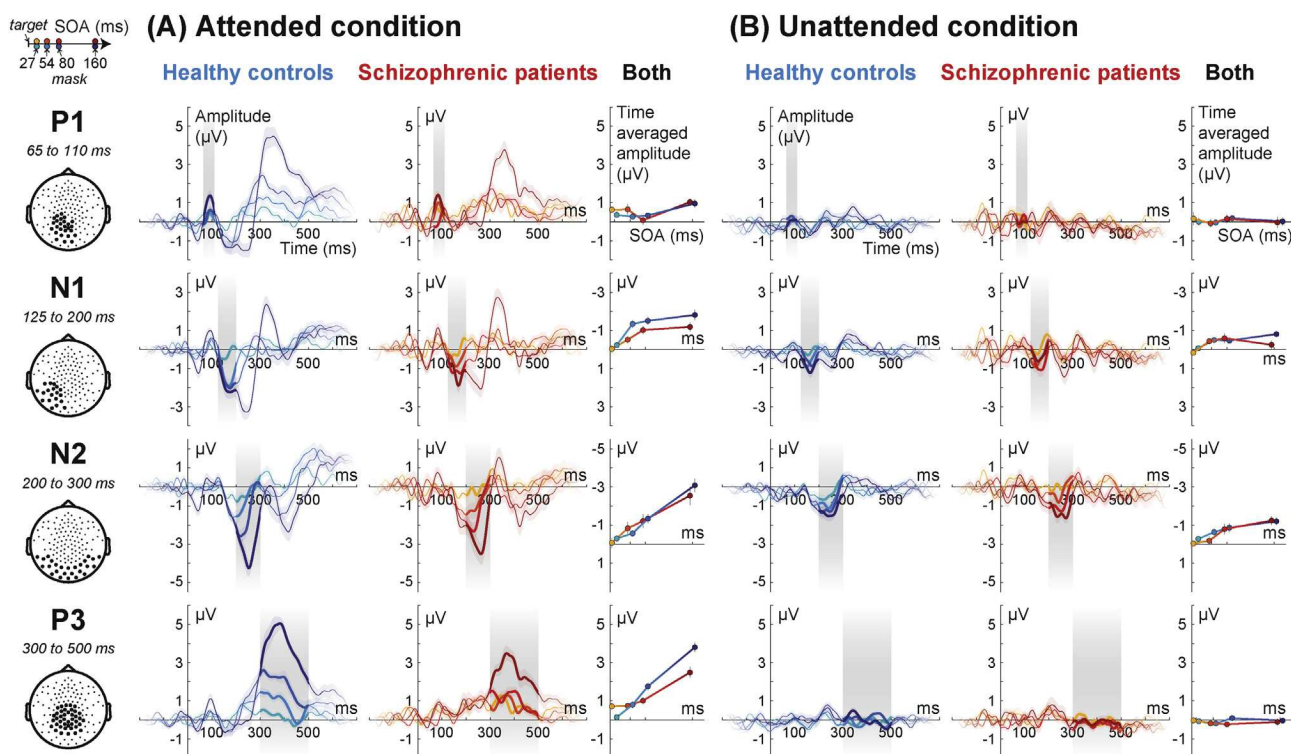


Fig. 4. Modulation of ERP components as a function of SOA

Each subplot shows the time course of ERPs as a function of SOA in the control and the patient groups under attended and unattended conditions. For each component, the preselected cluster of electrodes is depicted by black dots in the topographies at left. Preselected time-windows of interest, used for statistical analysis, are shown by grey rectangles. Colored shaded area around the curves represents one standard error of the mean. The averaged amplitude of each component in this window is also plotted (column marked “both”). Error bars represent one standard error of the mean.

therefore indicate that unattended stimuli could trigger ERPs up to ~270 ms after they were presented, but failed to induce a detectable P3 component.

### 3.2.2. Group effects

We then explored the group effects, with the hypothesis that late ignition would be reduced in the patient group under attended condition. Factorial ANOVAs were conducted on each target-evoked EEG component, with within-subject factors of SOA (27, 54, 80 and 160 ms) and attention (attended or unattended), a between-subjects factor of group (patients or controls), and subject identity as a random factor. The results are summarized in Table 2 and time-course ERP amplitude is shown in Fig. 4.

P3 was the only component for which a significant overall difference between schizophrenic patients and healthy controls was observed. For the P3, group also significantly interacted with SOA across all attention conditions ( $F_{3,90} = 6.47, p < 0.001$ ) and the triple interaction group  $\times$  SOA  $\times$  attention was significant ( $F_{3,90} = 6.41, p < 0.001$ , see Table 2, model 1).

To further explore this group difference, we conducted an ANOVA on the P3 component in each SOA condition, with factors of attention (attended or unattended) and group (patients or controls) and subject as a random factor. It revealed a significant group effect for long SOAs (80 ms:  $F_{1,30} = 5.80, p = 0.023$ ; 160 ms:  $F_{1,30} = 5.20, p = 0.030$ ) and a significant interaction between group and attention for SOA 160 ms only ( $F_{1,30} = 4.74, p = 0.037$ ).

A Group  $\times$  SOA effect on P3 was observed under attended conditions but not under unattended conditions (attended, see Model 2A: group  $\times$  SOA:  $F_{3,90} = 8.53, p < 0.001$ ; unattended, see Model 2U: group  $\times$  SOA:  $F_{3,90} = 0.95, p = 0.421, BF = 1/8.0$ ). No main effect of group was observed for P3 either in the attended (see Model 2A:  $F_{1,30} = 1.65, p = 0.209, BF = 1/2.1$ ) or in the unattended condition (see Model 2U:  $F_{1,30} = 0.17, p = 0.683, 1/BF = 4.3$ ).  $t$ -Test, however,

confirmed a significant difference between patients and controls for P3 under attended conditions at the longest SOAs (SOA 80 ms: Welch  $t_{29.3} = 2.10, p = 0.044$ ; SOA 160 ms:  $t_{29.6} = 2.50, p = 0.018$ , see Fig. 4A).

For the earlier ERP components P1, N1 and N2, no significant group effect or interaction was observed (see detailed statistics in Table 2, models 1, 2A and 2U).

To sum up, the main impairment observed in schizophrenic patients was an abnormal P3 for long SOAs under attended condition. The significant group  $\times$  SOA interaction suggested an abnormal ignition at long SOAs. The significant group  $\times$  attention interaction for the longest SOA suggested that this effect was restricted to the attended condition.

### 3.2.3. SOA effects

We then turned to the effects of SOA to explore how ERP amplitudes were modulated by the available time to process the target before the mask disrupted it. Across groups and conditions, SOA had a significant main effect on N1, N2 and P3 (Model 1: N1:  $F_{3,90} = 21.88, p < 0.001$ ; N2:  $F_{3,90} = 35.01, p < 0.001$ ; P3:  $F_{3,90} = 45.35, p < 0.001$ ) but not for P1 ( $F_{3,90} = 1.64, p = 0.187, BF = 1/18.0$ ).

The modulation of ERP amplitude by SOA under attended condition is shown in Fig. 3B and 4A. Results from controls (Table 2, model 3AC) replicated previous findings (Del Cul et al. 2007). P1 was not significantly affected by masking (SOA effect:  $F_{3,45} = 2.26, p = 0.094, BF = 1/1.6$ ). On the contrary, N1, N2 and P3 amplitudes significantly increased with SOA (N1:  $F_{3,45} = 12.74, N2: F_{3,45} = 29.49, P3: F_{3,45} = 69.58, p < 0.001, R^2$  larger than 0.4 for both components, see Fig. 3B).

Similarly, in the patient group, there was a significant effect of SOA on N1, N2 and P3 (N1:  $F_{3,45} = 6.60, N2: F_{3,45} = 13.42, P3: F_{3,45} = 16.82, p < 0.001$ , see Table 2, model 3AP). The significant effect of SOA on P1 amplitude vanished when excluding SOA = 160 ms ( $F_{2,30} = 1.47, p = 0.247, BF = 1/3.1$ ). As mentioned above (see Group

**Table 2**  
F, p-values and Bayes factors from ANOVAs on ERP components.

ERP component	P1	N1	N2	P3
<b>Model 1: Amplitude~Group × SOA × Attention</b>				
Group	$F_{1,30} = 0.06$ $p = 0.803$ BF = 1/6.7	$F_{1,30} = 2.03$ $p = 0.165$ BF = 2.5	$F_{1,30} = 0.24$ $p = 0.627$ BF = 1/5.3	$F_{1,30} = 1.67$ $p = 0.207$ BF = 1/3.2
SOA	$F_{3,90} = 1.64$ $p = 0.187$ BF = 1/18.0	$F_{3,90} = 21.88$ $p < 0.001$	$F_{3,90} = 35.01$ $p < 0.001$	$F_{3,90} = 45.35$ $p < 0.001$
Attention	$F_{1,30} = 4.92$ $p = 0.034$	$F_{1,30} = 13.14$ $p = 0.001$	$F_{1,30} = 5.14$ $p = 0.031$	$F_{1,30} = 69.05$ $p < 0.001$
Group × SOA	$F_{3,90} = 0.55$ $p = 0.649$ BF = 1/17.9	$F_{3,90} = 1.12$ $p = 0.347$ BF = 1/14.5	$F_{3,90} = 0.01$ $p = 0.961$ BF = 1/23.3	$F_{3,90} = 6.47$ $p < 0.001$
Group × attention	$F_{1,30} = 0.06$ $p = 0.810$ BF = 1/5.0	$F_{1,30} = 1.17$ $p = 0.288$ BF = 1/2.7	$F_{1,30} = 0.00$ $p = 0.961$ BF = 1/5.3	$F_{1,30} = 0.68$ $p = 0.415$ BF = 1/3.3
SOA × attention	$F_{3,90} = 4.04$ $p = 0.010$	$F_{3,90} = 3.60$ $p = 0.017$	$F_{3,90} = 12.01$ $p < 0.001$	$F_{3,90} = 67.11$ $p < 0.001$
Group × SOA × attention	$F_{3,90} = 1.64$ $p = 0.716$ BF = 1/9.4	$F_{3,90} = 1.20$ $p = 0.314$ BF = 1/11.8	$F_{3,90} = 1.76$ $p = 0.160$ BF = 1/6.8	$F_{3,90} = 6.41$ $p < 0.001$
<b>Model 2A: Amplitude~Group × SOA under attended conditions</b>				
Group effect	$F_{1,30} = 0.20$ $p = 0.658$ BF = 1/4.8	$F_{1,30} = 2.57$ $p = 0.119$ BF = 2.5	$F_{1,30} = 0.09$ $p = 0.769$ BF = 1/4.8	$F_{1,30} = 1.65$ $p = 0.209$ BF = 1/2.1
SOA effect	$F_{3,90} = 4.38$ $p = 0.006$	$F_{3,90} = 18.14$ $p < 0.001$	$F_{3,90} = 38.89$ $p < 0.001$	$F_{3,90} = 74.04$ $p < 0.001$
Group × SOA	$F_{3,90} = 0.80$ $p = 0.498$ BF = 1/6.8	$F_{3,90} = 0.91$ $p = 0.442$ BF = 1/7.7	$F_{3,90} = 0.82$ $p = 0.486$ BF = 1/8.8	$F_{3,90} = 8.53$ $p < 0.001$
<b>Model 2U: Amplitude~Group × SOA under unattended conditions</b>				
Group effect	$F_{1,30} = 0.00$ $p = 0.983$ BF = 1/5.3	$F_{1,30} = 0.50$ $p = 0.487$ BF = 1/3.1	$F_{1,30} = 0.35$ $p = 0.557$ BF = 1/3.8	$F_{1,30} = 0.17$ $p = 0.683$ 1/BF = 4.3
SOA effect	$F_{3,90} = 0.56$ $p = 0.644$ BF = 1/18.9	$F_{3,90} = 5.62$ $p = 0.001$	$F_{3,90} = 9.47$ $p < 0.001$	$F_{3,90} = 0.54$ $p = 0.655$ BF = 1/18.0
Group × SOA	$F_{3,90} = 0.13$ $p = 0.940$ BF = 1/11.3	$F_{3,90} = 1.52$ $p = 0.216$ BF = 1/6.5	$F_{3,90} = 0.49$ $p = 0.687$ BF = 1/8.9	$F_{3,90} = 0.95$ $p = 0.421$ BF = 1/8.0
<b>Model 3AC: Amplitude~SOA for controls under attended conditions</b>				
SOA effect	$F_{3,45} = 2.26$ $p = 0.094$ BF = 1/1.6	$F_{3,45} = 12.74$ $p < 0.001$	$F_{3,45} = 29.49$ $p < 0.001$	$F_{3,45} = 69.58$ $p < 0.001$
<b>Model 3AP: Amplitude~SOA for patients under attended conditions</b>				
SOA effect	$F_{3,45} = 2.86$ $p = 0.047$	$F_{3,45} = 6.60$ $p < 0.001$	$F_{3,45} = 13.42$ $p < 0.001$	$F_{3,45} = 16.82$ $p < 0.001$
<b>Model 3UC: Amplitude~SOA for controls under unattended conditions</b>				
SOA effect	$F_{3,45} = 0.44$ $p = 0.724$ BF = 1/10.1	$F_{3,45} = 4.43$ $p = 0.008$	$F_{3,45} = 4.05$ $p = 0.013$	$F_{3,45} = 1.41$ $p = 0.252$ BF = 1/6.1
<b>Model 3UP: Amplitude~SOA for patients under unattended conditions</b>				
SOA effect	$F_{3,45} = 0.30$ $p = 0.822$ BF = 1/10.5	$F_{3,45} = 3.06$ $p = 0.038$	$F_{3,45} = 5.61$ $p = 0.002$	$F_{3,45} = 0.41$ $p = 0.746$ BF = 1/9.8
<b>Model 4C: Amplitude~Attention × SOA in control group</b>				

(continued on next page)

Table 2 (continued)

ERP component	P1	N1	N2	P3
Attention effect	$F_{1,15} = 1.97$ $p = 0.181$ BF = 3.9	$F_{1,15} = 17.70$ $p < 0.001$	$F_{1,15} = 3.71$ $p = 0.073$ BF = 2.0	$F_{1,15} = 34.43$ $p < 0.001$
SOA effect	$F_{3,45} = 1.64$ $p = 0.193$ BF = 1/8.9	$F_{3,45} = 14.51$ $p < 0.001$	$F_{3,45} = 22.84$ $p < 0.001$	$F_{3,45} = 43.63$ $p < 0.001$
Attention × SOA	$F_{3,45} = 1.65$ $p = 0.191$ BF = 1/4.3	$F_{3,45} = 3.41$ $p = 0.025$	$F_{3,45} = 12.42$ $p < 0.001$	$F_{3,45} = 77.43$ $p < 0.001$
Model 4P: Amplitude–Attention × SOA in patient group				
Attention effect	$F_{1,15} = 3.01$ $p = 0.103$ BF = 1.9	$F_{1,15} = 2.35$ $p = 0.146$ BF = 1.2	$F_{1,15} = 2.01$ $p = 0.177$ BF = 1/1.1	$F_{1,15} = 35.54$ $p < 0.001$
SOA effect	$F_{3,45} = 0.83$ $p = 0.487$ BF = 1/14.6	$F_{3,45} = 8.65$ $p < 0.001$	$F_{3,45} = 14.09$ $p < 0.001$	$F_{3,45} = 10.42$ $p < 0.001$
Attention × SOA	$F_{3,45} = 2.75$ $p = 0.054$ BF = 1/4.4	$F_{3,45} = 1.79$ $p = 0.163$ BF = 1/4.6	$F_{3,45} = 3.03$ $p = 0.039$	$F_{3,45} = 13.09$ $p < 0.001$

Bold means that p values are statistically significant (i.e. under 0.05).

effects section), the only significant interaction that was observed between group and SOA occurs for the P3, reflecting a much reduced effect of SOA on P3 amplitude in patients compared to controls ( $F_{1,105} = 6.33, p < 0.001$ ). Such a reduced modulation of P3 by SOA in patients may underpin their lower objective and subjective behavioural performances compared to controls in the attended task (see Discussion).

In the unattended condition, in both groups, SOA had a significant effect on N1 and N2 (see Table 2, model 3UC and 3UP) but not on P1 and P3. The significant increase in N1 and N2 suggested that sensory information could still be processed as a function of SOA even when unattended (see Discussion). These SOA effects did not differ between patients and controls under unattended conditions (see Table 2, model 2U).

To sum up, SOA had an effect on N1 and N2 in both attended and unattended conditions without any significant difference between groups, and on P3 under attended conditions only, with a significant difference between patients and controls.

### 3.2.4. Attention effects and interactions between attention and SOA

We now report the interactions involving the attentional manipulation to see which component is significantly amplified by attention. Across groups and SOA, attention had a significant effect on all ERP components (P1:  $F_{1,30} = 4.92, p = 0.034$ ; N1:  $F_{1,30} = 13.14, p = 0.001$ ; N2:  $F_{1,30} = 5.14, p = 0.031$ ; P3:  $F_{1,30} = 69.06, p < 0.001$ , see Table 2, model 1) and a significant interaction between SOA and attention was observed for all ERP components (P1:  $F_{3,90} = 4.04, p = 0.010$ ; N1:  $F_{3,90} = 3.60, p = 0.017$ ; N2:  $F_{3,90} = 12.01, p < 0.001$ ; P3:  $F_{3,90} = 67.11, p < 0.001$ ), compatible with the idea that attention modulates the rate of accumulation of sensory information per unit of time (see Discussion).

No significant interaction between group and attention was observed (P1:  $F_{1,30} = 0.06, p = 0.810, BF = 1/5.0$ ; N1:  $F_{1,30} = 1.17, p = 0.288, BF = 1/2.7$ ; N2:  $F_{1,30} = 0.002, p = 0.961, BF = 1/5.3$ ; P3:  $F_{1,30} = 0.68, p = 0.415, BF = 1/3.3$ ). The triple interaction between group, SOA and attention did not reach significance for the early components (P1:  $F_{3,90} = 0.45, p = 0.716, BF = 1/9.4$ ; N1:  $F_{3,90} = 1.20, p = 0.314, BF = 1/11.8$ ; N2:  $F_{3,90} = 1.76, p = 0.160, BF = 1/6.8$ ), but did for the P3 ( $F_{3,90} = 6.41, p < 0.001$ ). Indeed, the attentional modulation effect on P3 was lower in the patients compared to the controls (see Table 2, model 4C and 4P; controls:  $F_{3,45} = 77.43, p < 0.001$ ; patients:  $F_{3,45} = 13.09, p < 0.001$ ;  $F_{3,45} = 13.09,$

$p < 0.001$ ) and this difference was significant for the longest SOA (group × attention for SOA 160 ms:  $F_{1,30} = 4.74, p = 0.037$ , see Group effect section).

No significant difference between patients and controls was observed for N1. However, in the control group, a main effect of attention and an interaction SOA × attention were significant for N1 (attention:  $F_{1,15} = 17.70, p < 0.001$ ; SOA × attention:  $F_{3,45} = 3.41, p = 0.025$ , see Table 2, model 4C) while it was not the case in the patient group (attention:  $F_{1,15} = 2.35, p = 0.146, BF = 1.2$ ; SOA × attention:  $F_{3,45} = 1.79, p = 0.163, BF = 1/4.6$ , see Table 2 model 4P).

To sum up, across groups, an attentional modulation was observed for all components and had a significant interaction with SOA. This effect of attention was different between the two groups for the P3 at the longest SOA.

## 4. Discussion

### 4.1. Summary of the results

We measured the effect of top-down attention on visual stimuli whose degree of masking varied by modulating the target-mask SOA duration. Our main results can be summarized as follows.

First, in the healthy control group, when subjects attended to the masked target, we replicated our previous observations of a monotonic increase of ERPs' amplitude (N1, N2, P3) as the target-mask interval increased (Del Cul et al. 2007). Inattention reduced the amplitude of all ERP components, decreased the slope with which the N1 and N2 varied as a function of SOA, and led to a complete disappearance of the P3 component. Attention therefore had both a modulatory influence on early perceptual processing and an all-or-none effect on the late P3 component.

Second, no difference was observed between the schizophrenic patient and the healthy control groups under unattended condition. In particular, the modulation of cerebral activity by SOA took place normally for N1 and N2. However, patients' consciousness thresholds, as assessed by subjective visibility and objective performance were abnormally elevated, and their P3 component was reduced relative to controls in the attended condition for long SOAs. Earlier components (P1, N1, N2) were not significantly affected.

#### 4.2. Persistence of bottom-up processing under unattended condition

One of the main goals of our experiment was to examine which of the ERP components evoked by a masked stimulus persist under a condition of inattention. The unattended condition, which involved continuous attention to the color of the fixation point, was specifically designed to induce a complete withdrawal of spatial, temporal and executive attention resources to the peripheral masked stimulus. For several minutes, this peripheral stimulus was therefore completely task-irrelevant and ignored. As a consequence, we could not record any behavioural or introspective measurements as to how this stimulus was processed. An indirect indication of strong inattention, however, was that target presence and target-mask SOA had no effect on the performance of the color estimation task, although this performance was far from ceiling.

We predicted that, in spite of this strong inattention, peripheral stimuli should still elicit early visual ERP components, up to about 300 ms, but should no longer yield a P3 waveform. This pattern is exactly what was observed. Under the unattended condition, the P1 component was strongly attenuated. The N1 and N2 components, although attenuated as well, were still observable and reflected a clear activation of occipito-temporal cortices similar to what was observed under attended condition. Furthermore, both N1 and N2 components continued to be modulated by SOA, suggesting that the accumulation of perceptual evidence from the target digit continued to occur even without attention. The results were however different for the P3, which collapsed to an undetectable level. These results are compatible with our previous postulate that brain states prior to 300 ms post-target (i.e. P1, N1 and N2) correspond to a series of largely automatic "pre-conscious" perceptual stages (Dehaene et al. 2006), while latter ones such as the P3 reflects an all-or-none stage of conscious access (Dehaene and Changeux 2011; Del Cul et al. 2007). Source reconstruction also suggests that the brain correlates of conscious access are reflected by a highly distributed set of activations involving the bilateral inferior frontal, anterior temporal and inferior parietal cortices. On the contrary, when attention is distracted during the inattention task, we observe a spatially reduced brain activity that was restricted to posterior visual and occipital areas. A relative preservation of early activations (P1, N1, N2) was previously described under other inattention paradigms such as the attentional blink (Harris et al. 2013; Marti et al. 2012; Sergent et al. 2005; Vogel and Luck 2002) or inattention blindness (Pitts et al. 2011). Such a preservation of early brain processes may explain why priming effects are repeatedly observed both in inattention blindness and attentional blink conditions.

#### 4.3. Attention and the amplification of evidence accumulation

The original contribution of the present experimental paradigm is to demonstrate, through the manipulation of SOA, that attention amplifies sensory evidence and its accumulation rate relative to strong inattention. The literature on attention has primarily focused on the issues of whether attention modulates early as well as late processes. Our study confirms that attention can have a strong modulating influence on early components, although withdrawal of attention does not completely eradicate them (Feng et al. 2012; Hillyard and Anllo-Vento 1998; Kastner and Ungerleider 2000; Luck and Ford 1998; Woodman and Luck 2003; Zotto and Pegna 2015). However, our study points to another way in which attention impacts perceptual processing. By manipulating the SOA between the target and a subsequent mask, we found that many processing stages integrate stimulus information, in the sense that their activation increases monotonically with SOA. This was particularly the case for N2 which, as noted earlier (Del Cul et al. 2007), starts at a fixed delay relative to target onset, ends at a fixed delay relative to mask onset, and appears to increase linearly in amplitude as a function of the interval elapsed between these two events. These three properties suggest that N2 might reflect an accumulation of

sensory evidence that continues until it is interrupted by the mask. Moreover, the present results extend these findings by showing that the slope of the SOA modulation, i.e. the amount of integrated information per unit of time, also called "drift rate", can be modulated by attention. Under conditions of inattention, the modulation of ERP amplitude by SOA was indeed either weakened or simply entirely absent, suggesting that attention might impact the temporal integration constant of perceptual networks. Crucially, the target was presented for the same duration in all conditions (14 ms). It therefore seems that the brain buffers this sensory information while being able to accumulate samples from it through a series of processing stages, with a slope proportional to attention, until another concurrent information (i.e. the mask) reinitializes the sensory buffer, thereby stopping the accumulation process. In summary, top-down attention seems to enable a specific mode of amplification and integration in which a fixed quantity of sensory evidence provided at input is able to trigger a series of successive stages of increasingly amplified activation, and which ultimately translates into a global ignition.

In accordance with previous theoretical models, we propose that peripheral brain processors accumulate sensory information which will be consciously perceived if it crosses a threshold and accesses a distributed global workspace able to stabilize and make it available to a variety of processes (Baars 1993; Dehaene 2011; Dehaene and Changeux 2011; de Lafuente and Romo, 2006). Importantly, accumulation of evidence can be carried out on unconscious perceptual information (Vlassova et al. 2014; Vorberg et al. 2003) and may precede conscious access (Vorberg et al. 2003). Our results concur with this idea by showing a significant increase in ERP amplitude with SOA even under unattended condition. However, they also refine these findings, indicating that such unconscious evidence accumulation process can be amplified by top-down attention and suggesting that conscious perception corresponds to a threshold crossing in evidence accumulation (Dehaene 2011; Kang et al. 2017; King and Dehaene 2014; Ploran et al. 2007; Shadlen and Kiani 2011).

#### 4.4. P3 increases beyond the minimal consciousness threshold

Prior research, using different criteria, indicates that the presence or absence of a P3 component tightly correlates with conscious access (using a variety of paradigms with fixed stimuli and variable subjective experience: Babiloni et al. 2006; Del Cul et al. 2007; Fernandez-Duque et al. 2003; Lamy et al. 2008; Pins and Ffytche 2003; Sergent et al. 2005). Recently, this view has been challenged by concurrent hypotheses proposing that P3 might reflect post-perceptual processing rather than truly being a neural correlate of consciousness. Indeed, P3 was observed to be absent even for consciously perceivable stimuli when these were task-irrelevant (Pitts et al. 2011, 2014; Shafto and Pitts 2015).

In our previous work (Del Cul et al. 2007), SOA varied only in the range 16–100 ms. Over this range and under attended condition, we observed a sigmoidal variation of objective and subjective indices of target visibility, and we found that P3 amplitude closely tracked this sigmoidal shape. Here, however, by extending the SOA to longer values (27–160 ms), we observed that the P3 amplitude continued to increase in the range 100–160 ms where subjective visibility reached a fixed ceiling. Still, P3 amplitude again closely tracked visibility in the sense that it was nil at SOA = 27 ms, precisely when subjects reported that stimuli were essentially invisible, and then increased for larger SOAs when the stimuli became visible. The P3 thus showed a threshold-like non-linearity at short SOAs (see Fig. 4A), unlike other waveforms such as the N2 which was already observable for stimuli that were judged invisible (i.e. SOA = 27 ms).

Such a continued P3 increase at long SOAs was unexpected and indicates a departure for the close parallelism previously suggested between conscious reports and P3 size (Babiloni et al. 2006; Del Cul et al. 2007; Fernandez-Duque et al. 2003; Lamy et al. 2008; Pins and

Ffytche 2003; Sergent et al. 2005). This aspect of our results suggests that, like previous ERP stages, P3 may reflect an evidence-accumulation process, but within a high-level cognitive route associated with subjective experience and reportability, above and beyond the mere sensori-motor mapping level (Dehaene 2011; Del Cul et al. 2009; King and Dehaene 2014; Shadlen and Kiani 2011). Several other studies have indeed shown how P3 is associated with the formation of decisions and can reflect evidence accumulation (Gold and Shadlen 2007; O'Connell et al. 2012; Twomey et al. 2015) as well as post-decision confidence (Boldt and Yeung 2015; Murphy et al. 2015). Given those studies, it seems possible that the binary subjective measure that we have used (seen/unseen) did not fully do justice to the rich introspection that subjects had about target visibility. Had we measured a more continuous parameter such as confidence or clarity, it seems possible that one or several of such behavioural indices would have grown continuously with SOA, paralleling the observed increase in P3 size.

#### 4.5. Abnormal attentional amplification in schizophrenia

Behaviourally, we replicated the previous findings according to which schizophrenic patients suffer from a higher objective and subjective thresholds for conscious perception during masking (Butler et al. 2003; Charles et al. 2017; Dehaene et al. 2003a; Del Cul et al. 2006; Green et al. 1999, 2011; Herzog and Brand 2015; Plomp et al. 2013). The main goal of our study was to evaluate whether this deficit was associated with impairments of bottom-up and/or top-down processing. Schizophrenic patients compared to healthy controls, showed anomalies in evoked brain activity only under attended conditions for long SOAs: the late non-linear ignition component associated with the P3 component was reduced. However, no difference was found under unattended condition. We emphasize the need for caution in interpreting those null findings in the unattended condition, as they might be due to a lack of power arising from the small sample size (16 patients and 16 controls). Nevertheless, our data were sensitive enough to detect a preservation of the modulation of the N1 and N2 by SOA in the patient group under unattended conditions. In other words, both the target processing and the initial accumulation of evidence as well as its modulation by SOA took place normally in patients when the stimulus was unattended. We therefore conclude that patients' deficit in perceiving masked stimuli probably mostly arises from a lack of appropriate top-down attentional amplification rather than from a mere bottom-up impairment.

At the level of the P3, the difference between patients and controls was significant only for long SOAs. The patients exhibited a detectable P3 in the attended compared to the unattended condition (see Fig. 4) but there was almost no modulation of its amplitude by SOA when SOA was shorter than 80 ms (see Fig. 4A). These results are consistent with the behavioural results showing reduced objective performances in the patient group only at long SOAs (Fig. 2).

In our work, no significant difference between patients and controls was observed for the N1. This finding contrasts with several previous studies that found a reduced N1 amplitude in the auditory modality (Brockhaus-Dumke et al. 2008; Turetsky et al. 2008) and in several visual masking paradigms (Neuhaus et al. 2011; Wynn et al. 2013). Careful examination of the present results suggests that a non-significant difference in N1 amplitude may be observable in Fig. 4A for SOA > 27 ms. Moreover, N1 topography also seems to be different in patients and controls at SOA 160 ms (see Fig. 3). According to source reconstruction, posterior negative cerebral activity is more ventral and more bilateral in patients compared to controls at SOA 160 ms (see Sources in Fig 3A). For SOA 54 and 80 ms, N1 is still visible in controls but not in patients and a frontal positivity is present in controls but not in patients for SOA 27 and 54 ms (Fig. 3B). Because of our small sample size ( $n = 16$  in each group), we may simply lack enough statistical power to demonstrate a significant statistical difference between groups for N1 under attended conditions, and this effect should be re-

investigated in future experiments.

In our experiment, patients showed essentially normal attentional amplification of the P1 and N2 components. By contrast, previous studies found that patients had an impaired P1 (Butler et al. 2007; Doniger et al. 2002; Foxe et al. 2001; Schechter et al. 2005). Moreover, it remains controversial whether N2 is spared or abnormal in patients (Luck et al. 2006; Salisbury et al. 1994). Once again, the absence of difference between patients and controls in our study should be interpreted with caution. It might indeed result from a lack of power due to the small sample size (16 patients and 16 controls). However, this result is in line with previous studies suggesting that attentional selection could be preserved when guided by strong bottom-up salience (Gold et al. 2017; Luck et al. 2006).

As reviewed in the introduction, some authors proposed that the elevated threshold for conscious access in schizophrenia was due to a specific dysfunction of the magnocellular pathway, while the parvocellular visual pathway was thought to be preserved (Butler et al. 2005, 2007; Javitt 2009; Kim et al. 2006; Martínez et al. 2012). Tapia and Breitmeyer (2011), however, revisited this issue and proposed that magnocellular channels contribute to conscious object vision mainly through a top-down modulation of re-entrant activity in the ventral object-recognition stream. The link between magnocellular circuits and visual masking in schizophrenia was also contested recently, as there seems to be no clear evidence of either hyper or hypo-activity of the magnocellular pathway in schizophrenia (Herzog and Brand 2015).

If the elevated threshold for conscious perception in schizophrenia was solely due to abnormal bottom-up sensory processing, one would expect subliminal and unattended processing to be abnormal too. However, first, even subtle measures of subliminal priming have repeatedly been shown to be fully preserved in schizophrenia (Dehaene et al. 2003a; Del Cul et al. 2006; for a review, see: Berkovitch et al. 2017) and our results are compatible with these observations since no difference was observed for short SOAs. Second, the present results extend this logic by showed that, following the total withdrawal of spatial, temporal and executive attention, the remaining brain activity evoked by a flashed stimulus is indistinguishable between patients and controls. By hypothesis, this activity should provide a proper measure of bottom-up processing, which therefore appears to be essentially intact.

Consequently, we suggest that previous reports of elevated masking threshold and abnormal conscious processing in schizophrenia (Butler et al. 2003; Charles et al. 2017; Dehaene et al. 2003a; Del Cul et al. 2006; Green et al. 1999; Herzog et al. 2004; Plomp et al. 2013) might stem from late impairments in processing stages associated with the P3 and which, in turn, are associated with the inability to deploy top-down attention. An abnormal P3 and ignition deficits had already been reported in schizophrenia in attended conditions (Bramon et al. 2004; Charles et al. 2017; Jeon and Polich 2003; Oribe et al. 2015; Qiu et al. 2014) and several studies showed that the difference in cerebral activity between attended and unattended conditions was reduced in schizophrenia (Force et al. 2008; Martínez et al. 2012; Michie et al. 1990). Moreover, other studies suggested impairments in top-down processing (Dima et al. 2010; Plomp et al. 2013) and selective attention (Fuller et al. 2006; Luck et al. 2006) in which schizophrenic patients were characterized by a narrower spotlight of spatial attention termed hyperfocusing (Hahn et al. 2012; Leonard et al. 2017; Sawaki et al. 2017).

The present study is therefore in line with the hypothesis of a top-down impairment in schizophrenic patients and refines previous results by distinguishing bottom-up versus top-down processes and suggesting that some top-down attentional amplification (underlying P1 and N2 components) can remain preserved in schizophrenia. Tentatively, one may suggest that the activations that were found to be preserved in schizophrenic patients (i.e. P1 and N2, but also P3 for short SOAs) might account for the preservation of subliminal processing.

More broadly, the present results fit with several other psychopathological aspects of schizophrenia (Berkovitch et al. 2017).

Schizophrenic patients exhibit anomalies in long-distance anatomical connectivity (Bassett et al. 2008; Benetti et al. 2015; Jones et al. 2006; Kubicki et al. 2005; Sigmondsson et al. 2001) and functional connectivity (Ford et al. 2002; Frith et al. 1995; Lawrie et al. 2002; Vinckier et al. 2014) in distributed networks that are thought to underlie the broadcasting of conscious information in the global workspace (Dehaene and Changeux 2011). Moreover, the long-range synchrony of gamma and beta-band oscillations is disturbed in schizophrenic patients (Cho et al. 2006; Lee et al. 2003; Mulert et al. 2011; Spencer et al. 2004; Uhlhaas and Singer 2010), while conscious perception in normal subjects is accompanied by late increases in gamma-band power (Doesburg et al. 2009; Gaillard et al. 2009; Melloni et al. 2007; Wyart and Tallon-Baudry 2009) and beta-band phase synchrony (Gaillard et al. 2009; Gross et al. 2004; King et al. 2013). Finally, abnormal regulation of NMDA receptors was suggested as a putative core pathology in schizophrenia (Coyle 2006; Jentsch and Roth 1999; Olney and Farber 1995; Stephan et al. 2009). NMDA receptors are broadly involved in connectivity and synaptic plasticity (Stephan et al. 2009) as well as inter-areal synchrony (Rivolta et al. 2015; Uhlhaas et al. 2014; van Kerkoerle et al. 2014). Recently, they have been shown to play a specific role in top-down cortico-cortical connectivity and the late amplification of sensory signals (Herrero et al. 2013; Moran et al. 2015; Self et al. 2012; van Loon et al. 2016). In particular, NMDA-receptor antagonists leave intact the feedforward propagation of visual information, and selectively impact on late recurrent processing (Self et al. 2012). NMDA receptor dysfunction could therefore be a plausible cause for the anomaly in conscious perception observed in the present work.

#### 4.6. Conclusion

Our study aimed to disentangle how sensory information processing is modulated by bottom-up (SOA) and top-down (attention) factors. We found that, in the absence of attention, bottom-up information was still processed and weakly modulated the early stages of information processing, prior to 300 ms. Attention, however, enabled a strong amplification of sensory signals that, in its late stages, certainly played an important part in conscious access. The abnormal consciousness threshold in schizophrenia seems tightly linked to a dysfunction of the latter top-down attentional amplification mechanisms.

#### Acknowledgements

This work was supported by INSERM, CEA, Collège de France, Fondation Roger de Spoelberch, and an ERC grant “Neuroconsc” to S.D.; Fondation pour la Recherche Médicale (40532) to L.B. and S.D.; a “Frontières du Vivant” doctoral fellowship involving the Ministère de l’Enseignement Supérieur et de la Recherche and Fondation Bettencourt to M.M. We gratefully acknowledge the hospitality of Marion Leboyer.

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**Part II.**  
**Conscious access and subliminal processing in healthy  
controls**



# **Chapter 4. Interactions between metacontrast masking and attentional blink: a pilot study before exploring ketamine effects on conscious access**

## **Introduction of the article**

The two previous studies support that dissociation between impaired conscious access and preserved unconscious processing in schizophrenia may be associated with top-down attentional amplification and dysconnectivity. Moreover, elevated consciousness threshold seems to play an important role in the advent of psychotic symptoms, notably in patients with bipolar disorder.

In the present study, we test a paradigm quite similar to the one used in chapter 2, in order to prepare a future project investigating ketamine effects on conscious and subliminal processing in healthy controls. Indeed, ketamine is an anaesthetic agent that can induce reversible psychotic-like symptoms when administered at low doses, providing a pharmacological model of psychosis. This pilot study aims at manipulating bottom-up and top-down factors, using masking and attentional blink, to explore mechanisms by which ketamine may disrupt conscious access. This chapter reports the results of the pilot study we conducted without ketamine.

## **Abstract**

Backward masking and attentional blink are two techniques used to render a stimulus subliminal. The former rests upon interference between a briefly presented target and a subsequent mask, i.e. interrupt bottom-up evidence accumulation, whereas the latter relies on distracting attention from a stimulus, and thus impairs conscious access by reducing top-down attentional resources availability. Previous studies showed that in attentional blink, the duration of the target modulated the blink effect, in particular, when the target was shortened, the blink effect was stronger. In the present study, we explored whether backward masking and attentional blink had a synergistic effect. A sound was played and followed after a variable delay by a masked digit. Participants had to identify the sound and/or to compare the digit to five and report its visibility. Sound-target and target-mask SOA were parametrically varied to

study the interaction between attentional blink and masking. We found that masking had a robust effect in both simple and dual-task conditions, whereas an attentional blink and a psychological refractory period were observed only in the dual-task condition, i.e. when participants should both categorize the sound and compare the digit to five. Crucially, masking and attentional blink interacted: attentional blink was more pronounced for short target-mask SOA duration. This paradigm can therefore be used to tease apart bottom-up and top-down factors. In a future project, we aim to explore ketamine effects on conscious access in healthy controls, and in particular to study whether they involve top-down or bottom-up processing disruption, by using this paradigm while cerebral activity is recorded with electroencephalography. We also discuss in this article which results may be obtained according to current knowledge about ketamine mechanisms.

## **Introduction**

Ketamine is a noncompetitive *N*-methyl-D-aspartate receptor antagonist that is used in medicine as an anaesthetic agent (Reich et al., 1989) or as an analgaesic agent (Bell, 2009; Suzuki, 2009). The anaesthetic effects of ketamine are supposed to rest upon disruption of long-distance prefrontal-parietal connectivity, reduction of alpha power and increase of gamma power (Blain-Moraes et al., 2014; Bonhomme et al., 2016; Lee et al., 2013; Uhrig et al., 2016; Vlisides et al., 2017; for a review, see: Mashour et al., 2018). The analgaesic effects are obtained with doses lower doses of ketamine, and can be achieved either with intravenous or oral delivery (Blonk et al., 2010).

With lower doses, it has been noted that ketamine could induce reversible psychotic-like symptoms such as delusional ideas in healthy controls subjects and bring forward symptoms that mimicked a relapse in patients with remitted schizophrenia (Krystal et al., 1994; Lahti et al., 2001; Lahti et al., 1995; Pomarol-Clotet et al., 2006). Moreover, delusional ideas observed in healthy controls administered with ketamine are associated with aberrant predictions error activations in the prefrontal cortex that are similar to those observed in patients with schizophrenia (Corlett et al., 2006; Murray et al., 2007). Finally, the hypothesis that schizophrenia involves NMDA dysfunction is supported by post-mortem studies, genetic and in vivo imaging (Coyle, 2006; Fuchs et al., 2001; Howes et al., 2015b). Ketamine does not reproduce the full range of symptoms observed in schizophrenia, but given its behavioural,

imaging and electrophysiological effects, it is used as a pharmacological model of early psychosis (Corlett et al., 2007, 2016; Vinckier et al., 2016)..

Across a variety of paradigms, an elevated threshold for conscious perception has been observed in persons with schizophrenia. By contrast, subliminal processing of masked or unattended stimuli appears to be preserved (for a review, see: Berkovitch et al., 2017). Such a dissociation between impaired conscious access and intact unconscious processing is better explained by a disruption of attentional amplification than by sensory processing impairment, which has no reason to spare subliminal processing (Berkovitch et al., 2017, 2018).

This elective impairment of conscious processing is thought to play a role in psychotic symptoms (Berkovitch et al., 2017). Therefore, psychotropic properties of low doses of ketamine may be underpinned by cognitive effects on consciousness.

The goal of the present project is two-fold. First, to confirm that low dose of ketamine provides a valid cognitive model of schizophrenia by showing that it induces an elevated consciousness threshold and a dissociated pattern of impaired conscious access and preserved subliminal processing. Second, to investigate the mechanisms by which ketamine may disrupt conscious access using high-resolution electroencephalography, in particular to see whether it causes impaired top-down amplification. Indeed, NMDA receptors were shown to be involved in attentional amplification, long-range connectivity and synchrony which are crucial for conscious access (Anticevic, Corlett, et al., 2015; Herrero et al., 2013; Krystal et al., 2017; Moran et al., 2015; Rivolta et al., 2015; Self et al., 2012; Uhlhaas et al., 2014; van Kerkoerle et al., 2014; van Loon et al., 2016).

This project capitalizes upon a study which demonstrated that patients with schizophrenia had an elevated consciousness threshold in visual masking associated with a decreased P3 component for attended stimuli, while subliminal and unattended stimuli were processed with no difference compared with healthy controls (Berkovitch et al., 2018). In this previous work, a digit target was presented for a brief fixed duration (14 ms), and followed, after a variable stimulus-onset-asynchrony (SOA), by a metacontrast mask consisting of surrounding letters. A fixed amount of sensory evidence was therefore initially injected while a variable amount of time was available to accumulate the evidence before the processing of the mask disrupted it. Importantly, there were two main conditions of attention. In the attended condition, subjects were asked to focus their attention on the peripheral masked digits and to

report their visibility (as in the original studies by Del Cul et al., 2006, 2007). In the unattended condition, attention to masked stimuli was withdrawn through the use of a highly demanding concurrent task: subjects were asked to focus on small and changing colour circles presented at fixation and to report which colour was predominant, while the same masked digits were presented in the periphery of the visual field. In the distraction condition, the brain activity evoked by masked digits was drastically reduced in patients and healthy controls, but early bottom-up visual activation could still be detected and did not differ between the two groups. By contrast, under focused top-down attention, a major impairment was observed: in patients, contrary to controls, the late non-linear ignition associated with the P3 component was reduced. Interestingly, the patients showed an essentially normal attentional amplification of the P1 and N2 components. These results suggest that some but not all top-down attentional amplification processes are impaired in schizophrenia, while bottom-up processing seems to be preserved. Only few studies explored attentional blink in schizophrenic patients. They repeatedly found that patients had an exaggerated attentional blink effect compared to controls (Cheung et al., 2002; Li et al., 2002; Wynn et al., 2006), associated with a decreased P3 (Mathis et al., 2012).

In the present project, we want to see whether similar results will be obtained with the administration of ketamine to healthy subjects. In addition, we aim to further explore how attentional resources will be allocated under ketamine. Therefore, we modulate attentional availability with task relevance, like in the previous paradigm (i.e. target attended or unattended) (Berkovitch et al., 2018), but we add a dual-task condition in which attention is parametrically manipulated. The main task is similar to that used by Berkovitch et al. (2018): participants have to indicate if a target digit, presented for a brief fixed duration (17 ms), and followed by a metacontrast mask, is greater or smaller than 5. However, this time, the distracting task is to identify if a sound, played at a varying delay before the digit is displayed, was the syllable “ka” or “pi”. Varying the delay between the sound and the digit in the dual-task enables us to drive attention away from the digit in a parametric manner, with a known maximum of inattention that induces an “attentional blink” or a “psychology refractory period” in the literature. Indeed, when participants are asked to focus on a stimulus presented just before a target, this engagement slows down their response to the target, a phenomenon called the psychological refractory period (Pashler, 1994; Welford, 1952), or even prevents its detection, an effect which is referred to as the attentional blink (Raymond et al., 1992; Shapiro, 1991). Both psychological refractory period and attentional blink are supposed to rest upon the same mechanism: conscious information would be processed serially creating a bottleneck when two

tasks should be performed at the same time (Marti et al., 2012, 2015; Sigman et al., 2005; Zylberberg et al., 2010).

To sum up, our experimental design manipulates three variables: (1) the stimulus relevance by instructing participants to attend the sound, the digit or both, (2) the amount of allocated attention in the dual-task, as a function of the delay between the sound and the digit (sound-target SOA, to measure the resulting attentional blink and psychological refractory period), (3) the amount of visual masking, as a function of the delay between the digit and the metacontrast mask (masking SOA).

This experimental setup enables us to study the interaction between two ways of disrupting conscious access, namely attentional blink and metacontrast masking, and also to determine whether unconscious processing is equally preserved under ketamine in these two situations of conscious access disruption. The hypothesis that ketamine affects top-down amplification predicts that (1) the threshold for conscious perception should be elevated under ketamine in the attended condition, (2) the synergistic effect between metacontrast masking and attentional blink on conscious processing should be amplified by ketamine, (3) crucially, performance in the unattended condition and subliminal processing should not be affected by ketamine. Importantly, the parametric modulation of attention allows to explore the mechanisms by which ketamine disrupts conscious access. Indeed, it was previously proposed that ketamine caused an increased feed-forward/feed-back imbalance through NMDA blockade and AMPA upregulation (Autry et al., 2011; Corlett et al., 2009), even if a recent study found that both feed-forward and feed-back were disrupted (Grent-'t-Jong et al., 2018). In light of these results, external stimuli may not access the global neuronal workspace as a direct result of decreased feed-back amplification. Alternatively, the global neuronal workspace may not be able to select relevant information and could be saturated by random feed-forward signals preventing pertinent stimuli from entering its bottleneck. In this latter case, we expect to observe interference by irrelevant sound in the simple task on the digit. Critically, this interference will depend on sound-target SOA, akin to an attentional blink. Finally, ketamine might impair consciousness only by feed-forward disruption, in this case, only masking effects will be inflated by ketamine regardless of attentional resources devoted to the stimulus.

Since parametric interactions between attentional blink and visual masking had not been previously studied, we conducted a pilot behavioural study on healthy controls without ketamine administration to ensure that this experimental design was efficient, in particular in



eliciting an attentional blink. In classical attentional blink studies, the target is embedded in a continuous stream of distractors and participants are asked to perform an objective task on the target when they detect it (Shapiro et al., 1997). This method provides a measure of performance on seen targets and quantifies the proportion of missed targets. In our study, because both attentional distraction and visual masking were combined, we were not sure whether participants would on some occasions effectively not detect the target because of attentional blink. First, we could not embed the digit in a series of distractors because this was not compatible with metacontrast masking. Indeed, metacontrast masking is more efficient when the stimulus is displayed at an unpredictable location on the screen (Alpern, 1953; Enns et al., 2000). Consequently, embedding the digit in a series of distractors would have made its location fully predictable, thereby decreasing the efficiency of the masking effect. Second, detection and discrimination performances could be discrepant. Indeed, comparing a digit to 5 forced participants to extract abstract features of the stimulus, since the shape of the stimulus alone was not sufficient in our experiment (the digits smaller and greater than 5 were chosen so that their shapes were as close in appearance as possible: 3 could be mistaken for an 8 and 2 for a 7). By contrast, determining whether the target was present or absent was easier, comparing actual trials and catch trials where the target digit is replaced by a blank. Nevertheless, in classical attentional blink tasks, participants are asked to detect a target among look-alike distractors (e.g. a particular letter, among different letters), which requires not only to detect it, but also to identify it. Previous studies evidenced an attentional blink on objective performance for stimuli that were not embedded in a series of distractors (e.g. Duncan et al., 1994; Nieuwenstein et al., 2009; Sergent et al., 2005). Duncan and colleagues used two backward masked targets that appeared subsequently at unpredictable locations (the first one could appear left or right, the second up or down) and they obtained an attentional blink for objective performance in a forced-choice task (Duncan et al., 1994). Nieuwenstein and colleagues compared attentional blink when targets were preceded or not by distractors. They also modulated the duration of the target and showed that objective performance was more affected when target was preceded by distractors but also when its duration was shortened (Nieuwenstein et al., 2009). These results suggest that we have a good chance to observe an interaction between attentional blink and visual masking (i.e. a parametric interaction between sound-target SOA and masking SOA). To deal with potential discrepancies between discrimination and detection performance, we systematically assessed both objective performance and subjective visibility: participants were asked to venture an objective answer

(smaller or greater than 5) even in trials rated as unseen. Here we present the results of this pilot study.

## **Material and methods**

### **Participants**

Nineteen right-handed participants (11 females; mean age: 22.4 years old; range: 19–33 years old) were tested. All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. Participants gave informed consent and received financial compensation (15€ for a session of 1h30).

### **Design and Procedure**

The experimental paradigm is summarized in Figure 1. We used a variant of the masking paradigm designed in previous studies in normal and clinical populations (Berkovitch et al., 2018; Charles et al., 2017; Del Cul et al., 2006, 2007; Reuter et al., 2007, 2009). Stimuli presentation began with a central fixation cross. A sound was played after a jittered delay (between 1000 and 1667 ms), so it could not be predictable. The sound was an isolated syllable “*ka*” or “*pi*” pronounced by a female voice during 195 ms. After a first delay (sound-target stimulus onset asynchrony, SOA, of 100, 300, 500 or 700 ms, randomly intermixed across trials), a digit (2, 3, 7 or 8, hereafter denominated “the target”) was presented for a fixed duration of 17 ms at a random position above or below the fixation cross. After a second delay (masking SOA of 33, 50, 67 or 167 ms randomly intermixed across trials), a metacontrast mask appeared at the target location for 200 ms. It was composed of four letters (two horizontally aligned M and two vertically aligned E) surrounding the target stimulus location without superimposing or touching it. Twenty percent of the trials were mask-only trials (catch trials): the target was replaced by a blank screen of the same duration, 17 ms. The exact same sequences of stimuli were presented under three distinct conditions, which differed only in the instructed task.

The dual-task instructions were to pay attention both to the sound and to the masked digit, and to give three behavioural responses: (1) determine as fast as possible whether the sound was “*ka*” or “*pi*”, (2) decide as fast as possible whether the digit was greater or smaller than 5 (which provided an objective measure of target perception) and (3) report the digit visibility using a categorical response “seen” or “not seen” (providing a subjective measure of

conscious access). When performing the simple digit-related task, participants had to answer questions about the digit only, i.e. (1) decide as fast as possible whether it was greater or smaller than 5 and (2) report the digit visibility using a categorical response “seen” or “not seen”, and were asked to ignore the sound. Finally, in the simple sound-related task, participants had to answer the question about the sound only, i.e. determine as fast as possible whether the sound was “ka” or “pi”, and ignore the digit.

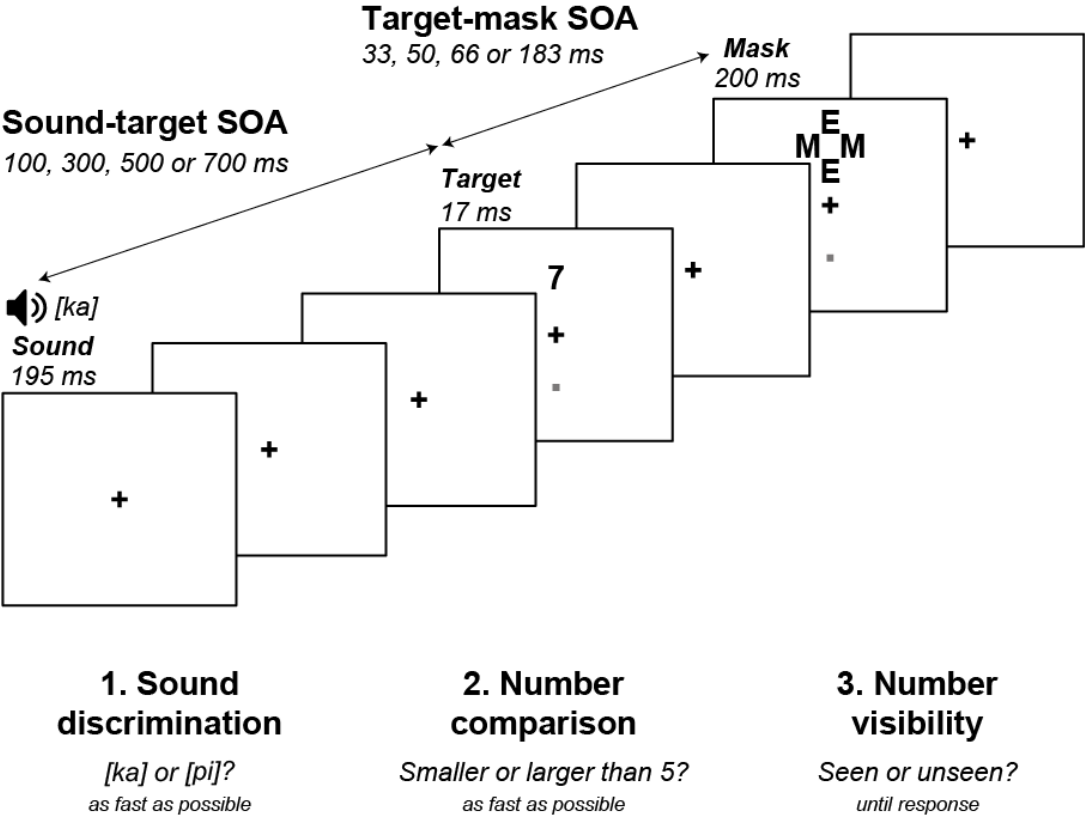


Figure 1. Experimental paradigm. A sound (an isolated syllable “ka” or “pi”) was played. After a first delay (sound-target stimulus onset asynchrony, SOA), a digit target was briefly displayed (17 ms) at a random position above or below the fixation cross and subsequently masked after a second delay (target-mask SOA). The exact same sequences of stimuli were presented under three distinct conditions, which differed only in the requested task. In the dual-task condition, subjects were asked to: (1) determine as fast as possible whether the sound was “ka” or “pi”, (2) decide as fast as possible whether the digit was larger or smaller than 5 and (3) report the digit visibility using a categorical response “seen” or “not seen”. In the simple digit-related task condition, participants had to answer questions about the digit only (i.e. 2 and 3), and were asked to ignore the sound. On the contrary, in the simple sound-related task condition, participants had to answer the question about the sound only (i.e. 1) and ignore the digit. Responses and reaction times were recorded.

Participants provided answers to the number and sound objective questions by pressing as fast as possible specific keys of a keyboard. At each block, one hand was dedicated to the sound-related task, the other to the digit-related task, hands were counterbalanced across blocks and participants. However the answer “*smaller than 5*” and “*ka*” were always assigned to the left most button for each hand. In the dual-task condition, participants were instructed to answer the sound-related task first and not to group their answers (i.e. they had to answer to the sound as quickly as possible without waiting for the digit to appear). In the dual and the simple digit-related tasks, as soon as participants had responded to the number and/or the sound objective questions (or after five seconds in the absence of response), a screen for the visibility task appeared. The response words “Vu” (“Seen”) and “Non Vu” (“Unseen”) were displayed on the screen, randomly assigned to the right and left of the fixation point. Participants responded by pressing one of the two buttons on the side of the response they wanted to select (e.g. left side for “Vu” if it was presented on the left of the fixation cross). The mapping between the keys and the response options was randomized on a trial-by-trial basis to decouple participants’ responses to the objective question from the response to the visibility question. No time limit was assigned to the visibility question and the “Seen” and “Unseen” response choices remained on the screen until a response was given.

Instructions for both attended and unattended tasks were given at the beginning of the experiment and were reminded before each block. Subjects completed eight blocks in total: four “dual-task” blocks of 80 trials each (i.e. 320 trials), two “simple digit-related task” blocks of 40 trials each (i.e. 80 trials), and two “simple sound-related task” blocks of 40 trials each (i.e. 80 trials). Block order was counterbalanced across participants. Feedback on accuracy and response times was provided to participants at the end of each block.

Participants were trained to the three conditions at the beginning of the experiment. To facilitate learning, the training blocks order was the same for all participants: first they performed the simple sound-related task, then the simple digit-related task and finally the dual-task, so that complexity progressively increased. They did at least 20 trials of each task before starting the experiment, and training continued until performances reached a ceiling.

In the dual-task condition, there were 20 trials, including 5 mask-only trials, in each combination of sound-target SOA (4 levels, i.e. SOA of 100, 300, 500 or 700 ms) and masking SOA (4 levels, i.e. SOA of 33, 50, 67 or 167 ms). Under each simple task condition there were 5 trials, including one mask-only trial, in each combination of sound-target SOA (4 levels, i.e.

SOA of 100, 300, 500 or 700 ms) and masking SOA (4 levels, i.e. SOA of 33, 50, 67 or 167 ms).

### **Behavioural data analysis**

In the sound-related task we measured the performance (% correct) in determining which sound was played (T1: objective measure of sound discrimination performance), and the response time (ms). In the digit-related task, we measured the performance (% correct) in comparing the target digit against 5 (T2: objective measure of conscious access), the response time for providing this answer (ms), and the rate (%) of seen trials (T3: subjective measure of conscious access).

Analyses of variance (ANOVAs) were conducted on each of those behavioural measures, with masking SOA and sound-target SOA as within-subject factors. We excluded from the analyses mask-only trials, trials with response times above 2000 ms or under 200 ms for the sound-related question (T1), trials with response times above 2500 ms or under 300 ms for the digit objective question (T2), and trials where participants gave responses for T2 before giving responses for T1. For response times analysis in the dual-task, only trials on which participants correctly answered the sound task were taken into account. A sensitivity index ( $d'$ , a statistic measure used in signal detection theory) was computed by confronting the subjective visibility (seen versus not seen) against the presence or absence of a digit (target versus mask-only trials).

## **Results**

Results are summarized in Figure 2.

### **Visual masking**

We first analysed the effect of the visual masking SOA on performance in the digit-related task, in order to explore the masking effect. The visual masking SOA significantly influenced the proportion of correct answers in comparing the target digit to 5 (i.e. objective performance), and the fraction of seen trials (i.e. subjective visibility) both in the simple and dual-task conditions (simple task: objective performance:  $F_{3,54} = 44.17$ ,  $p < 0.001$ , subjective visibility:  $F_{3,54} = 69.27$ ,  $p < 0.001$ ; dual-task: objective performance:  $F_{3,54} = 95.48$ ,  $p < 0.001$ , subjective visibility:  $F_{3,54} = 81.33$ ,  $p < 0.001$ ) (Figure 2A and 2B left panel).

The visual masking SOA also had a significant effect on response times for objective performance in the digit-related task both in the simple and dual-task conditions (dual-task:  $F_{3,54} = 3.44$ ,  $p = 0.023$ , simple task:  $F_{3,54} = 3.9$ ,  $p = 0.014$ ) (Figure 2C middle and right panels).

### **Attentional blink**

We now turn to the effect of the sound-target SOA on performance in the digit-related task, in order to investigate the attentional blink effect. The only significant effect of the sound-target SOA was on the objective performance in the dual-task condition ( $F_{3,54} = 3.28$ ,  $p = 0.028$ , Figure 2A middle panel), suggesting that the sound-related task significantly interfered with the processing of the digit. Surprisingly, subjective visibility was not influenced by the sound-target SOA in the dual-task condition ( $F_{3,54} = 2.47$ ,  $p = 0.071$ , Figure 2B middle panel). In the simple task condition, neither objective performance nor subjective visibility was influenced by the sound-target SOA (objective performance:  $F_{3,54} = 0.13$ ,  $p = 0.95$ ; subjective visibility:  $F_{3,54} = 0.79$ ,  $p = 0.50$ , Figure 2A and 2B right panel).

We examined the effect of response times for the sound-related task (RT1) on performance in the digit-related task in the dual-task condition. For each subject, we split trials into short and long RT1 (below and above the median), and computed a repeated measure ANOVA with short/long RT1, visual masking SOA and sound-target SOA as within-subject factors. No significant effect of short/long RT1 was observed on objective performance in comparing the digit to 5 ( $F_{1,18} = 3.91$ ,  $p = 0.064$ ) or on subjective visibility ( $F_{1,18} = 3.19$ ,  $p = 0.091$ ).

### **Psychological refractory period**

We further analysed the effect of the sound-target SOA on response times for the objective question of the digit-related task (RT2), in order to explore the psychological refractory period. The sound-target SOA only had an effect on response times in the dual-task condition (dual-task:  $F_{3,54} = 45.16$ ,  $p < 0.001$ , simple task:  $F_{3,54} = 1.00$ ,  $p = 0.40$ , Figure 2C left and middle panel). These results indicate that RT2 was significantly longer for short sound-target SOAs. The slope of the regression line was  $-0.85 \pm 0.55$  between sound-target SOA 100 and 300 ms and tended towards 0 as the lag increased ( $-0.59 \pm 0.52$  between lag 300 and 500 ms, and  $-0.09 \pm 0.44$  between lag 500 and 700 ms). This result suggests that at short sound-target SOAs, reducing the sound-target SOA increased RT2, whereas at long sound-target

SOAs, the sound-target SOA duration did not significantly influence RT2 indicating that at long sound-target SOAs, the sound-related task and the digit-related task could be sequentially performed.

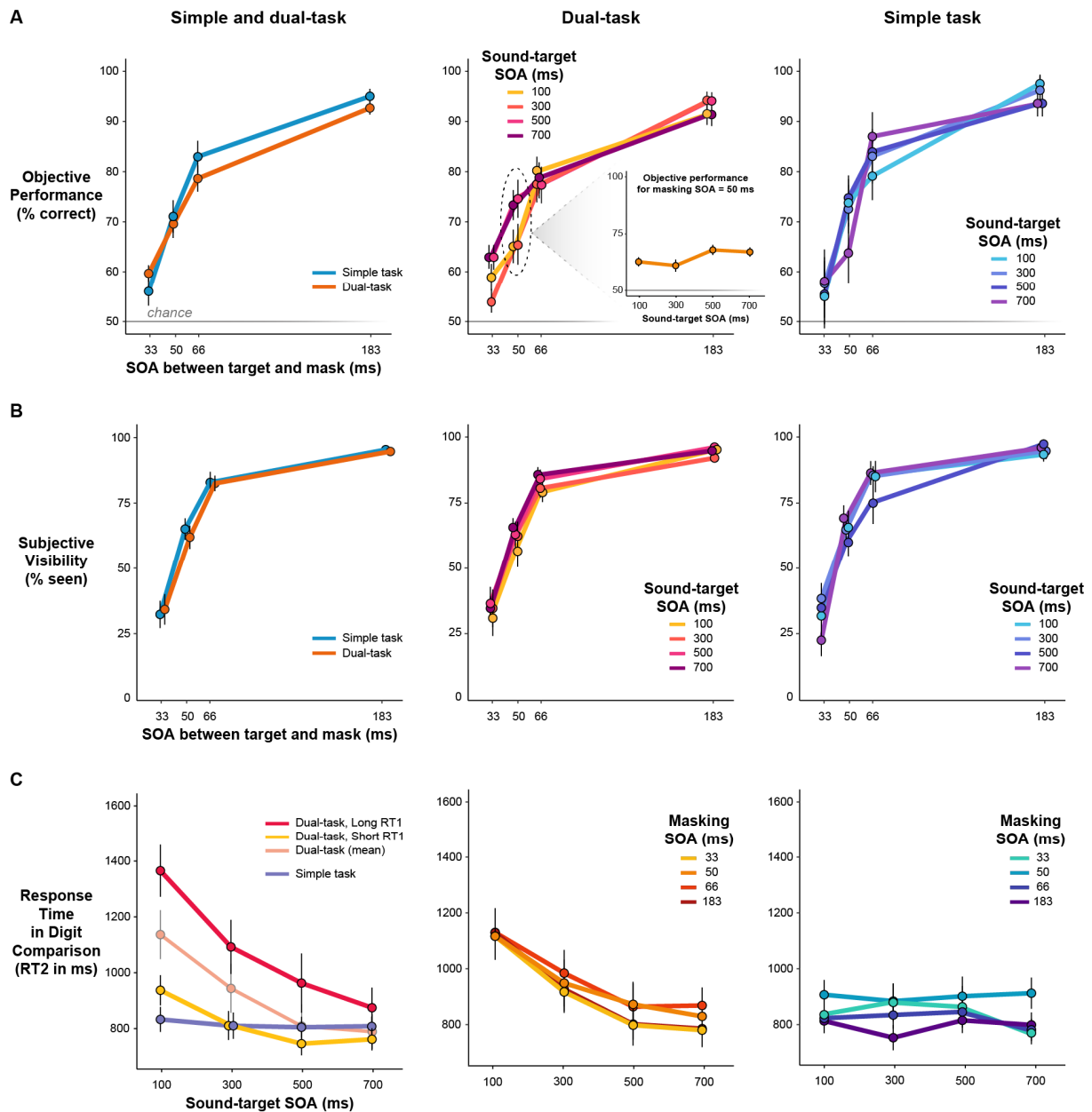
Overall, RT1 and RT2 were significantly correlated (Pearson  $r = 0.69$ ,  $t_{17} = 3.92$ ,  $p = 0.001$ ). The mean correlation between RT1 and RT2 was strong at short sound-target SOAs (100 ms: Pearson  $r = 0.81$ ,  $t_{17} = 5.64$ ,  $p < 0.001$ ) and became progressively weaker as the sound-target SOA increased (SOA 300 ms:  $r = 0.68$ ,  $t_{17} = 3.83$ ,  $p = 0.001$ ; 500 ms:  $r = 0.64$ ,  $t_{17} = 3.43$ ,  $p = 0.003$ ; 700 ms:  $r = 0.63$ ,  $t_{17} = 3.35$ ,  $p = 0.004$ ). This means that, at short sound-target SOAs, a large part of the variance of RT2 was due to the variable completion of the task on the sound.

When splitting dual-task trials into short and long RT1, RT2 were significantly influenced by short/long RT1 ( $F_{1,18} = 34.49$ ,  $p < 0.001$ ) and by the interaction between short/long RT1 and sound-target SOAs ( $F_{3,54} = 22.25$ ,  $p < 0.001$ , Figure 2C left panel), suggesting that the processing of the sound delayed the processing of the digit.

### **Interaction between masking SOA and sound-target SOA**

A significant interaction effect of masking SOAs and sound-target SOAs on objective performance was found in the dual-task condition ( $F_{9,162} = 2.16$ ,  $p = 0.027$  Figure 2A middle panel) but not in the simple task condition ( $F_{9,162} = 0.63$ ,  $p = 0.78$ , Figure 2A right panel). This interaction reflects that the effect of sound-target SOA was maximal at short masking SOAs, i.e. when the digit was more efficiently masked and therefore more difficult to perceive.

No significant interaction effect of masking SOAs and sound-target SOAs was found either on subjective visibility (dual-task:  $F_{9,162} = 1.67$ ,  $p = 0.099$ , simple task:  $F_{9,162} = 0.80$ ,  $p = 0.62$ , Figure 2B middle and right panels) or on RT2 (dual-task:  $F_{9,162} = 0.58$ ,  $p = 0.81$ , simple task:  $F_{9,162} = 1.02$ ,  $p = 0.43$ , Figure 2C middle and right panels).



*Figure 2.* Masking effects, attentional blink, psychological refractory period and their interactions. (A) Effect of masking SOA, sound-target SOA and condition (simple versus dual-task) on objective performance, i.e. comparing the target digit with 5. A significant effect of masking SOA is observed in simple and dual-task (left panel). In the dual-task, sound-target SOA significantly interact with masking SOA (middle panel) and an attentional blink is observed at the shortest sound-target SOA (100 and 300 ms) when the target digit is efficiently masked (masking SOA 33 and 50 ms). The small lineplot represents performance for masking SOA 50 ms according to sound-target SOA. In the simple digit-related task, no significant interaction between masking SOA and sound-target SOA is observed (right panel). (B) Effect of masking SOA, sound-target SOA and condition (simple versus dual-task) on subjective performance, i.e. judging the digit as “Seen”. A significant effect of masking SOA is observed in simple and dual-task (left panel). No effect of sound-target SOA is observed either in simple or in



dual-task. (C) Effect of sound-target SOA, response times for the sound task (short i.e. below the median vs. long RT1, i.e. above the median), masking SOA and condition (simple versus dual-task) on response times for the digit comparison task, i.e. comparing the target digit with 5 (RT2). In the dual-task, a significant effect of sound-target SOA, of RT1 and of their interaction is observed on RT2 corresponding to a psychological refractory period (left and middle panels). In the simple digit-related task, no significant effect of sound-target SOA, of RT1 or of their interaction is observed (right panel). A significant effect of masking SOA was observed both in simple and dual-task conditions (middle and right panel). Error bars corresponds to one standard error of the mean. Dots have been jittered a bit whenever required.

### **Measures of sensitivity for subjective visibility ( $d'$ )**

We previously reported that we found a significant effect of attentional blink on objective performance, but not on subjective visibility. Objective and subjective performances were significantly correlated but the correlation coefficient was moderate (Pearson  $r = 0.49$ ,  $t_{17} = 2.29$ ,  $p = 0.035$ ). This result may reflect a dissociation between participants' discrimination and detection capabilities and suggests that, in some trials, subjects may have correctly detected the target while failing in the discrimination task (comparison of the target digit with 5). To further investigate the sound-target SOA effect on the performance in detecting the target digit, we computed  $d'$  values by confronting the subjective visibility against the presence or absence of a digit (target versus mask-only trials).

Overall, measures of  $d'$  were significantly different from zero even in the shortest masking SOA condition (dual-task SOA 33 ms:  $d' = 1.06$ ,  $t_{18} = 5.76$ ,  $p < 0.001$ ; simple task SOA 33 ms:  $d' = 1.15$ ,  $t_{18} = 5.9$ ,  $p < 0.001$ ).  $D'$  analyses confirmed the results observed for subjective visibility:  $d'$  measures were significantly influenced by masking SOA (dual-task:  $F_{3,54} = 57.3$ ,  $p < 0.001$ , simple task:  $F_{3,54} = 44.2$ ,  $p < 0.001$ ) but neither by sound-target SOA (dual-task:  $F_{3,54} = 0.90$ ,  $p = 0.45$ , simple task:  $F_{3,54} = 2.32$ ,  $p = 0.085$ ), nor by the interaction between the two (dual-task:  $F_{9,162} = 1.27$ ,  $p = 0.26$ , simple task:  $F_{9,162} = 0.91$ ,  $p = 0.52$ ).

### **Performance and response times for the sound-related task**

Performance in discriminating the sound was overall very high (96.7% in the dual-task condition, 97.2% in the simple sound-related task condition). Still, in the dual-task condition, this performance was significantly influenced by the sound-target SOA ( $F_{3,54} = 4.14$ ,  $p = 0.010$ ). This effect was mainly driven by the shortest SOA (100 ms: 95.1% vs. 97.2% on average at the

other SOAs). When excluding the shortest sound-target SOA, performance on the sound task was not influenced by the sound-target SOA anymore ( $F_{2,36} = 0.30$ ,  $p = 0.74$ ), suggesting that participants were probably hindered in discriminating the sound when the digit appeared shortly after the beginning of the sound.

All other analyses on performance and response times for the sound-related task yielded non-significant results. In the dual-task, the masking SOA had no influence on the performance in the sound task ( $F_{3,54} = 1.55$ ,  $p = 0.21$ ). In the simple sound-related task, performance for the sound task was not influenced by the masking SOA ( $F_{3,54} = 0.86$ ,  $p = 0.47$ ), nor by the sound-target SOA ( $F_{3,54} = 2.29$ ,  $p = 0.089$ ). Response times for the sound-related task were not influenced by masking SOAs or sound-target SOAs, neither in the dual-task, nor in the simple task (all  $p > 0.1$ ).

These analyses suggest that accuracy and speed for discriminating the sound were not influenced by T2, except at the shortest sound-target SOA.

## Discussion

This behavioural study was designed to probe whether attentional blink and masking effects could be obtained simultaneously in a single experimental setup and whether they interacted. Participants were sequentially presented with a sound and a masked digit. Sound-target SOA and target-mask SOA were parametrically manipulated in a  $4 \times 4$  design. Depending on blocks, participants had to identify the sound (task 1, T1), to compare the digit to 5 (task 2, T2) or to do both, as fast as possible. When performing T2, they also assessed the target digit visibility. Overall, our results revealed a combined effect of masking and attentional blink on the digit-related tasks. The masking had a very robust effect on all consciousness measures, i.e. objective performance and subjective visibility, both under simple (T2) and dual-task (T1+T2) conditions. Conversely, the sound-target SOA effects were only observed when participants had to perform both T1 and T2, yielding an attentional blink and a psychological refractory period.

In the present experiment, the attentional blink only impacted the ability to discriminate the digits (i.e. compare them with 5), but not their detection (i.e. subjective visibility and  $d'$  measures). This may be explained by a difference in difficulty between the two tasks. Indeed, in the digit comparison tasks, participants could not rely on low-level features of the target digit

such as its shape: 2, 3, 7 and 8 were chosen because 2 and 3 could be respectively mistaken for 7 and 8 in a short glimpse, while still being detected. Moreover, the target digit was not embedded within a sequence of distractors. An attentional blink effect on objective performance has previously been evidenced in such conditions (Duncan et al., 1994; Nieuwenstein et al., 2009), but in most of the other studies, the attentional blink effect corresponded to the inability to detect a target among distractors, which in this case, is quite difficult to disentangle from the ability to discriminate it from the distractors (Shapiro et al., 1997).

Earlier studies manipulated the difficulty of task 1 (T1) by masking the first target (Brisson et al., 2014), by proposing a greater number of alternative choices or multiple relevant stimuli for T1 (Duncan et al., 1994; Jolicoeur, 1999), or by asking participants to answer as fast as possible when performing T1 (Jolicoeur, 1999). In all these studies, the attentional blink effect was shown to increase with the difficulty of T1. Similarly, the slower participants performed for T1, the larger the attentional blink effect and the longer the psychological refractory period were (Jolicoeur, 1999; Marti et al., 2012). In the present experiment, T1 was quite simple (distinguishing between “*ka*” or “*pi*”) but participants had to answer as fast as possible. We found a significant effect of RT1 on RT2 but not on the objective performance in the digit-related task or on the subjective visibility of the target digit, suggesting that information regarding T2 could be retrieved after a dwell time. Differential effects on RT and performance may be accounted for by a phenomenon of retrospective attentional amplification (Sergent, 2018; Sergent et al., 2013; Thibault et al., 2016). Indeed, in our paradigm, the mask appeared at the same location as the digit and was always visible so it could have played a role of retro-cue that improved conscious perception.

Importantly, our study manipulated the difficulty of T2 through visual masking. We observed a synergistic effect between attentional blink and visual masking: the effect of T1 on the objective performance in T2 was strengthened when the target digit was strongly masked, i.e. when the difficulty of T2 increased. This finding is compatible with previous results indicating that the attentional blink effect could be enhanced when the T2 target is presented only briefly (Nieuwenstein et al., 2009).

More broadly, our results are in accordance with the theory recently proposed by Marti and colleagues (Marti et al., 2015). Their empirical data suggested that multitasking relied on multiple central processes that each operates in series. Indeed, using magnetoencephalography, they observed that cerebral processes associated with task 1 (T1) were shortened by the

detection of a second target. This finding was not consistent with previous theoretical models of multitasking. Resource-sharing models posited that multiple tasks were processed in parallel with limited resources that had to be shared between the tasks (Kahneman, 1973; Tombu et al., 2003) and thus predicted that T1 processes would be longer rather than shorter in the presence of a second target. By contrast, the bottleneck hypothesis proposed that target 1 and target 2 were serially processed (Marti et al., 2012; Pashler, 1994; Sigman et al., 2005) and therefore predicted that T1 processes should not be affected by T2. Marti et al. reckoned that the second target captured top-down attentional resources and competed with T1 resulting in a shortening of T1 processes. Still, T1 strongly inhibited the processing of target 2. Indeed, considering that the global neuronal workspace is occupied by one information at a time, as soon as target 1 enters the workspace, target 2 would be stored in decaying sensory buffers, awaiting T1 to be completed before it can be consciously processed (Marti et al., 2012, 2015; Sergent et al., 2005; Zylberberg et al., 2010). This postponing would correspond to the psychological refractory period. However, if the delay is too long or the decay too strong, target 2 could be merely missed, which constitutes an attentional blink effect (Marti et al., 2012). In the present experiment, in accordance with the above findings, we observed an attentional blink and a psychological refractory period but the performance in discriminating the sound (T1) was affected by the display of the target digit when the shortest sound-target SOA was used, reflecting that target 2 may have captured part of the attentional resources devoted to T1.

To sum up, this paradigm simultaneously induced masking and attentional blink effects. Accordingly, this experimental design can be adapted to an EEG experiment in order to investigate the effect of ketamine on consciousness threshold and its mechanisms. Ketamine is likely to elevate consciousness threshold and boost masking effects. Given the effects of ketamine on feed-back and/or feed-forward signalling (Autry et al., 2011; Corlett et al., 2009; Grent-'t-Jong et al., 2018), we predict that it will modify attention allocation, leading to an increased attentional blink. Specifically, we expect to observe an interference effect between T1 and T2 even in the simple task condition, i.e. when one of the two tasks is not relevant. Such an observation would fit the aberrant salience theory (Kapur, 2003). Indeed, considering ketamine as a pharmacological model of psychosis, it may reflect that schizophrenic patients have trouble amplifying relevant information or preventing the amplification of irrelevant information.

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# **Chapter 5. Violations of expectations enhance stimulus identification**

## **Introduction of the article**

The study presented in the chapter 2 suggests that an elevated consciousness threshold may favour the advent of psychotic symptoms but the precise mechanisms underlying such a causal effect remain unclear. The predictive-coding framework posits that perception is the result of a combination between expectations and sensory inputs. In healthy controls, an extensive literature suggests that the identification and the detection of a stimulus are facilitated by previous knowledge and expectations. Furthermore predictive-coding provides an interesting framework to explain psychotic symptoms. In particular, delusions may be understood as a failure to update beliefs according to contradicting sensory evidence. Therefore, understanding how predictions and consciousness interact may shed light on the pathophysiology of delusions in schizophrenia.

In this chapter, we explore whether conscious representations and visibility are influenced by environment predictability. We present healthy controls with masked stimuli embedded into predictable or stochastic sequences and compare objective performance and subjective visibility. Our results suggest that participants have better performance on stimuli violating their expectations than on stimuli that were not associated with expectations or confirming expectations.

## **Abstract**

Perception has been described as the result of a combination of sensory inputs and expectations. In this sense, expectations may bias conscious perception. On the other hand, surprise was shown to attract attention which is known to facilitate conscious access. Many previous paradigms suggested that the confirmation of expectations promoted detection and discrimination of upcoming stimuli, but confirming stimuli were usually more frequently presented, more relevant for the task or more strongly associated with a cue than violating stimuli and crucially not compared with a fully random condition. Thus, whether confirmation of expectations, violations or both enhance conscious access compared to the absence of expectations remains unclear. In the present study, we contrasted the effects of confirmed

predictions, violated ones and random condition on objective reports and subjective visibility. Participants were presented with variable length sequences which could be fully random or predictable. They ended by a masked target that, in the case of predictable sequences, violated and confirmed the expectations built from the sequences in half-half of the trials, or by a catch. Crucially, transition probabilities were balanced such that the only difference between random and regular sequences was the rule-based expectations that the regular sequences induce. We evidenced that stimuli violating expectations were better discriminated than those confirming expectations or not associated with an expectation (in the random sequences). Analysis of catch trials revealed a significant bias towards violation responses. However, additional analyses controlling for this bias indicated that the stimulus orientation was still significantly better discriminated in the violation condition than in the confirmation and the random conditions at the shortest SOA. Overall, our results suggest that objective performance in discriminating a stimulus are influenced by regularities that are automatically extracted from the environment and used to generate expectations, and that violated expectations may be significantly better processed than confirmed predictions and random stimuli.

## **Introduction**

Conscious representations often emerge in response to an external stimulation, but only a small fraction of the environment indeed reaches consciousness. Two main factors have a crucial role to determine whether a given information will be consciously processed or not. First, the amount of input sensory evidence is critical to consciously perceive a stimulus. Consistently, many studies showed that shortly or weakly presented stimuli remained subliminal (for a review, see: Kouider & Dehaene, 2007). Second, top-down factors, notably attention, expectations and goals, are also crucial to select and amplify relevant information so it can be consciously perceived (Posner et al., 1994). Accordingly, when attention is captured by a demanding task, unattended events, including striking ones, can merely be ignored (e.g. the presence of a gorilla in a video: Simons et al., 1999).

One recent and influential theoretical proposals in neuroscience assumes that the brain is continuously predicting forthcoming events based on previous observations and beliefs (Friston, 2005; Rao et al., 1999; Spratling, 2017). Within this predictive-coding framework, perception results from the combination of top-down predictions and bottom-up sensory inputs (von Helmholtz, 1867). Expectations therefore bias perception especially when sensory inputs

are ambiguous, in visual illusions, bistable perception or binocular rivalry (Denison et al., 2011; for a review, see: Panichello et al., 2013). Mechanisms through which expectations influence perception have extensively been studied in the past and previous results indicate that even earliest cerebral sensory areas tuning and responsiveness depend on expectations (for recent reviews, see: de Lange et al., 2018; Summerfield et al., 2014). Regarding conscious access, predictive-coding framework predicts that expectations should modulate both conscious discrimination and detection (King et al., 2014a). For instance, it was shown that expecting a particular object category (e.g. animal, tool, etc.), facilitated its recognition under degraded conditions (Eger et al., 2007). As for detection, two opposite hypotheses can be made. On the one hand, considering conscious access as a perceptual decision relying on an accumulation of evidence, expectations should facilitate the detection of a confirming stimulus because accumulation of evidence could start from a higher point (Dehaene, 2011; Kang et al., 2017; King et al., 2014a; Lafuente et al., 2006; Lau, 2008; Ploran et al., 2007; Shadlen et al., 2011). On the other hand, consciousness can be seen as a continuous “stream of thoughts”, as coined by William James, whose content is continuously updated (Salti et al., 2018). In this sense, changes and surprises in the environment that violate expectations would preferentially access consciousness to update the current internal model.

Many studies indicated that a previous exposure to a stimulus increased its visibility when it was degraded or briefly presented (Aru et al., 2016; Mayer et al., 2016; Melloni et al., 2011; Moca et al., 2011). However, in these studies, the very same stimulus was repeated, so this result may rely on habituation mechanisms, i.e. low-level adaptation, rather than on a genuine modulation effect of higher-level expectations. Similarly, visibility for the same amount of sensory input differs according to the visibility of the preceding stimulus. In particular, visibility is higher for a given stimulus preceded by a visible stimulus, e.g. when its masking or degradation progressively increased so that it becomes more and more difficult to perceive, than in the opposite case, i.e. when it is initially totally invisible and becomes more and more visible (Gaillard et al., 2006; Mayer et al., 2016; Melloni et al., 2011; Moca et al., 2011), a phenomenon called perceptual hysteresis (Kleinschmidt et al., 2002). Even at the trial-to-trial level, the visibility of a given stimulus boosts the conscious access to the subsequent one (Lamy et al., 2017). This “awareness priming” may result from the expectation that a stimulus would be present rather than absent (King et al., 2014a). Interestingly, awareness priming and feature-specific priming can interact in promoting conscious access. In one study,

shape-specific priming on a target was observed only when the prime both had the same shape and was visible (Lin et al., 2014).

On another note, attention seems to be strongly attracted by surprising events (Itti et al., 2009) but a facilitating effect of expectation violation on conscious access has rarely been reported and, if so, was not replicated (Mudrik et al., 2011; Hung et al., 2015; Sklar et al., 2012; but: Moors et al., 2016 ). On the contrary, several studies suggested that confirmed expectations could accelerate the entry of visual stimuli into awareness. For instance, shorter response times were observed for identifying predicted masked stimuli compared to unpredicted ones (Chang et al., 2015; De Loof et al., 2016; Pinto et al., 2015). Still, this effect was not always accompanied with effects on accuracy (De Loof et al., 2016) and was recently not replicated (Gayet et al., 2018). More importantly, in these experiments the time to access consciousness is confounded with the duration of others cognitive processes such as decision-making or motor reaction times, which have been both pervasively shown to slow down in case of incongruency or surprise (Bang et al., 2017; Rahnev et al., 2011). Consequently, objective or subjective assessments of consciousness may provide more reliable measures to study of the modulator effects of expectations on access to consciousness than the time at which a stimulus pop into consciousness.

Two recent studies focused on the effects of expectations on conscious access using such measures. First, Meijs et al. (2018) used an attentional blink paradigm in which the identity of the first target was predictive of the identity of the second one. They showed that whenever target 1 accurately predicted target 2, the latter was more often detected (i.e. both judged as seen and correctly identified). However, this study only contrasted confirmed to violated predictions. Indeed, a condition in which no target 1 was presented was included but in this case no or a drastically reduced attentional blink occurred, rendering this condition incomparable to confirmation or violation conditions. Second, Stein et al. (2015) conducted a series of experiments in which they consistently evidenced that valid cues enhanced the detectability of a stimulus. At the beginning of each trial, a cue provided information about the stimulus, be it its category (animals, tools etc.), or its physical properties (gabor orientation). Then, a target stimulus briefly appeared on the screen at one among four possible positions and participants were asked to report its location. Effects of valid cues were compared either to no cue or invalid cue conditions. Importantly, in this latter case, half of the cues was valid and the other half was invalid, so that cues were not informative and could not bias responses for the

subsequent stimulus. Participants were better at locating the stimulus in the valid cue condition. Nevertheless, in all these experiments, at least four different kinds of target stimuli were used, therefore their predictability was different in confirmation, violation and in neutral conditions. Indeed, at each trial, valid cues predicted only one stimulus category, whereas invalid cue and no cue conditions corresponded to much more possible situations (all categories but one were predicted in the case of invalid cue condition while all categories were predicted in the no cue condition), leading to asymmetrical entropy between the valid cue condition and the other conditions. For instance, if there were four possible categories, since the cue was valid 50% of the time, trusting the cue allowed to predict to good category in 50% of the cases while betting on another category was correct in 16.7% of the cases (50% divided by three possible invalidly cued categories). Unfortunately, no comparison was conducted between the invalid cue and no cue conditions to investigate asymmetry effects and their implication in the observed differences in performances.

Overall, the vast majority of studies suggests that expectations facilitate conscious access. Though, most of them only contrast confirmed and violated expectations without including a fully random condition, in which expectations are equal for all forthcoming stimuli. Moreover, in some cases, biases may have favoured confirmed expectations against violations because predictions were helpful to correctly perform the task. To a lesser extent, violations may also facilitate conscious access, compared to a condition without prediction. Because of these mixed and sometimes confounded results, it is worth investigating again whether expectations genuinely modulate access to consciousness. Importantly, confirming and violating conditions must not be of any help to perform the task and should be compared to a random condition.

In the present study, we tried to meet these criteria, by contrasting the effects of confirmed predictions, violated ones and random condition on objective reports and subjective visibility. Participants were presented with variable length sequences, composed of two kinds of stimuli, which could be fully random or predictable, when the alternations of stimuli constituted patterns. They ended by a masked target that could, in the case of predictable sequences, either violate or confirm the expectations built from the sequences. Participants were asked to report the masked stimulus and to judge its visibility (subjective measure) on a trial-by-trial basis. Half of the sequences was regular and the other half was random. Importantly, within regular sequences, half of the time the predictions were confirmed and the other half,



they were violated, thereby making the predictions not relevant for the task. Ultimate repetitions and alternations were also balanced between all conditions. Thus, we could study effects of predictability (regular sequences versus random ones), surprise (violation versus confirmation), and ultimate transition (repetition versus alternation of the ultimate stimulus) on objective and subjective responses, without favouring any of these conditions. Crucially, transition probabilities were balanced, thereby ensuring that the frequencies of stimulus-type and alternations/repetitions were also balanced, such that the only difference between random and regular sequences was the rule-based expectations that the regular sequences induce.

## **Material and methods**

### **Participants**

Twenty-six right-handed participants (18 females; mean age: 22 years old; range: 18–28 years old) were included. All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. Participants gave informed consent, and received financial compensation (20€ for a session of 2h). Three participants were excluded: one escaped the program during the experiment, one could not perceive the stimuli at the longest SOA (mean subjective visibility = 1.67 on a scale from 1 to 4, while mean for other participants was 3.08 on average), and one reported having seen most of the “catch” trials, in which there was no target (mean subjective visibility for catch trials = 2.59, while mean for other participants was 1.43 on average).

### **Design and procedure**

The experimental paradigm is summarized in Figure 1. Trials began by a white central fixation cross displayed on a black background. After one second, five empty white circles arranged like a five dice face (size: 1 degree of visual angle) appeared in the centre of the screen. Each stimulus of the sequence corresponded to the white filling of three of these circles, forming a diagonal oriented to the left or to the right (i.e. like a three dice face when oriented to the right or a mirrored three dice face when oriented to the left) and lasted 200 ms. Interstimulus interval was 400 ms long. Each sequence contained between 8 and 11 stimuli and the five empty white circles remained on screen during the whole sequence, including the interstimuli periods. Participants were asked to fixate the central circle throughout the sequence. We choose these stimuli because they induced a feeling of motion between right and left tilts. They had small

size to be seen as a whole and avoid involvement of spatial attention as much as possible. Then, an ultimate stimulus (the target, coloured in red) that could be oriented to the left (50%) or the right (50%) was displayed during 17 ms, and followed after a variable delay (stimulus onset asynchrony SOA: 33 ms, 50 ms or 433 ms) by a backward mask composed of red randomly arranged lines, and lasting 500 ms. Since the length of the sequence varied on a trial-by-trial basis, participants were forced to maintain their attention throughout the trial not to miss the target, allowing a build-up of sequence-based expectations. In 20% of the trials, no target was displayed: the five empty circles turned red but remained empty. We refer to these trials as “catch” trials. To focus participants’ attention and help the processing of the sequential aspect of the stimulation, a sound was played in synchrony with each stimulus of the sequence. This also helped participants to identify the target stimulus, as it comes with the ultimately played sound. This sound was composed of three frequencies (350, 700, 1400 Hz), with rising and falling periods of 7 ms and a duration of 50 ms. At the end of each sequence, a response screen appeared asking participants for their responses.

Participants were instructed to pay attention to the whole sequence including the target and gave two behavioural responses on a trial-by-trial basis: (1) determine whether the target was oriented to the left or to the right (forced-choice objective answer) by pressing buttons with the left hand, (2) report the target visibility using a four-level perceptual awareness scale (Overgaard et al., 2006) by pressing buttons with the right hand (subjective measure of conscious access). The four levels of visibility were the following: “non-visible” corresponds to “no experience of the stimulus”, “weakly visible” corresponds to “brief glimpse of the stimulus but could not recognize what it was”, “merely visible” corresponds to an “almost clear impression of the stimulus”, and “totally visible” corresponds to a “clear impression of the stimulus” (Overgaard et al., 2006). Participants were said to rate catch trials as “non-visible”. Selected responses appeared on red. Feedback was provided every 30 trials, indicating the rate of correct answers to the objective question on non-catch trials.

Participants performed four blocks of 120 trials (480 trials in total). Within a block, sequences could be regular or random (2 blocks for each condition). Regular sequences (Reg) were alternations between two stimuli having the same orientation (A-A-B-B-A-A-B-B ... or B-B-A-A-B-B-A-A...). The target could correctly continue the sequence (confirmation, e.g. A-A-B-B-A-A-B-B-A) or not (violation, e.g. A-A-B-B-A-A-B-B-**B**). Because length of sequences could be odd or even (from 8 to 11), confirmation/violation and alternation/repetition between

the target and the immediately preceding stimulus could be orthogonalized: there were as many regular sequences confirmed by a repeated and an alternated stimulus and as many regular sequences violated by a repeated and an alternated stimulus. Random sequences (Rnd) were composed of as many left and right-oriented stimulus (more or less one when odd) and as many repetitions and alternations between two subsequent stimuli (more or less one when even). In each block, there was as many left and right-oriented stimuli to avoid habituation effects, and there were as many repetitions and alternations between the target and the preceding stimulus.

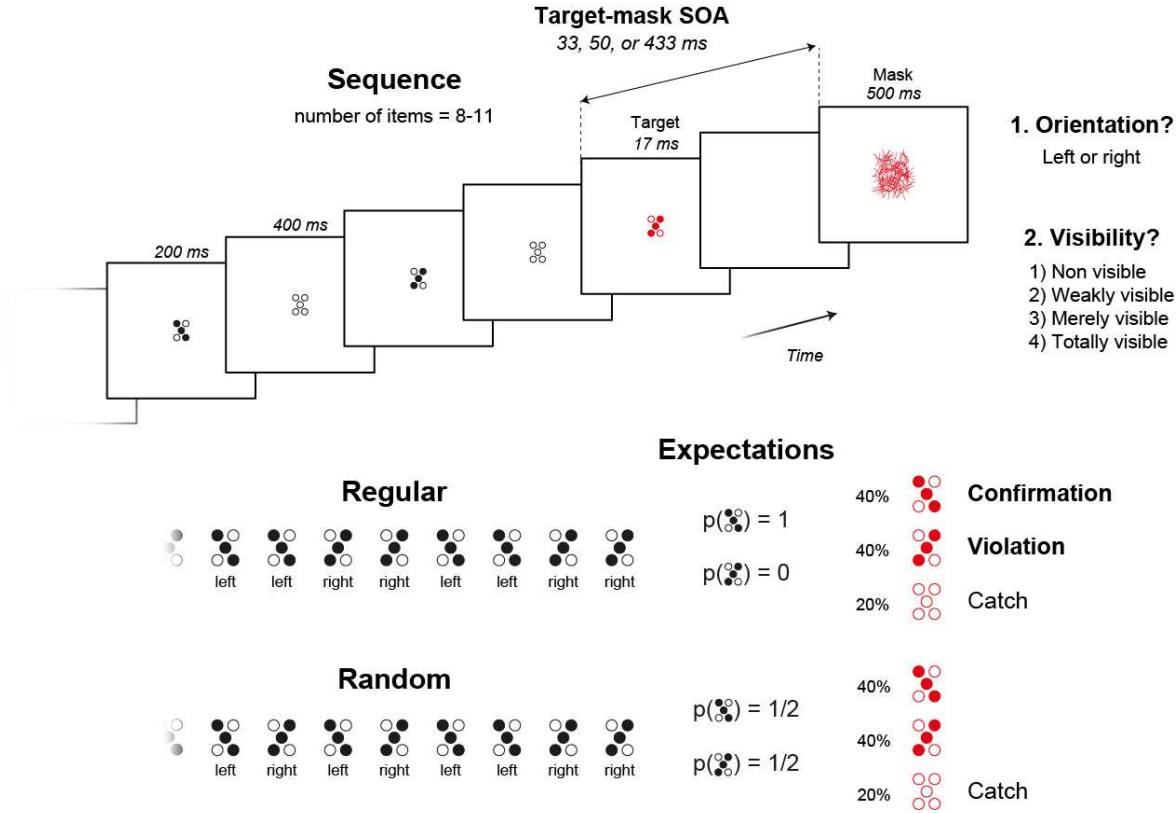


Figure 1. Experimental design. Small shapes oriented to the left or to the right were displayed at the centre of the screen, separated by empty shapes, inducing a feeling of motion between left and right tilts. They appeared in random order (e.g. A-B-A-B-B-A-B...) or were arranged in patterns forming regular sequences (A-A-B-B-A-A-B-B...) in order to create expectations about a masked target shape (in red). In the case of regular sequences, the target could confirm or violate expectations generated by the preceding regular sequence (e.g. after the sequence A-A-B-B-A-A-B-B, an A was a confirmation while a B was a violation) and was a catch in 20% of the cases. Participants had to judge orientation (left or right) and to say how much they had seen the target using a four-level perceptual awareness scale.

The block order was counterbalanced between participants (Rnd-Reg-Reg-Rnd or Reg-Rnd-Rnd-Reg). Before starting the main experiment, participants had two representative training blocks of 30 trials each. Order of training blocks was counterbalanced as well.

Instructions were given at the beginning of the experiment. Participants were not informed that there were two different kinds of blocks or sequences so instructions did not differ between blocks. A slow demonstration of what a sequence looks like was presented just after instructions, thus all participants distinctly saw catches, left and right-oriented targets before starting the experiment. They were explicitly instructed to focus on the central circle of the stimulus and were informed that left and right-oriented stimuli were equally frequent in the experiment.

### **Behavioural data analysis**

Objective performance was assessed through measures of sensitivity ( $d'$ ) confronting reported orientation (left vs right-oriented response) to actually presented stimulus (left vs right-oriented stimulus). Subjective visibility was assessed through measures of sensitivity ( $d'$ ) as well, confronting subjective response (non-visible vs. at least weakly visible) against the presence or absence of a target (target vs. catch trials). Analyses of variance (ANOVAs) and paired  $t$ -tests were conducted on objective performance (excluding catch trials) and subjective visibility, with masking SOA, ultimate transition (repetition vs. alternation between the target and the immediately preceding stimulus) orientation (left vs. right), predictability (random versus. regular) and surprise (confirmed vs. violated) as within-subject factors. For ultimate transitions and orientations, a first analysis was systematically conducted to explore main effects and their interactions with SOA. Wherever significant,  $t$ -values are presented SOA by SOA, otherwise  $F$ -values are reported for the main effects and interactions with SOA. General linear models with subjects' identity as a random effect were used to further analyze the differences between confirmed and violated sequences.

## **Results**

### **Masking effect**

We first analyzed the effect of masking – through the manipulation of target-mask SOA – on objective and subjective measures across all trials (Figure 2). We observed a strong effect

of SOA on the ability to discriminate orientation of the masked stimulus, i.e. objective performance (objective  $d'$  measures: SOA 33 ms: 0.21, SOA 50 ms: 0.78, SOA 433 ms: 3.64;  $F_{2,50} = 316.2$ ,  $p < 0.001$ ), and on visibility ratings (subjective  $d'$  measures: SOA 33 ms: 0.68, SOA 50 ms: 1.33, SOA 433 ms: 2.62;  $F_{2,50} = 88.17$ ,  $p < 0.001$ ). Note that both objective and subjective  $d'$  were significantly larger than zero at all SOA, including the shortest one (SOA 33 ms: objective  $d'$ :  $t_{25} = 3.45$ ,  $p = 0.002$ , subjective  $d'$ :  $t_{25} = 6.23$ ,  $p < 0.001$ ).

### **Effects of repetition and orientation on performances**

An effect of ultimate transition (repetition > alternation) was observed on objective  $d'$  measures at the intermediate SOA (SOA 33 ms:  $t_{25} = 1.14$ ,  $p = 0.26$ , SOA 50 ms:  $t_{25} = 2.50$ ,  $p = 0.020$ , SOA 433 ms:  $t_{25} = -0.57$ ,  $p = 0.58$ ) but no effect of orientation (left vs. right), was observed on correct answer rates ( $F_{1,25} = 0.06$ ,  $p = 0.81$ , no interaction with SOA:  $F_{2,50} = 1.47$ ,  $p = 0.24$ ).

In catch trials, target was absent so it could neither be a repetition nor an alternation of the preceding stimulus. Thus, to examine repetition effects on subjective visibility, we computed two distinct subjective  $d'$  measures for repeated and alternated trials. The first compared subjective response (non-visible vs. at least weakly visible) on non-catch repeated trials and on catch trials. The second one was calculated in the same way, using subjective responses on non-catch alternated trials and on catch trials. These two  $d'$  measures were compared and no significant effect was observed ( $F_{1,25} = 0.96$ ,  $p = 0.34$ , interaction with SOA:  $F_{2,50} = 0.75$ ,  $p = 0.48$ ), suggesting that repetition did not enhance detection.

Similarly, no effect of orientation (left vs. right), was observed when comparing subjective  $d'$  restricted to left-oriented target to subjective  $d'$  restricted to right-oriented target ( $F_{1,25} = 0.013$ ,  $p = 0.91$ , interaction with SOA:  $F_{2,50} = 0.03$ ,  $p = 0.97$ ).

### **Effect of sequence type and of expectation violations**

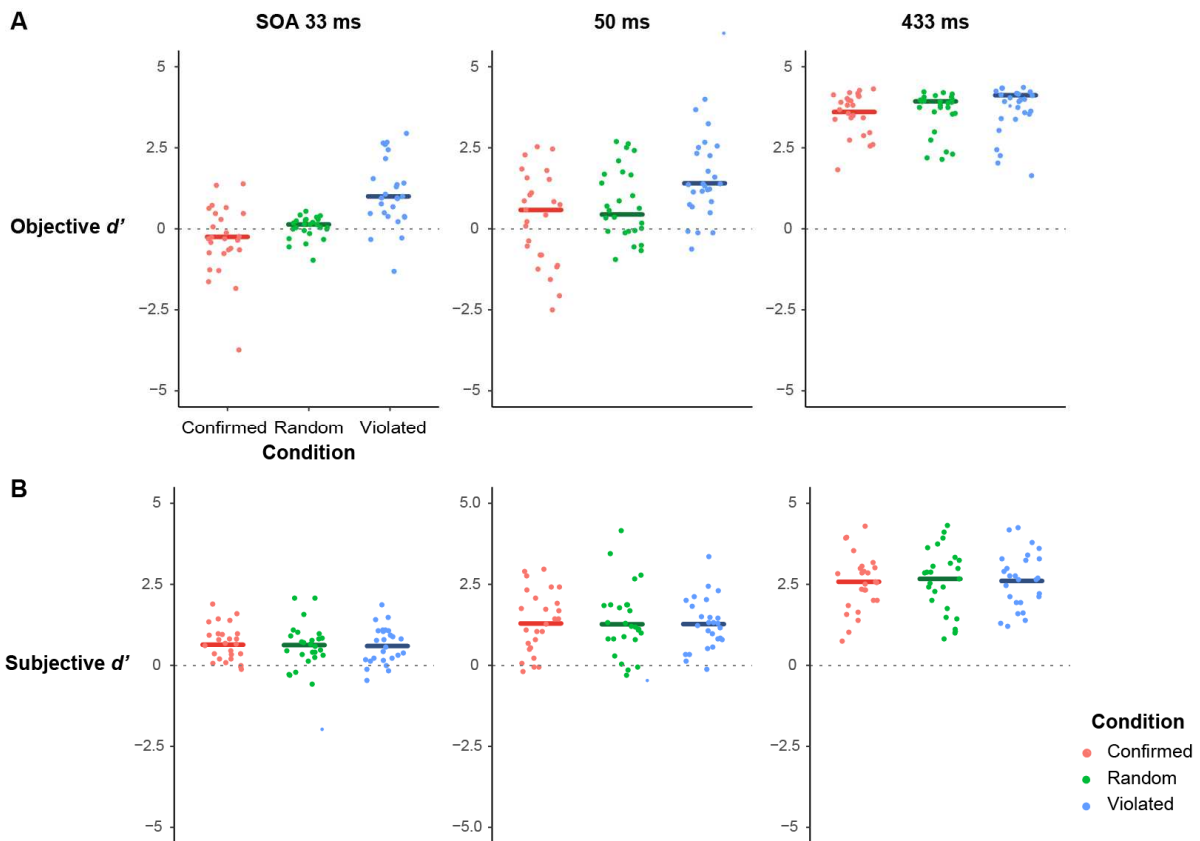
An ANOVA with condition (random vs. confirmed vs. violated) and SOA as within-subject factors revealed that they had a significant main effect on objective performance, i.e. objective  $d'$ , and that they interacted (condition:  $F_{2,50} = 11.54$ ,  $p < 0.001$ ; SOA:  $F_{2,50} = 271.7$ ,  $p < 0.001$ ; interaction condition  $\times$  SOA:  $F_{4,100} = 8.51$ ,  $p < 0.001$ ) (Figure 2A).

At the longest SOA (433 ms), no difference was observed on objective performance between the three conditions (objective  $d'$ : random: 3.61 vs. confirmed: 3.62 vs. violated: 3.64:  $F_{2,50} = 0.02$ ,  $p = 0.98$ ). Similarly, sequence type (regular vs. random) and violation did not have any effect (regular vs. random:  $t_{25} = 0.08$ ,  $p = 0.94$ , violation vs. confirmation:  $t_{25} = 0.11$ ,  $p = 0.91$ ).

At the shortest SOA (33 ms), we observed a significant effect of conditions on objective performance (random: 0.12 vs. confirmed: -0.33 vs. violated: 1.06:  $F_{2,50} = 14.20$ ,  $p < 0.001$ ). Similarly, sequence type and violation had significant effects (regular vs. random:  $t_{25} = 2.14$ ,  $p = 0.042$ ; violation vs. confirmation:  $t_{25} = 3.92$ ,  $p < 0.001$ ). Participants had better performance in violated than in random sequences ( $t_{25} = 4.24$ ,  $p < 0.001$ ) and in random than in confirmed sequences ( $t_{25} = 2.30$ ,  $p = 0.030$ ). Interestingly, although SOA was very short, objective  $d'$  was significantly greater than zero for violating targets ( $t_{25} = 5.36$ ,  $p < 0.001$ ), while this was not the case for other conditions (random:  $t_{25} = 1.47$ ,  $p = 0.15$ , confirmed:  $t_{25} = -1.59$ ,  $p = 0.13$ ).

At the intermediate SOA (50 ms), we observed a significant effect of conditions on objective performance (random: 0.76 vs. confirmed: 0.31 vs. violated: 1.53:  $F_{2,50} = 9.81$ ,  $p < 0.001$ ). No main effect of the sequence type was observed (regular vs. random:  $t_{25} = 0.69$ ,  $p = 0.50$ ) but violation had a significant effect (violation vs. confirmation:  $t_{25} = 3.32$ ,  $p = 0.003$ ). Again, participants had better performance in violated than in random sequences ( $t_{25} = 3.04$ ,  $p = 0.006$ ) and in random than in confirmed sequences ( $t_{25} = 2.46$ ,  $p = 0.021$ ).

By contrast, no effect of sequence type was observed on subjective visibility (main effect of the sequence type:  $F_{2,50} = 0.38$ ,  $p = 0.69$ ; SOA:  $F_{2,50} = 72.50$ ,  $p < 0.001$ ; interaction sequence type  $\times$  SOA:  $F_{4,100} = 0.518$ ,  $p = 0.72$ ) (Figure 2B).



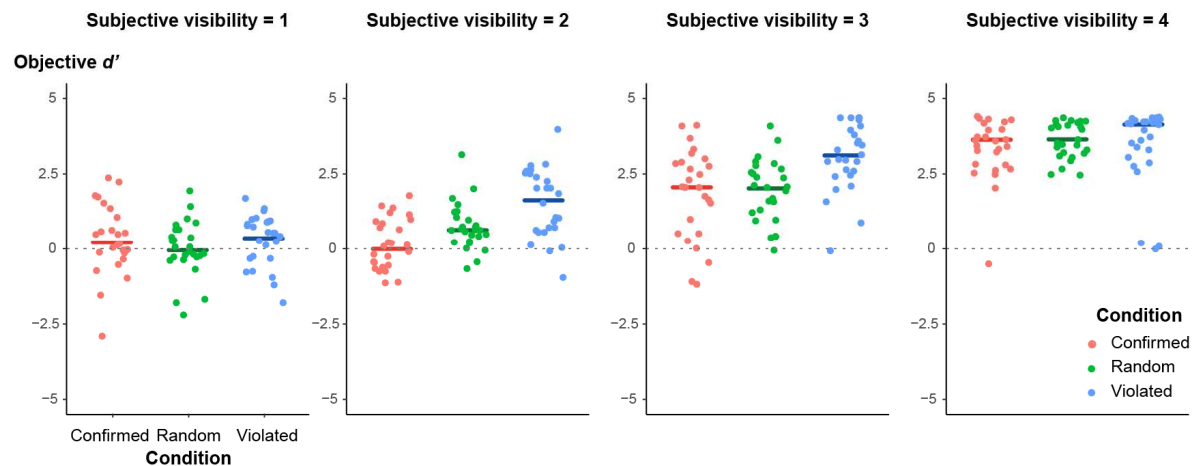
*Figure 2.* (A) Objective measures of sensitivity ( $d'$ ), confronting reported orientation (left vs right-oriented response) to actually presented stimulus (left vs right-oriented stimulus), according to target-mask SOA and conditions. A significant effect of condition was observed (violation > random > confirmation) for objective  $d'$  at the shortest and the intermediate SOA (33 and 50 ms) but not at the longest SOA (433 ms). (B) Subjective measures of sensitivity ( $d'$ ), confronting subjective response (non-visible vs. at least weakly visible) against the presence or absence of a target (target vs. catch trials), according to target-mask SOA and conditions. No significant effect of condition was observed on subjective  $d'$ . Each point represents the mean for each participant in a given condition. Horizontal bars represent the median of the group.

### Objective performance according to subjective visibility

Since objective performance was differently affected by conditions according to the SOA (interaction condition  $\times$  SOA:  $F_{4,100} = 9.99$ ,  $p < 0.001$ ), we examined effects of visibility, by splitting trials according to subjective visibility ratings (rated from 1 to 4 with perceptual awareness scale, PAS Overgaard et al., 2006). Results are presented in Figure 3.

On totally visible trials (PAS = 4) and on non-visible trials (PAS = 1), no effect of condition was observed on objective performance (PAS 1:  $F_{2,50} = 0.76$ ,  $p = 0.47$ ; PAS 4:  $F_{2,50}$

= 0.57,  $p = 0.57$ ). By contrast, a significant effect was observed on trials with intermediate levels of visibility (PAS 2–3). Objective performance in violated sequences was higher than in random ones which was itself higher than in confirmed sequences (objective  $d'$ : PAS 2: violated: 1.53, random: 0.71, confirmed: 0.11,  $F_{2,50} = 23.74$ ,  $p < 0.001$ , PAS 3: violated: 3.00, random: 1.95, confirmed: 1.82,  $F_{2,50} = 14.74$ ,  $p < 0.001$ ).



*Figure 3.* Objective measures of sensitivity ( $d'$ ), confronting reported orientation (left vs right-oriented response) to actually presented stimulus (left vs right-oriented stimulus), according to subjective visibility, rated with using a four-level perceptual awareness scale (PAS). A significant effect of condition (violation > random > confirmation) was observed at the intermediate subjective visibility ratings (i.e. PAS = 2 or 3) but not when subjective visibility was very high or very low (i.e. PAS = 1 or 4). Each point represents the mean for each participant in a given condition. Horizontal bars represent the median of the group.

### Analysis of catch trials and study of biases

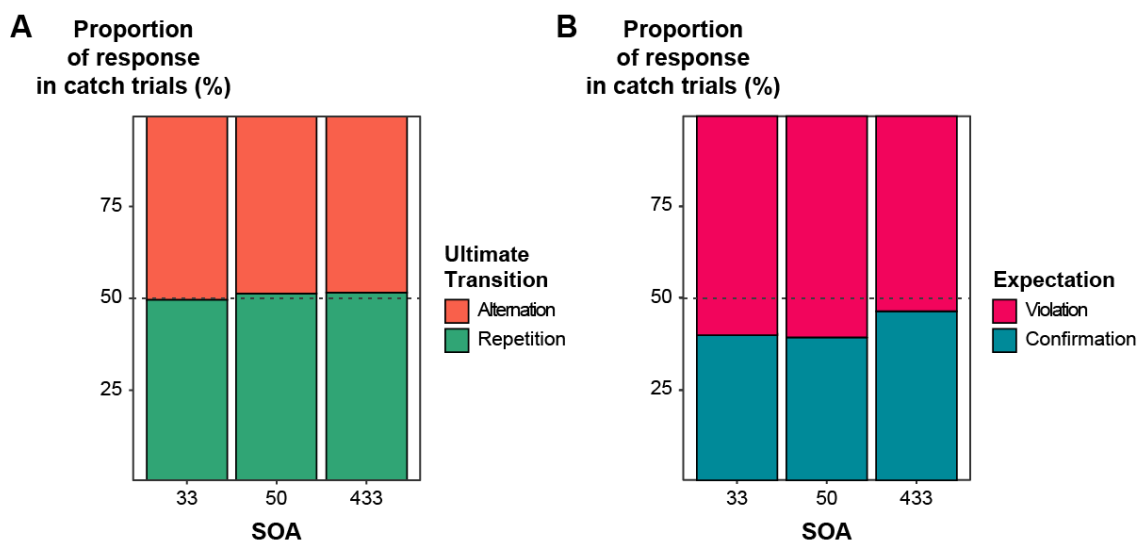
The particular pattern of results we observed, i.e. violation > random > confirmation still might have resulted from a bias or a strategy. Indeed, objective  $d'$  measure controlled only for one bias (i.e. left/right) but other sorts of biases may exist in the present experiment (repeated/alternated, confirmed/violated). We further explored a potential bias towards violations by analyzing participants' responses in catch trials in order to see whether they exhibited biases (Figure 4).

We calculated the proportion of violation answers, i.e.  $\text{prop}_{\text{viol}} = n_{\text{viol}} / (n_{\text{viol}} + n_{\text{conf}})$  for each participant in catch trials following regular sequences and performed t-tests to compare this proportion to 0.5. Unexpectedly, we found that participants chose significantly more often



the stimulus corresponding to a violation of the sequence than to a confirmation at the shortest and the intermediate SOA (SOA 33 ms:  $\text{prop}_{\text{viol}} = 59.62\%$ ,  $t_{25} = 3.77$ ,  $p < 0.001$ , SOA 50 ms:  $\text{prop}_{\text{viol}} = 60.46\%$ ,  $t_{25} = 2.96$ ,  $p = 0.0064$ ) but not at the longest SOA (433 ms:  $\text{prop}_{\text{viol}} = 53.61\%$ ,  $t_{25} = 1.47$ ,  $p = 0.16$ ).

Additional analyses of catch trials showed that participants did not preferentially select a stimulus corresponding to a repetition or an alternation of the last stimulus of the sequence (SOA 33 ms:  $\text{prop}_{\text{rep}} = 49.40\%$ :  $t_{25} = -0.44$ ,  $p = 0.66$ ; SOA 50 ms:  $\text{prop}_{\text{rep}} = 51.20\%$ :  $t_{25} = 0.66$ ,  $p = 0.51$ ; SOA 433 ms:  $\text{prop}_{\text{rep}} = 51.44\%$ :  $t_{25} = 0.70$ ,  $p = 0.48$ ) (Figure 4, next page).

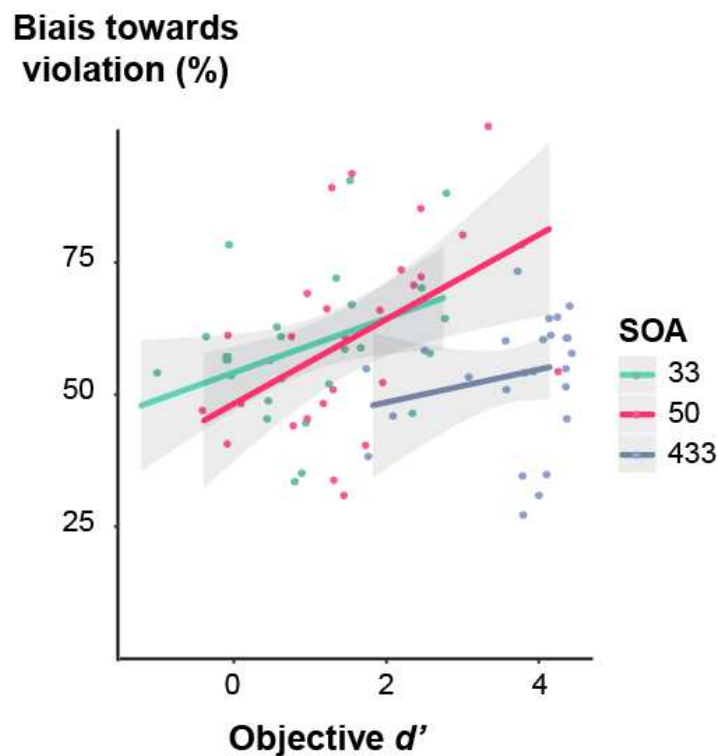


*Figure 4.* Bias study in catch trials. Since no target was presented in catch trials, they allowed to study potential biases in subjects' responses. (A) Proportion of responses in catch trials corresponding to a repetition and an alternation of the ultimate stimulus of the sequence at each SOA. No bias towards repetition or alternation was observed. (B) Proportion of responses in catch trials following regular sequences corresponding to a violation and a confirmation of the preceding sequence at each SOA. At the shortest and the intermediate SOA (33 and 50 ms), participants significantly chose more often the stimulus corresponding to a violation than to a confirmation of the preceding sequence. By contrast, no significant bias towards violation was observed at the longest SOA (433 ms).

### Analysis of prediction effect despite bias towards violation answers

Since participants exhibited a bias towards violation responses in catch trials, we reckoned whether our previous findings could at least partially result from such a bias. Indeed, if participants significantly selected an answer more frequently (e.g. the violation answer), their performance in this condition would artificially have increased while their performance in the

alternative condition would have symmetrically decreased. To control for this effect on non-catch trials, we computed a variable representing the bias for each participant at each SOA (for violated trials: bias towards violation =  $\text{prop}_{\text{viol}}$  in catch trials, for confirmed trials: bias towards confirmation =  $\text{prop}_{\text{conf}}$  in catch trials, no bias for random trials: variable = 0.5). The bias towards violation was significantly correlated to the objective  $d'$  on violated trials across SOA ( $r = 0.43$ ,  $t_{24} = 2.35$ ,  $p = 0.028$ ), at the shortest and the intermediate SOA (SOA 33 ms:  $r = 0.40$ ,  $t_{24} = 2.13$ ,  $p = 0.044$ ; SOA 50 ms:  $r = 0.51$ ,  $t_{24} = 2.89$ ,  $p = 0.008$ ), but not at the longest SOA (i.e. 433 ms:  $r = 0.19$ ,  $t_{24} = 0.92$ ,  $p = 0.037$ ) (Figure 5).



*Figure 5.* The bias towards violation was significantly correlated with objective  $d'$  in the violated non-catch trials at the shortest and the intermediate SOA (33 and 50 ms), but a post-hoc analysis confirmed that violated targets were nevertheless significantly better processed than random and confirmed ones at the shortest SOA (33 ms), even when including a “bias variable” in the model.

We entered this bias variable in a linear model with condition as fixed effect and subjects’ identity as random effect, and compared the conditions two by two. Thus, each trial was associated with the corresponding bias variable (e.g. for trials ending by a violating target with SOA 33 ms, we entered the proportion of violation answers of this given participant in catch trials at SOA 33 ms), so that the variance in participants’ responses due to this bias was

absorbed by this variable, and the effect observed for the “condition” variable corresponds to a genuine non-biased effect.

At the shortest SOA (33 ms), a significant bias effect was observed when comparing violation vs. confirmation ( $t = 3.55$ ,  $p = 0.002$ ) and violation vs. random ( $t = 2.79$ ,  $p = 0.012$ ), but, crucially, the main effects of condition remained significant (viol vs. conf:  $t = 2.16$ ,  $p = 0.043$ ; viol vs. rand:  $t = 2.87$ ,  $p = 0.010$ ) suggesting that not all the effect of violation on objective  $d'$  was explained by the response bias. A significant negative bias effect was observed when comparing confirmation vs. random ( $t = -3.74$ ,  $p = 0.001$ ) and the main effect condition vanished when the bias was taken into account (conf vs. rand:  $t = -0.31$ ,  $p = 0.38$ ).

At the intermediate SOA (50 ms), a significant bias effect superseded the main effects of conditions (violation vs. confirmation, bias:  $t = 3.24$ ,  $p = 0.004$ , condition:  $t = 1.70$ ,  $p = 0.096$ ; violation vs. random, bias:  $t = 3.82$ ,  $p = 0.001$ , condition:  $t = 1.62$ ,  $p = 0.11$ ). No significant bias effect was observed for confirmation vs. random ( $t = -1.78$ ,  $p = 0.084$ ) and the main effect of condition remained non-significant when the bias was taken into account (conf vs. rand:  $t = -1.33$ ,  $p = 0.16$ ).

Overall, this bias analysis suggested that differences observed between confirmed and random conditions were confounded with the bias, but crucially the differences between violation and confirmation and violation and random remained significant at the shortest SOA.

## **Discussion**

In the present experiment, we aimed to study the effects of predictions on discrimination accuracy and subjective visibility reports of a masked stimulus. We presented sequences of left and right-oriented stimuli randomly ordered or organized in patterns (A-A-B-B) that could end either by a masked left or right-oriented target (SOA 33, 50 and 433 ms) or by a catch. Importantly, in regular sequences, that target could either violate or confirm the predictions induced by the preceding sequence (e.g. A-A-B-B-A-A-B-B-**B** and A-A-B-B-A-A-B-B-**A** respectively) in half-half of the cases. Similarly, the frequency of left and right-oriented targets, and of repetitions and alternations were counterbalanced between the conditions.

By manipulating the target-mask SOA, we could evidence that, when stimuli were difficult to perceive, those violating expectations induced higher performance in orientation

discrimination than those confirming expectations or not associated with an expectation (in the random sequences). In particular, at the shortest SOA (33 ms), sensitivity measures of discrimination ( $d'$ ) were significantly different from zero for violated sequence only. By contrast, subjective visibility was not modulated by expectations.

Analysis of catch trials revealed that participants were more prone to choose an answer violating the sequence than correctly completing the sequence. However, additional analyses controlling for this response bias indicated that the stimulus orientation was still significantly better discriminated in the violation condition than in the confirmation and the random conditions at the shortest SOA (33 ms).

These results do not support previous findings, showing that participants are better at detecting and/or discriminating stimuli that confirmed their predictions (e.g. Meijs et al., 2018; Stein et al., 2015). The bias we observed in catch trials was also unexpected. Indeed, an earlier study where participants were exposed to a regular sequence of stimuli ending by the simultaneous presentation of a violating and a confirming stimulus under binocular rivalry showed that participants were significantly biased towards the confirming stimulus (Denison et al., 2011).

A putative explanation for these diverging results is that in our study, confirming stimuli were not more frequently presented, more relevant for the task or more strongly associated with a cue than violating stimuli.

In the attention blink paradigm used by Meijs et al. (2018), the identity of a first target correctly predicted the identity of the second target in the majority of the trials. Authors found significant effects of predictions both on discrimination and detection, the former being intrinsically biased by the predictions and the latter being supposedly orthogonal to them. However, in attentional blink, as targets are embedded in a series of distractors, detection of a target among distractor is quite difficult to disentangle from an ability to discriminate a target from some distractors. Thus, even detection may have been influenced by a conscious strategy consisting in betting on the predicted target. This possible confound is compatible with the disappearance of the effect when the first target was missed or when participants were unaware of the associative link between the two targets – whilst attentional blink was still observed, confirming that the subliminal processing of the predictor occurred. Our paradigm avoids this possible bias since predictions were confirmed as frequently as they were violated.

In Stein's et al. (2015) experiment, the task was entirely orthogonal to predictions which was an advantage compared to our task because no bias towards a response could be confounded with an effect of predictions. Participants were asked to locate a stimulus whose identity was correctly or incorrectly cued. Their ability to locate targets depended on the cue validity. However, there were more than two categories of stimuli, thereby rendering valid cues more informative than invalid cues. Indeed, even if cues were valid in 50% of the trials only, participants had more chance to expect the right category if they rely on the cue than if they randomly chose an alternative category. In our paradigm, left and right-oriented stimuli were equiprobable and orthogonal to predictions, therefore guaranteeing a perfect symmetry between expecting a confirmation and a violation.

Finally, Denison et al. (2011) presented a series of rotating gabors ending by two possible competing stimuli in binocular rivalry, one continuing the rotation stream, the other counterclockwise. They found that participants' perception was biased towards the stimulus continuing the rotation stream. Many similarities exist between this study and ours, in particular, the continuing and the interrupting stimuli are equiprobable in both experiments. Still, a major difference with our study is that both confirming and violating stimuli were presented simultaneously, so there was no correct or incorrect answer. Accordingly, it is impossible to know whether participants would have better performed in detecting one or the other stimulus if only one of them was presented.

Our results are also challenging regarding current theories of conscious access. Bayesian inferences theory posits that expectations should help conscious access (King et al., 2014a). Interestingly, this theoretical framework predicts different results for discrimination and detection: expectations about properties of a stimulus should enhance its discrimination while expectations about the presence or absence of the stimulus would modulate its detectability. The absence of prediction effects on subjective visibility in our study is fully compatible with this postulate. Indeed, in our experiment, priors regarding the presence or absence of a stimulus were not manipulated: they were equal between random, violated and confirmed trials all along the experiment (20% of catch trials). However, according to this framework, regular sequences should have induced increased performance compared to random ones and no difference should have been observed between violations and confirmations since they are equiprobable (King et al., 2014a). Finally, if participants did not generate expectations, no difference would have been observed between random and regular sequences. Crucially, this is not what we found.

Participants were sensitive to these irrelevant regularities and had better performance only in case of violation.

The observation that participants are influenced by regular sequences, even irrelevant for the task, is compatible with previous proposals (Atas et al., 2014; Cleeremans et al., 2002; Destrebecqz et al., 2001) and suggests that the detection of regularity and the use of predictions are automatized and permanent (Friston, 2005; Kimura et al., 2009; Meyniel et al., 2016; Rose et al., 2005). Importantly, the processing of unexpected events plays a crucial role in learning. In particular, as known for long, babies look longer at surprising events (Spelke et al., 1992). Furthermore, violated expectations increase cerebral activity (Kouider et al., 2015) and enhance learning in infants (Stahl et al., 2015, 2017).

The bias we observed towards violation can be explained by several hypotheses that are not mutually exclusive. First, emphasized processing of violated trials may have induced learning and be generalized to ambiguous trials. Indeed, effects of violations were particularly pronounced at the shortest SOA and trials rated as weakly seen (non-visible trials did not suffer from any bias). Second, if participants automatically expected confirmation, both violation and catch might have been considered and processed as prediction-errors, the first one being a real violation, and the second one being an omission, yielding a common “unexpected” response pattern, resulting in the choice of the violating orientation in the forced-choice objective task (Bekinschtein et al., 2009; Wacongne et al., 2011). Finally, and more speculatively, if confirmation truly enhanced visibility, participants may have combined expectations about presence/absence and orientation, and rightly concluded from weakly seen trials that they were more likely to be violations than confirmations.

Additionally, the discrepancy between the strong effect on objective performance and the absence of effect on visibility can be accounted for by two hypotheses. First, as proposed above, subjective visibility may have been used by participants as a piece of evidence to decide whether the stimulus was rather a violation or a confirmation. Second and more interestingly, the enhanced ability to discriminate violations and to integrate prediction-error signals may partly rely on a better subliminal processing of these stimuli. Still, it cannot be the only explanation of our results since no significant effect of violation was observed on trials rated as non-visible with the perceptual awareness scale.

Overall, our results suggest that objective performance in discriminating a stimulus are influenced by regularities that are automatically extracted from the environment and used to generate expectations. Moreover, violated expectations seems to be significantly better processed than confirmed predictions and random stimuli. By contrast, expectations may not influence subjective visibility. Ours results are at odds with previous studies showing a positive effect of confirmation on visibility or identification. This can be explained by differences in the design. In particular, we carefully controlled for the relevance and the frequency of violations and confirmations. However, our task was not orthogonal to predictions and we observed a bias even if violation effects were still present in the post-hoc analysis controlling for this bias. These discrepant results highlight the difficulty to find an optimal design to study effects of expectations on access to consciousness. Although our finding needs further replication, it opens new considerations regarding the processing of unexpected events, in particular its conscious or non-conscious nature, and emphasizes a plausible mechanism by which subjects integrate prediction-error signals to update their conscious representations.

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## **Chapter 6. Subliminal syntactic priming**

### **Introduction of the article**

The last chapter of the thesis is devoted to a work on conscious and subliminal processing of syntactic features. Language is one of the most complex processing of the human brain. Still we are able to read without much effort, suggesting that several aspects of word processing proceed unconsciously. Subliminal priming has been previously observed according to orthographic and semantic features. In this study, we explore whether syntactic features can also cause subliminal priming across five behavioural experiments. We show the existence of grammatical priming (e.g. a noun followed by another noun), syntactic priming (e.g. a determiner followed by a noun), isolated syntactic feature priming (e.g. “they lemons”, where the expression is ungrammatical but the plural feature is repeated) and propose a theoretical framework for syntactic categorization of written words.

### **Abstract**

Subliminally presented words have been shown to cause priming at orthographic and semantic levels. Here, we investigate whether subliminal priming can also occur at the syntactic level, and use such priming as a tool to probe the architecture for processing the syntactic features of written words. We studied the impact of masked and unmasked written word primes on response times to a subsequent visible target that shared or did not share syntactic features such as grammatical category and grammatical number. Methodological precautions included the use of distinct lists of subliminal primes that were never consciously seen, and the verification that participants were at chance in a prime-classification task. Across five experiments, subliminal priming could be induced by the repetition of the same grammatical category (e.g. a noun followed by another noun), by the transition between two categories (e.g. a determiner followed by a noun), or by the repetition of a single grammatical feature, even if syntax is violated (e.g. “they lemons”, where the expression is ungrammatical but the plural feature is repeated). The orthographic endings of prime words also provided unconscious cues to their grammatical category. Those results indicate the existence of a representation of abstract syntactic features, shared between several categories of words, and which is quickly and unconsciously extracted from a flashed visual word.

## Introduction

Written and spoken sentences can be understood without much effort, suggesting that several aspects of word processing proceed automatically, unconsciously, and in an encapsulated manner (Fodor, 1983; Ullman, 2001). Indeed, at the single-word level, a series of subliminal priming experiments have demonstrated unconscious processing at orthographic (Kouider, Dehaene, et al., 2007) semantic (Dehaene, Naccache, et al., 1998; Van den Bussche et al., 2007; Yeh et al., 2012) and morphological levels (Frost, Deutsch, Gilboa, et al., 2000; Giraud et al., 2001). Subliminal priming even occurs at the emotional (Gaillard et al., 2006; Naccache et al., 2005; van Gaal et al., 2014) and possibly the phonological levels (Wilson et al., 2011), although the latter remains somewhat debated (Kouider, Dehaene, et al., 2007).

One type of processing which has received comparatively little attention, however, is the extraction of the syntactic features of words, such as determining whether a word is a noun or a verb, whether it is masculine or feminine, plural or singular, etc. In the present work, we aimed to examine whether the syntactic properties of words and their grammatical relationships can also be extracted in the absence of conscious perception, and to propose a model of the first steps of syntax processing.

Syntax is a core computational component of language which is necessary to properly construct the meaning of sentences (Friedmann et al., 2003). Several behavioral and brain-imaging experiments support a “syntax-first” model (Friederici, 2012) in which syntactic properties are quickly extracted, using a dedicated cortical circuit (Pallier et al., 2011), and guide the subsequent computation of sentence meaning (Friederici et al., 2004). Relatively few studies, however, have examined the relations between syntactic processing and conscious perception. Early studies with dichotic listening suggested that unattended sentences may still be processed at a deep level (Aydelott et al., 2012, p. 201; Bentin et al., 1995; Cherry, 1953; Eich, 1984; Mackay, 1973; Moray, 1959; Rivenez et al., 2006), although subsequent research has questioned both this conclusion (Aydelott et al., 2015; Dupoux et al., 2003) and the unconscious nature of the stimuli (Holender, 1986; Newstead et al., 1979). Using event-related potentials (ERPs), violations of grammatical agreement in gender or number were found to elicit a mismatch negativity even when attention was distracted away from the auditory stimuli (Pulvermüller et al., 2003, 2007). Again, however, the unconscious nature of the stimuli could be questioned.

More recently, experimenters have used better controlled paradigms of subliminal masking, attentional blink or continuous flash suppression to ensure non-consciousness at the single-trial level. Several teams used continuous flash suppression (CFS) to present an entire sequence of words in one eye and rendering it invisible by presenting flickering color patterns to the other eye. Axelrod et al. (2014) showed that, during CFS, meaningful sentences caused slightly larger brain activity than lists of pseudowords in language-related areas of the inferior frontal and superior temporal cortex. Sklar et al. (2012) presented a series of experiments suggesting that sentences containing semantic violations break through CFS and become conscious quicker than expressions without semantic violations, but this result failed to be replicated (Rabagliati et al., 2018). Hung and Hsieh (2015) used CFS to hide a single word or morphologically complex pseudoword, and showed that this item popped into conscious awareness faster when it was syntactically incongruent with two previous conscious words or pseudowords. This methodology has been criticized, however (Stein et al., 2011), and CFS no longer appears as a useful means of eliciting deep unconscious language processing (Rabagliati et al., 2018).

Turning to other methods, Batterink and Neville (2013) used the attentional blink to distract attention from a critical word that rendered a sentence ungrammatical, and showed that even an undetected syntactic anomaly still induced a left anterior negativity in ERP recordings, presumably reflecting an unconscious processing of syntax. Finally, three studies used subliminal priming with masked written words to explore the syntactic representation of words. The first one reported priming from a subliminal determiner onto a conscious noun, as a function of whether the two words shared the same grammatical gender in German (Ansong et al., 2013), although in the stimuli, gender was partially confounded with plural. The second study showed that the morphological features of a masked conjugated verb (indicating active, passive, or reflexive) could prime another verb with the same features (Deutsch, Frost, & Forster, 1998). The third study reported magneto-encephalography evidence that Japanese participants were sensitive to the unconscious agreement between a conscious noun, a subliminal transitive or intransitive verb, and a subsequent conscious verb (Iijima et al., 2014), although no behavioral evidence of subliminal priming was obtained. Here we aimed to systematize those prior results by performing a series of experiments assessing the impact of conscious and unconscious primes on a grammatical categorization task in healthy controls. In five successive experiments, we asked whether the processing of a syntactic feature (e.g. plural) could be facilitated by an unconscious prime. If we could demonstrate such subliminal priming,



it would not only extend the range of cognitive operations known to occur without consciousness, but also, importantly, provide information about the organization of the representation(s) and processes that underlie the extraction of the syntactic features of words. Contemporary linguistic theorizing postulates that, for the purpose of unification with other words during sentence parsing, each word must be labeled according to a set of positive or negative syntactic features. For instance, the verb “rained” may be labeled as +verb, -transitive, +singular, +past, etc. (as reviewed e.g. by Sportiche et al., 2013). In the present work, we propose to use priming as a tool to study (1) the psychological reality of syntactic features, and (2) the various cue and cognitive architecture by which such features are extracted.

Our research is guided by a theoretical framework, shown in Figure 1, which derives from a careful consideration of the various cues available to the participant in order to determine the syntactic features of a word: pseudo-morphology, lexicon, and prior context. We now present each of those levels in turn.

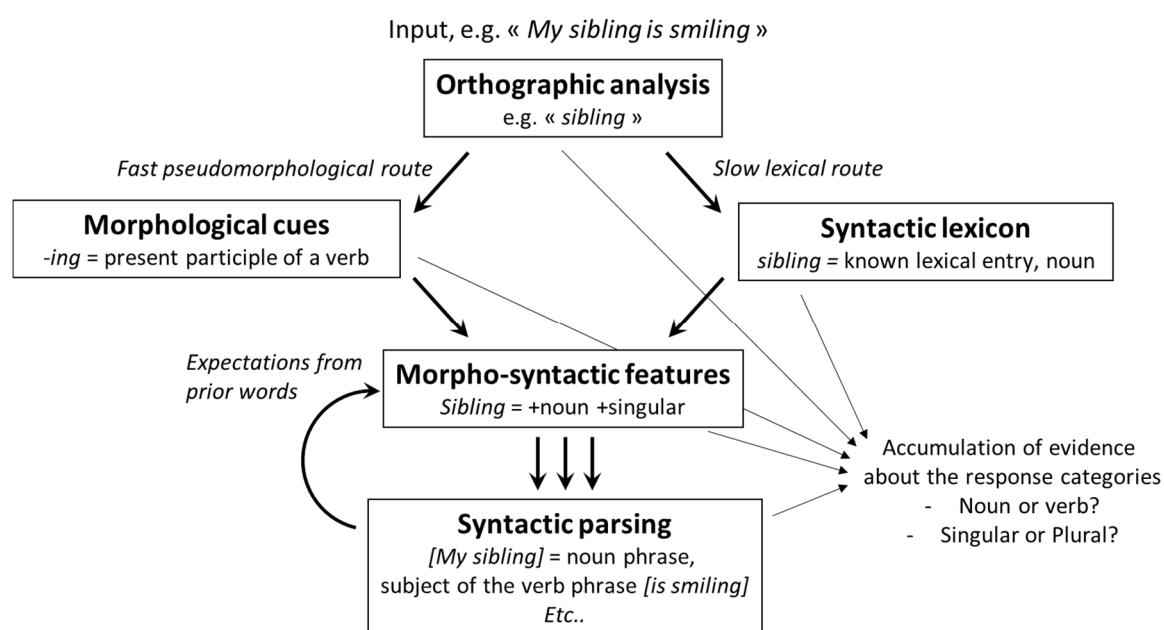


Figure 1. Tentative theoretical framework for syntactic categorization of a visually presented word. We propose that syntactic features are retrieved via two parallel routes: pseudo-morphological (left) and lexical (right). Following orthographic analysis, morphological cues are quickly extracted and cause a bias towards specific grammatical features (e.g. in English, a word ending with *ing*, such as *smiling*, suggests a present participle of a verb or a nominalized verb). In parallel, a slower lexical route retrieves the stored syntactic features of known words. This route can override the fast one (for instance *sibling* ends with *-ing*, suggesting a verb, but the lexicon correctly encodes it as a noun). Information

from the two routes is combined with the current sentence context to yield an estimate of the syntactic features of the current word which is then used for sentence parsing. In turn, parsing creates a syntactic context that biases the processing of subsequent words (i.e. may induce priming). The present experiments test the hypothesis that, in a syntactic categorization task, participants' decisions reflect a combination of multiple sources of evidence arising from each of these representational levels.

The presentation of a written word is thought to quickly induce an automatic analysis of its orthographic features, culminating in an invariant representation of abstract letter identities and their order (visual word form). Following this stage, our framework tentatively proposes that two routes to syntax are available. The first route provides a tentative morphological analysis of the incoming string: it detects the presence of potential morphemes such as prefixes and suffixes that often provide highly consistent cues about grammatical category and other syntactic features (for instance, the *-ed* ending suggests a verb in the past tense). We label this route as “pseudomorphological” because it need not suffice to converge on the proper morphological analysis (“biped” is a noun, not the past tense of the verb “bip”). Considerable behavioral and brain-imaging analysis suggests that such morphological analysis occurs at a high speed (Beyersmann et al., 2016; Bick et al., 2010; Devlin et al., 2004; Frost, Deutsch, Gilboa, et al., 2000) and, importantly, even when it is inappropriate (e.g. the word *brother* may be automatically parsed as *broth+er*, see (Rastle et al., 2004)).

The second route to syntax postulated in our theoretical framework is lexical. In parallel to pseudo-morphological analysis, the syntactic identity of the word would be retrieved from the “syntactic lexicon”, a representation that stores the syntactic features of known words. The postulation of such a representation is necessary, and must eventually override the preceding shallow analysis of pseudo-morphemes, because there are many words whose syntactic features are unmarked morphologically (e.g. *women* = +noun, +plural ; *ran* = +verb, +past-tense), or whose initial morphological decomposition is misleading (such as *biped*). The syntactic lexicon would therefore correspond to an internal memory store that specifies, for each word, its grammatical category as well as all the syntactic features necessary to assign it a precise role in the parse tree (grammatical number, gender, tense, number and type of arguments, etc). Explicit models of lexical-syntactic representations of words have been previously proposed and suggest that words having irregular forms are stored as full forms (e.g. *feet* is directly stored as a plural noun) while regular forms would be stored as lemma that can be associated with morphological signals (e.g. *cats* can be decomposed in *cat* noun + *-s* plural) (Fieder et al., 2014; Nickels et al., 2015). Moreover, these models posit that some grammatical features are ultimately associated

with conceptual representations (e.g. singular/plural with unique/multiple, noun/verb with entity/event etc.) (Nickels et al., 2015).

Finally, the third cue to syntactic features is the context of preceding words. The sentence context, once parsed, can induce syntactic expectations about the upcoming word and help to resolve ambiguities due to homographs (e.g. *the walk* versus *they walk*). When contextual expectations contradict the morphological or lexical features of the incoming word, a mismatch signal may arise (Batterink et al., 2013; Friederici et al., 2004; Neville et al., 1991; Pulvermüller et al., 2003).

In normal sentences, the three types of information provided by morphological cues, the syntactic lexicon, and sentential context, must ultimately be reconciled in order to yield a unified interpretation of the most likely syntactic features of the current word in the current context. This interpretation is passed on to the syntactic parser and may, in turn, bias the syntactic categorization of subsequent words (Figure 1).

Given this theoretical framework, the present experiments had two major goals. First, we wanted to test the postulated architecture for syntactic feature retrieval, and particularly the existence of distinct pseudo-morphological and lexical contributions to syntactic feature retrieval. The framework proposes that multiple cues are computed in parallel and may converge or, on the contrary, diverge in their conclusions. To test this idea, we used priming as a tool, asking whether a syntactic categorization task (e.g. decide whether a target word is a noun or a verb, or is singular or plural) could be primed by another word (the prime). Primes and targets never shared the same orthography, but in different experiments, they could (1) possess congruent or incongruent pseudomorphemic cues (e.g. both ending with verb cues); (2) share the same category in the syntactic lexicon, or not (e.g. both being verbs); and (3) create a contextual expectation convergent or divergent with the target's genuine category (e.g. determiner followed by noun, pronoun followed by verb). In this way, we tested the existence and efficiency of each of the three routes to syntactic features proposed in our framework.

Second, we also probed whether some or all of the postulated architecture could operate unconsciously. Thus, we compared the effect of conscious primes versus subliminal primes that were masked below the threshold for conscious identification (both at short SOAs). Because masking reduces the activation evoked by a written word at all stages of the reading circuit (Dehaene et al., 2011), the unmasked, conscious condition provided the best chance of

obtaining strong priming effects that probe the postulated architecture for syntactic-feature extraction (Figure 1). However, only the masked, unconscious condition provides a specific test of the fast and unconscious nature of the observed effects. Studying unconscious processing is important because according to the main theories of consciousness (Baars, 1993; Dehaene & Naccache, 2001; Dennett, 2017; Tononi, 2004), once a word is conscious, any information it conveys can become globally broadcasted throughout the cognitive processing system. Only subliminal priming provides a specific test of the hypothesis that the three types of postulated information (pseudomorphological, lexical and contextual knowledge) are quickly extracted and processed even when the incoming stimulus is unable to gain access into the vast stores of the participants' conscious knowledge.

In detail, we conducted a total of five behavioral studies in French. On each trial, a masked or unmasked prime was briefly flashed and followed by a visible target word. Participants had to classify the target either according to its grammatical category (noun or verb; experiments 1-4) or to its grammatical number (singular or plural; experiment 5). Experiment 1 and 2 tested grammatical category priming, i.e. the ability of a prime belonging to a grammatical category to accelerate the processing of a target belonging to the same grammatical category (e.g. a noun followed by a noun, or a verb followed by a verb), and examined the respective contributions of pseudomorphological versus lexical information. Experiment 3 explored whether syntactic priming could also be induced by the contextual relationship between two words (e.g. a determiner followed by a noun, or a pronoun followed by a conjugated verb). In experiments 4 and 5, we examined whether individual syntactic features, rather than syntactic categories, could induce priming. Experiment 4 evaluated whether a determiner could prime a noun, or a pronoun a verb, even when their grammatical number disagreed (e.g. "they cooperates"). Conversely, experiment 5 evaluated whether a singular word could prime another singular word, or a plural another plural, even when their categories formed an ungrammatical phrase (e.g. "they lemons"). To anticipate on the results, all experiments provided evidence that grammatical categories and grammatical features can induce conscious as well as unconscious priming effects.

## Experiment 1

Experiment 1 evaluated whether masked and unmasked words cause grammatical category priming. We used French verbs and nouns as primes and targets and studied whether a noun could prime another noun, and a verb another verb.

To specifically study such grammatical category priming, several methodological precautions were taken. All verbs were in the infinitive form, thus sidestepping any issues of agreement or grammaticality (all of the two-word combinations that we presented were ungrammatical in French). Because orthographic (Kouider, Dehaene, et al., 2007) and possibly phonological (Wilson et al., 2011) features can be processed subliminally, we excluded all words that were homophones or homographs of words from other grammatical categories, and we built pairs of nouns and verbs that were well matched in orthography, length, and frequency. Because emotional valence can be subliminally processed (Gaillard et al., 2006; Naccache et al., 2005; van Gaal et al., 2014), we chose words with neutral emotional valence.

Most importantly, the experiment was designed to test the respective contribution of pseudomorphological and lexical information in determining the syntactic category of primes and targets, by orthogonally varying them. In French, word ending is a strong cue to grammatical category (Arciuli et al., 2009), especially in French where many verbs end in “er”, and such affixes have been shown to induce priming (Frost, Deutsch, & Forster, 2000; Giraud et al., 2001). Thus, we used pairs of nouns and verbs that were matched according to their ending. Furthermore, in each prime-target pair, the prime ending differed from the target ending. Those precautions ensured that (1) the task could only be performed by retrieving the category of the target from the syntactic lexicon, because word-ending information alone did not suffice; (2) similarly, syntactic-category priming (noun-noun or verb-verb), if observed, could only be explained by retrieval of the prime’s syntactic category from the syntactic lexicon; (3) our experiment also allowed measurement of the putative effects induced by word endings alone, i.e. through the pseudo-morphosyntactic route, and this separately for the prime and for the target. The dual-route model presented in Figure 1 predicted that both the word-ending (pseudo-morphological route) and the true syntactic category (lexical route) of the prime, as well as the irrelevant morphological indication provided by the target ending, would influence the categorization of the target word, and we probed whether they did so for unconscious as well as conscious primes.

## **Material and methods**

### ***Participants***

Twenty-two right-handed native French speakers (8 males; mean age 23.9 year; range 18-30 year) were tested. All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. No participant took part in more than one experiment. Participants gave informed consent before taking part, and received financial compensation (10€ for a session of 45 minutes). Six participants were excluded: 4 had an error rate of more than 10% and two could not see the unmasked prime in the visibility task ( $d'$  measured at 0.6 and -0.2).

### ***Stimuli***

Sixty French masculine nouns and sixty infinitive verbs served as prime and target stimuli. We created pairs consisting of one noun and one verb that were similar in orthography, ending (“er”, “ir” or “re”), number of letters (mean 7,1; range 3-10), and frequency in French (mean 19 per million; range 0.09-232), for instance “écuyer” (“rider”, noun) and “écumer” (“to skim”, verb). We excluded words belonging to more than one grammatical category, homophones or homographs of words from other grammatical categories, words having a strong emotional valence and nouns having a verb-like pseudo-morphology. For instance, the noun “berger” (“shepherd”) was excluded because it could have been construed as a verb constructed from the noun “berge” and the ending “er” (see e.g. Rastle et al., 2004).

For each participant, 30 noun-verb pairs out of 60 were randomly selected to serve as masked primes, while the others served both as targets and as unmasked primes. This methodological precaution is important as it implies that the masked primes were never consciously seen and, therefore, could not induce direct sensori-motor priming (see e.g. Abrams et al., 2000; Naccache et al., 2001). Consequently, both primes and targets consisted of very similar words such as “écuyer” and “écumer”, which could only be distinguished by their (arbitrary) assignment to the noun or verb grammatical category in the French lexicon. The final list of stimuli was generated by randomly pairing primes and targets, with the further constraint that they should not share the same initial letter nor the same ending (last three letters). All target words appeared equally often in each of the congruent and incongruent conditions, for a total of 240 masked trials and 240 unmasked trials. All trial types were randomly intermixed.

## *Procedure*

Each trial consisted of a precisely timed sequence of a prime presented for 33 ms and a target presented until the participant answered. The presentation of the prime could be masked or unmasked depending on the masking conditions. On masked trials, the prime was preceded by a first forward mask (i.e., “#####”) for 267 ms and a second forward mask (i.e., “pXpXpXpXpXpX”) for 100 ms, and followed by a backward mask (i.e., “XqXqXqXqXqXq”) presented for 100 ms prior to the target. On unmasked trials, the two masks surrounding the prime (i.e., the second forward mask and the backward mask) were replaced by blank screens (see Figure 2). Such a masking technique (a variant of (Kouider, Dehaene, et al., 2007)) was required in order to contrast conscious versus unconscious trials with the same prime duration (33 ms) and prime-target stimulus onset asynchrony (SOA, 133 ms). With standard techniques such as the Forster paradigm (Forster et al., 1984), where prime-target asynchrony is very short, it is very difficult to obtain complete invisibility in the masked condition and full visibility in the conscious condition while keeping timing variable constant. We run pilot experiments and empirically adapted the masks and timing to the specific words used, taking into account that they varied in length and frequency. All stimuli appear at the center of screen in the same fixed-size font (courier new bold, subtending 1.15 degree of vertical visual angle) in black lowercase letters on a white background.

Participants were asked to determine as quickly as possible the grammatical category of the target word (noun or verb) by pressing a right-hand or left-hand button (buttons were assigned at the beginning of the experiment, and their assignment was counterbalanced between participants). They were asked to pay attention solely to the word that stayed on screen (i.e., target) and to ignore any other event (i.e., prime or masks). Each participant performed a training block of 60 trials, where each target word was presented once, then 8 blocks of 60 trials, with a short pause after every block. The aim of the training (also used in previous studies, e.g. (Dehaene, Naccache, et al., 2001)) was to familiarize participants with the procedure and the target words so that their subsequent performance would be better and more uniform.

After the main experiment, participants performed a forced-choice test (visibility task) in order to check whether the specific syntactic feature tested (i.e. grammatical category) could be consciously perceived. Participants were told about the presence of a hidden prime preceding each target word, and were asked to guess whether it was a noun or a verb. They were told that only response accuracy was important, not response speed, and that they had to venture an

answer even if they did not see the prime. They were informed that the target grammatical category was incongruent with the prime grammatical category 50% of the time. Each trial comprised the same sequence of masks and stimuli as in the experiment, except that the target stayed on screen for 500 ms. In addition, just after the target, the response words “NOM” (noun) and “VERBE” (verb) appeared. To avoid response priming, those categories were randomly assigned to the right and left of the fixation point. Participants responded by pressing the button on the side of the word they wanted to select. The two alternatives remained on screen until a response was made.

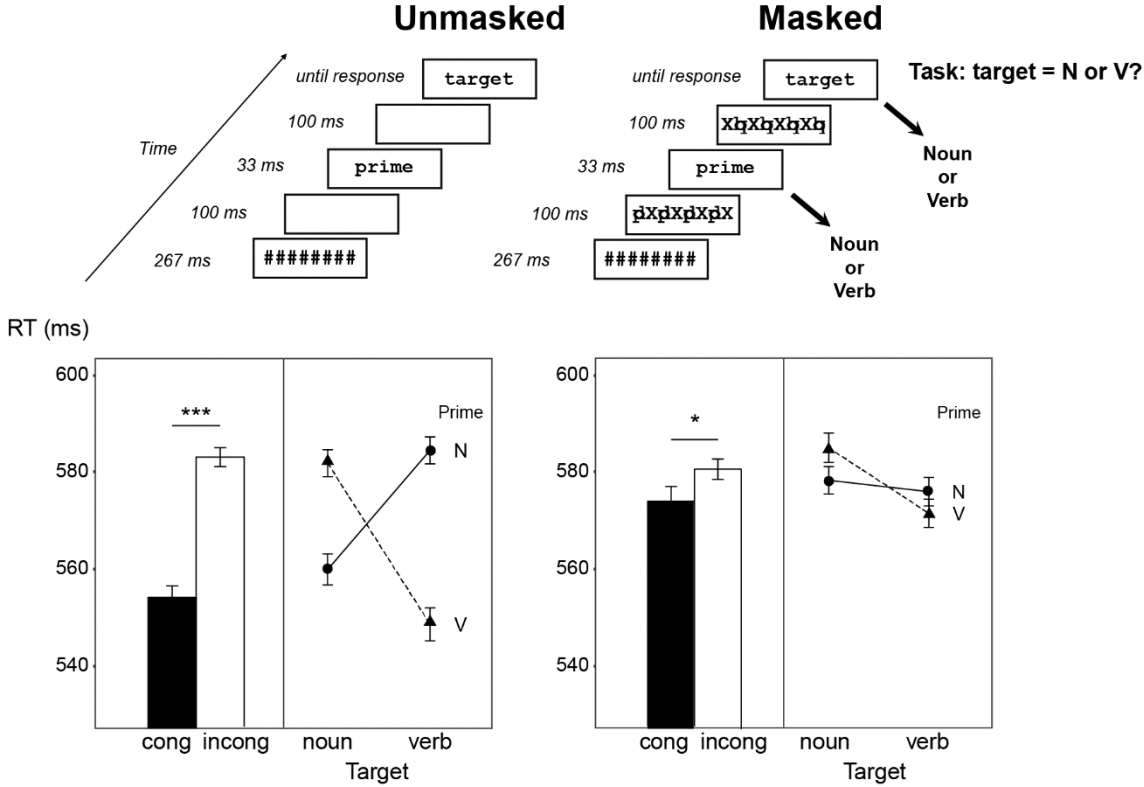


Figure 2. Procedure and results of experiment 1. Participants classified target words as nouns or verbs, each of which was preceded by a masked or unmasked noun or verb prime. On the left: unmasked conditions, on the right: masked conditions. At the bottom, barplots show reaction times for congruent (black bars) and incongruent (white bars) trials, lineplots show reaction times as a function of prime category (N = noun, solid line; V = verb, dashed line) and target category. Error bars represent one standard error of the mean (SEM). \*\*\* =  $p < 0.001$ ; \* =  $p < 0.05$ .



## Results

### *Behavioral priming in response times*

Overall error rate was 7% (range 2-10%). We performed an analysis of variance (ANOVA) on median of correct response times for each participant (excluding reaction times above 1200 ms or +/- 3 standard deviations away from the mean for each participant) during the grammatical categorization task, with factors of visibility (masked/unmasked), prime category (noun/verb) and target category. This analysis revealed a main effect of visibility (masked vs. unmasked;  $F_{1,15} = 34.83$ ,  $p < 0.001$ ): responses were 10 ms faster overall in the unmasked condition (567 ms versus 577 ms), presumably because removal of the masks rendered the target easier to process. There was no main effect of the category of the target ( $F_{1,15} = 1.87$ ,  $p = 0.19$ ) and of the prime ( $F_{1,15} = 1.54$ ,  $p = 0.23$ ). Crucially, a prime category  $\times$  target category interaction indicated the presence of an overall grammatical category priming effect (congruent: 563 ms; incongruent: 580 ms, difference: 17 ms,  $F_{1,15} = 59.45$ ,  $p < 0.001$ ). Furthermore, a triple interaction with visibility ( $F_{1,15} = 29.12$ ,  $p < 0.001$ ) indicated greater priming in the unmasked compared to the masked condition. Nevertheless, grammatical category priming was found under both unmasked (552 ms versus 581 ms, difference: 29 ms,  $F_{1,15} = 67.64$ ,  $p < 0.001$ ) and masked conditions (574 ms versus 580 ms, difference: 6 ms,  $F_{1,15} = 4.68$ ,  $p = 0.048$ ) (see Figure 2).

### *Prime visibility*

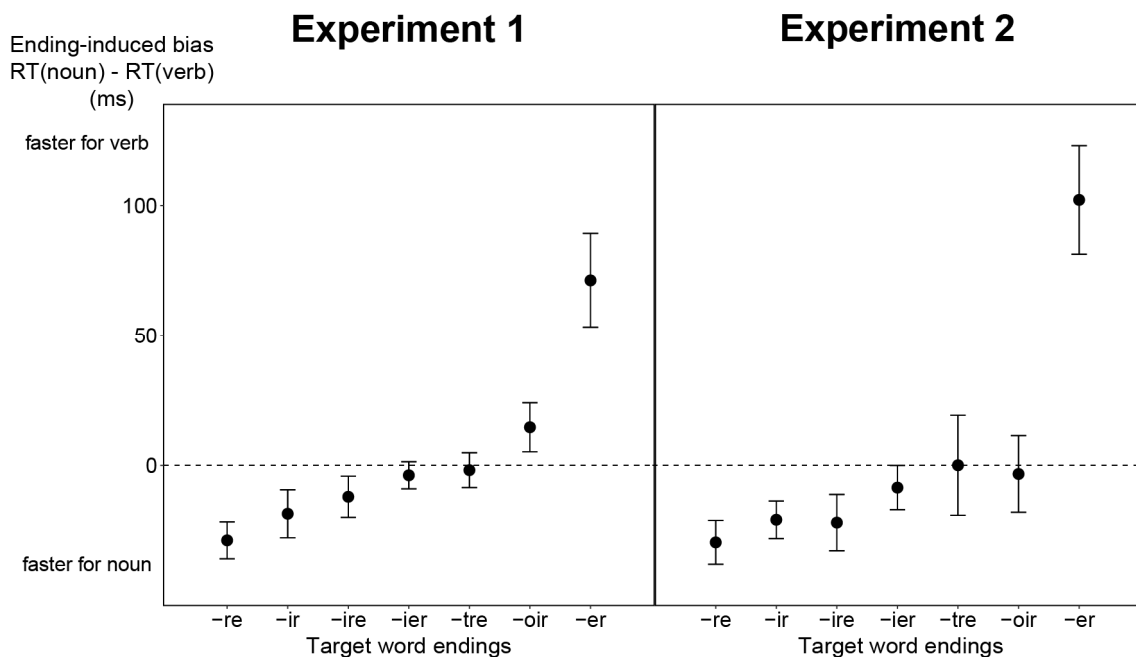
Data from the forced-choice prime categorization task was used to evaluate prime visibility. Measures of  $d'$  values for each participant confirmed that they were unable to consciously categorize the primes in the masked condition (50.6% correct;  $d' = 0.03$ ;  $t_{15} = 0.4$ ;  $p = 0.69$ ), whereas they could do so in the unmasked condition (93.6% correct;  $d' = 3.06$ ;  $t_{15} = 26.1$ ;  $p < 0.001$ ). There was no positive correlation between the size of the priming effect and the prime visibility in the masked condition, but if anything a negative correlation (Pearson  $r = -0.5$ ,  $t_{14} = -2.17$ ,  $p = 0.048$ ) and the intercept of this regression was significant (5.4 ms,  $t_{14} = 2.50$ ,  $p = 0.025$ ), indicating that priming remained significant even at null  $d'$  (see Greenwald et al., 1996).

### *Word ending analysis*

We next evaluated whether word-ending cues had an independent impact on the noun-verb categorization task, thus testing the existence of a pseudo-morphological level of processing that biases the retrieval of syntactic features. The words we used ended with one of seven possible endings ("er", "ier", "ir", "ire", "oir", "re", "tre"), each of which was used for at least ten words. We first examined if those endings biased responses towards the verb or the noun category. An ANOVA on median reaction time showed a significant interaction between grammatical category and target ending ( $F_{6,48} = 8.88$ ,  $p < 0.001$ ; note that this analysis was restricted to the 9 participants without any missing measures in each condition), suggesting that some endings cued specific grammatical categories. For instance, participants were significantly faster to answer “verb” than “noun” for words ending in “er” (difference: 84 ms,  $t_8 = -4.26$ ,  $p = 0.003$ ) but faster to answer “noun” than “verb” for a word ending by “re” (difference: 16 ms,  $t_8 = 2.71$ ,  $p = 0.027$ ). Thus, target ending influenced the syntactic categorization task even though, by design, it was orthogonal to the genuine category of the target word.

Next, we evaluated whether *prime* ending had an effect on the target-based decision. First, we used the target-based RTs to compute a variable that we called the “ending-induced bias” (EIB) for each of our seven endings in French. EIB was defined as the mean difference  $RT_{\text{noun}} - RT_{\text{verb}}$  for each target ending (see Figure 3, left panel). It was therefore positive for endings such as “er” or “oir” which favor a “verb” response, and negative for endings such as “re” or “ir” which favor a “noun” response. Second, we applied this variable to the prime words, and used a mixed-effect regression model to examine whether the prime-related EIB biased the speed of responding to the target. The variable of interest, called “prime ending congruity” was the prime-ending variable multiplied by a +1/-1 variable coding for target category, thus measuring the congruity between the amount of noun-verb bias induced by the prime ending and the correct noun/verb response induced by the target. Other variables of non-interest were the category of the prime, the presentation condition (masked/unmasked), their interaction between themselves and with other variables of interest, and the frequency of the target word in French. We again observed a target-ending effect ( $t = -5.70$ ,  $p < 0.001$ ; trivially reflecting the fact that EIB was derived from the same data), but we did not find any significant prime ending congruity effect, neither for unmasked ( $t = 0.23$ ,  $p = 0.38$ ) nor for masked primes ( $t = -0.28$ ,  $p = 0.38$ ).

Our model assumes that the pseudo-morphological route is fast and eventually overridden by the genuine information provided by the lexical route. To explore whether prime ending affected only the earliest stages of grammatical category processing, we analyzed separately short and long RT trials (respectively inferior and superior to the median). Still, no effect was found in this analysis neither for unmasked nor for masked conditions (short RT unmasked:  $t = -0.15$ ,  $p = 0.39$ ; masked:  $t = -0.34$ ,  $p = 0.37$ ; long RT unmasked:  $t = 0.50$ ,  $p = 0.34$ ; masked:  $t = 1.02$ ,  $p = 0.23$ ).



*Figure 3.* Word endings modulate the speed with which target words are classified as nouns or verbs. For each ending, the y axis shows the bias towards verbs, as measured by the difference in mean response time (RT) to nouns and to verbs. Positive values indicate a faster response to verbs than to nouns. On the x axis, word endings have been sorted according to the biases measured in experiment 1. In both experiments 1 and 2, word endings induced reproducible and highly similar biases towards one or the other response ( $r = 0.97$ ). Error bars represent one *SEM*.

## Discussion

A significant grammatical category priming was found in both unmasked and masked conditions. In the latter, participants were unable to consciously perceive the primes and were at chance in discriminating their grammatical category. Furthermore, the prime-target word pairs were specifically chosen to avoid any bias due to orthographic, phonological, syntactic, semantic, or morphological priming. Finally, in the masked condition, a distinct list of prime

words was used, which were never seen nor categorized as targets. This design allowed us to formally exclude the possibility that priming arose from automatized stimulus-response mappings (Abrams et al., 2000; Damian, 2001). We therefore concluded that the grammatical category of a word (noun or verb) can be subliminally extracted from masked words and can prime the noun-verb judgment for another word of the same category. Because grammatical category was manipulated independently of word ending, with minimal pairs such as *écuyer* (N) vs *écumer* (V), prime category information could only have arisen from a stored lexicon, and we therefore conclude that the lexical route to syntactic category can be activated consciously as well as unconsciously. Unsurprisingly, and in accordance with many prior studies, conscious priming was parallel to, but significantly greater than, subliminal priming (Cheesman et al., 1986; Dehaene, Naccache, et al., 2001; Kouider & Dehaene, 2007; Kouider, Dehaene, et al., 2007; Merikle et al., 2001).

The dual-route model of syntactic-feature extraction also predicted that word ending would have an independent influence on the syntactic categorization task. In agreement with this prediction, we found that, independently of the target's grammatical category, the target's final letters, which carry pseudomorphological information in French, biased participants towards the verb or noun response. This finding strongly supports the dual-route model, as it indicates that two different variables, genuine word category and the (often erroneous) category induced by pseudo-morphemes, had orthogonal influences on syntactic categorization.

Surprisingly, however, no such word-ending effect was found on the prime. We will discuss this finding after the presentation of experiment 2, where we examined one possible cause for its absence

## **Experiment 2**

Experiment 2 aimed to replicate experiment 1 with a few changes. Most crucially, we reasoned that the relatively long stimulus-onset-asynchrony (SOA) separating the prime and the target (133 ms) could have weakened the priming effects and, in particular, might explain why we found a target-ending effect but not prime-ending effect. If the pseudo-morphological route is fast and quickly over-ridden by the slower lexical route, as postulated in our theoretical framework, then the prime effect induced specifically by the prime ending might be very short-lived. In experiment 2, the prime-target SOA under masked condition was therefore reduced to 50 ms. This required small changes to the masking paradigm (Figure 4), and piloting also

showed that we could maintain prime invisibility while relaxing the strong masking conditions imposed in experiment 1 (one forward mask instead of two), again in the hope of increasing the amount of priming.

Another limit of experiment 1 that the unmasked prime word could appear as targets, thus affording the possibility that their response (left or right) was automatized and led to stimulus-response priming. This was not true for masked primes, which never appeared as conscious targets. As a consequence, the larger difference between masked and unmasked priming in experiment 1 (29 vs. 6 ms) could have arisen in part from a difference in stimulus-response priming. We corrected this small problem in experiment 2 by using three separate lists of words (randomly varied across participants) that served respectively as masked primes, unmasked primes, and target words.

## **Material and methods**

### ***Participants***

Twenty-one right-handed native French speakers (6 males; mean age 23.3 year; range 19-29 year), fulfilling the same criteria as in experiment 1, were tested. Two participants were excluded: one had an error rate of more than 10% and one had a mean reaction time (RT) of over 800 ms.

### ***Stimuli***

The same 120 words as in experiment 1 were used. For each participant 20 pairs of matched nouns and verbs were randomly assigned to serve as masked primes, 20 as unmasked primes and the remaining 20 as targets.

### ***Procedure***

On unmasked trials, the visual sequence was exactly the same as in experiment 1 (267 ms forward mask “#####”, 100 ms blank screen, 33 ms prime, 100 ms blank screen, and finally the target presented until the response). On masked trials, the sequence comprised a 433 ms forward mask “#####”, 16 ms blank screen, 33 ms prime, 16 ms backward mask “XXXXXXXXXX”, and target. This procedure ensured that prime duration (33 ms) was equal and identical to experiment 1, but that the masking was lighter (see Figure 4). Note

that the SOA between prime and target was now shorter on masked compared to unmasked trials (50 ms versus 133 ms). The task was the same as in experiment 1, i.e. determining as quickly as possible the grammatical category of the target word (noun or verb).

The procedure was as in experiment 1 except that a control repetition-priming block was inserted before the final visibility task. During this block, using the same task, 160 masked-only trials were used. The masked primes were identical to the targets on 25% of the trials, different but congruent for grammatical category on another 25%, and incongruent on the remaining 50%, so that overall 50% of the trials were congruent and 50% were incongruent. In this block, both prime and target words were the 20 nouns and 20 verbs used as targets in the main block.

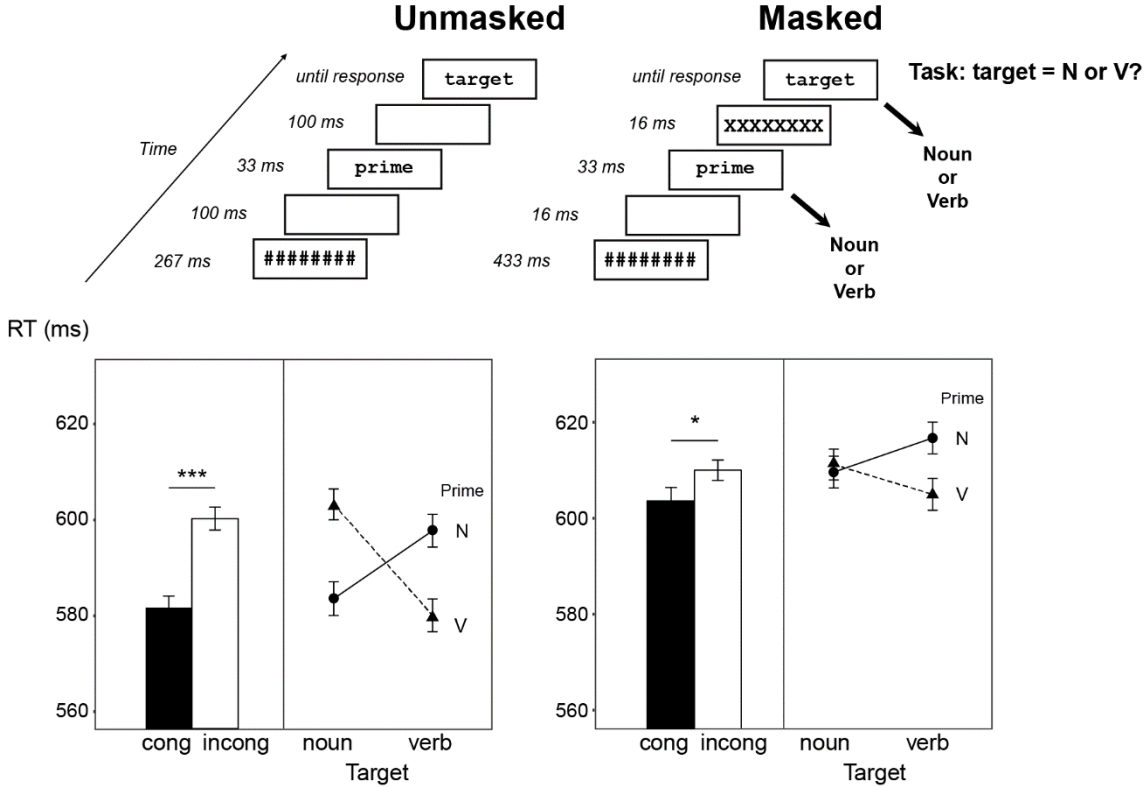


Figure 4. Procedure and results of experiment 2. Participants classified target words as nouns or verbs, each of which was preceded by a masked or unmasked noun or verb prime. Same format as Figure 2. Error bars represent one SEM. \*\*\* =  $p < 0.001$ ; \* =  $p < 0.05$ .

## Results

### *Behavioral priming in response times*

Overall error rate was 5% (range 1-8%). For the main block, an analysis of variance (ANOVA) on the median of correct response times for each participant, with the same exclusion criterion as in experiment 1, revealed results similar to experiment 1. There was a main effect of presentation type (masked vs. unmasked;  $F_{1,18} = 53.26$ ;  $p < 0.001$ ): responses were 20 ms faster overall in the unmasked condition (591 ms versus 611 ms). There was no main effect of the category of the target ( $F_{1,18} = 0.15$ ,  $p = 0.70$ ) and of the prime ( $F_{1,18} = 0.64$ ,  $p = 0.43$ ). Crucially, there was a significant grammatical category priming effect (interaction of prime category and target category; congruent 595 ms versus incongruent 607 ms, difference: 12 ms,  $F_{1,18} = 20.07$ ,  $p < 0.001$ ). As expected, a triple interaction with visibility ( $F_{1,18} = 8.21$ ,  $p = 0.010$ ) indicated greater priming in the unmasked compared with the masked condition. The grammatical category priming was found both in unmasked (582 ms versus 600 ms, difference: 18 ms,  $F_{1,18} = 20.8$ ,  $p < 0.001$ ) and masked conditions (607 ms versus 614 ms, difference: 7 ms,  $F_{1,18} = 5.55$ ,  $p = 0.030$ ) (see Figure 4). In a comparison of experiments 1 and 2, the size of the grammatical category priming effect was similar, both in the unmasked condition (29 ms vs. 18 ms; Welch  $t_{df=32.8} = -1.79$ ;  $p = 0.082$ ) and in the masked condition (6 ms vs. 7 ms; Welch  $t_{df=33} = 0.284$ ;  $p = 0.78$ ).

### *Prime visibility*

Measures of  $d'$  values for each participant confirmed that they were unable to consciously perceive the category of the primes under masked condition, as they performed slightly below chance (45.5% correct;  $d' = -0.24$ ;  $t_{18} = -2.60$ ;  $p = 0.018$ ), whereas they performed well in the unmasked condition (89.5% correct;  $d' = 2.70$ ;  $t_{18} = 17.47$ ;  $p < 0.001$ ). There was no significant correlation between the priming effect and the prime visibility in the masked condition ( $t_{17} = -0.34$ ,  $p = 0.74$ ) and the intercept of this regression was significant in the expected direction (8.3 ms,  $t_{17} = 2.00$ , one-tailed  $p = 0.031$ ), indicating that grammatical priming occurred at null visibility.

### *Word ending analysis*

An ANOVA on median reaction time again showed a significant interaction between grammatical category and target ending ( $F_{6,78} = 9.93$ ,  $p < 0.001$ ), indicating that some endings

cued specific grammatical categories. We again calculated the ending-induced bias (EIB) as the mean difference  $RT_{\text{noun}} - RT_{\text{verb}}$  (see Figure 3, right panel). EIB variables were highly correlated between experiment 1 and 2 (correlation coefficient  $r = 0.97$ ,  $t_{12} = 14.07$ ,  $p < 0.0001$ ), showing that the same endings reproducibly biased decisions towards nouns or towards verbs. We then used the same mixed-effect regression model as in experiment 1 to examine whether prime ending biased RTs to the target. This time, we could use the EIB calculated from the independent data in experiment 1, thus avoiding any circularity in the analysis. There was a highly significant effect of target EIB ( $t = -5.70$ ,  $p < 0.001$ ). Furthermore, crucially, there was now a highly significant prime-ending congruity effect for masked primes ( $t = -3.23$ ,  $p = 0.005$ ). For unmasked primes, the effect was non-significant ( $t = -1.08$ ,  $p = 0.22$ ), but a median split suggested a marginal effect in the appropriate direction when we analyzed only the fast response times (below each participant's median;  $t = -2.04$ , one-tailed  $p = 0.027$ ).

## Discussion

Experiment 2 replicated the presence of grammatical category priming with unmasked primes that had never been explicitly categorized by the participants (which was not the case in experiment 1). The size of this unmasked priming effect was 18 ms, only slightly and non-significantly smaller than the 29 ms in experiment 1. Most crucially, under masked condition, the grammatical category priming effect was replicated and was comparable to experiment 1 (7 ms versus 6 ms). Modifying the masks and reducing the prime-target SOA thus did not affect the amount of category priming. Overall, the results suggest that, even though unconscious syntactic-category priming is a small effect, it is a robust and reproducible phenomenon that resists variations in prime-target SOA and masking type. This finding confirms that the grammatical category of a subliminal word can be subliminally retrieved from the lexicon and can prime another word of the same category.

Independently of this category effect, we also found a prime ending effect: masked words primed the noun or verb response in direct proportion to how their endings, when present in the target words, biased RTs towards the noun or verb category. Those results indicate that word-endings may unconsciously bias responses toward the verb or noun category, independently of the word's true category. Changes in prime-target SOA between experiments 1 and 2 may explain the fluctuations of this effect. Indeed, it was only found when the SOA was very short (50 ms), i.e. for masked primes in experiment 2, but not in the other conditions where SOA was longer (133 ms) i.e. masked and unmasked primes in experiment 1, and



unmasked primes in experiment 2. When we selected only the shortest responses (RTs < median), a marginal prime-ending effect reappeared for unmasked primes in experiment 2.

These results are fully compatible with the proposed theoretical framework for syntactic-feature extraction (Figure 1): the prime-ending effect arises only as a fast and transient effect, quickly replaced in time by the effect of the true grammatical category of the word in the French lexicon. Remember that, according to the proposed dual-route model, grammatical category is retrieved through two parallel routes. A tentative category is activated based on morphological cues, particularly word ending (fast pseudo-morphological route). Later, the correct grammatical category is retrieved from the syntactic lexicon (slow lexical route). In case of a mismatch between those two categories, the real grammatical category supersedes the one hypothesized from morphological cues. The existence of the two routes is supported by the presence of two independent and orthogonal effects in our data, while the superseding assumption is supported by the fact that participants performed at a very high level (95% correct) even on trials where target ending conflicted with target category.

The speed of the slow lexical pathway is likely to be modulated by the familiarity and the conditions of word presentation (the more familiar and visible, the faster). The latter property fits with the absence of prime-ending effect in experiment 1 under unmasked condition, even for short RTs, given that the unmasked prime words had also been presented as targets. It also fits with prior findings of “pseudo-morphological decomposition” according to which a word such as “brother” is transiently decomposed into its apparent morphemes “broth” and “er” (Rastle et al., 2004). Our results complement those prior findings by showing that the terminal morpheme of a noun or word can cue a specific grammatical category.

### **Experiment 3**

In experiment 3, we sought to test the third postulated source of syntactic information in our theoretical framework (Figure 1): the syntactic context provided by previous words. Thus, whereas experiments 1 and 2 studied word-end and category-based repetition priming (noun-noun or verb-verb), experiment 3 probed whether priming could be induced by syntactic context in the absence of any repetition of a given syntactic category. The task still was to categorize a visible target word as a noun or a verb, but the prime word was either a determiner or a pronoun. Determiners are generally followed by nouns, and pronouns by verbs – and conversely, a determiner followed by a verb or a pronoun followed by a noun are ungrammatical

constructions in French. Thus, the presence of a determiner should induce a strong and possibly unconscious grammatical expectation for a noun, and a pronoun should lead participants to expect a verb. We therefore expected that the grammatical pairings (det-noun and pronoun-verb) would cause priming relative to the ungrammatical pairings.

This design also allowed us to address another issue. In experiments 1 and 2, participants were actively engaged in a grammatical categorization task on target words. Thus, the category priming that we observed could be due to a subliminal accumulation of evidence towards one of the two imposed response categories. The results undoubtedly imply that subliminal words provided unconscious evidence towards the noun and verb categories, but we cannot exclude that this categorization was, at least in part, induced by the task itself which, as proposed in Figure 1, may rely on an accumulation of all available sources of evidence. In other words, experiments 1 and 2 do not necessarily imply that the noun and verb categories are automatically and unconsciously extracted whenever a word is processed, only that they *can* be extracted when required (for a similar discussion, see e.g. Dehaene, Naccache, et al., 1998; Greenwald et al., 2003b). However, if we observed priming by determiners and pronouns in experiment 3, even though the target categories are noun versus verb, it would strongly suggest that at least part of the observed priming effect is due to an automatic categorization of the primes even when their category is irrelevant for the task.

## **Material and methods**

### ***Participants***

Twenty-two right-handed native French speakers (6 males; mean age 24 year; range 19-30 year) were tested. Six participants were excluded: three had an error rate of more than 10%, two had a mean reaction time of over 800 ms and one did not respect instructions.

### ***Stimuli***

Primes were either a singular masculine determiner “un” (“a”) or “le” (“the”), or a masculine 3<sup>rd</sup> person singular personal pronoun “on” (“one”) or “il” (“he”). As in the first two experiments, we created pairs of noun and verb similar in orthography, length, frequency and ending, for instance “rôle” (“role”) and “rôle” (“prowls”). We identified thirty French countable masculine nouns and thirty verbs conjugated in the 3<sup>rd</sup> person singular present tense, paired so that they were similar in orthography, ending, number of letters (mean 6.6; range 4-

9), and frequency in French on average (mean 15.6 per million; range 1.29-392). We excluded all words that were homophones or homographs of words from other grammatical categories, words with a strong emotional valence, and nouns derived from verbs, for example “blocage” (“blocking”) derived from “bloquer” (“to block”). We also excluded direct transitive verbs. Also note that the primes formed pairs (“il/le” and “on/un”) that were similar in orthography, number of letters, and frequency (mean 11887.4 per million, range 8586-13653).

Participants all saw the same 60 target words (30 nouns and 30 verbs), but half of the participants had “le” (“the”) and “il” (“he”) as unmasked primes and “un” (“a”) and “on” (pronoun “one”) as masked primes, while the other half had the reverse assignment. Primes and targets could form a noun phrase, for instance “le sport” (“the sport”), a verb phrase, for instance “il dort” (“he sleeps”), or an ungrammatical pairing such as “il sport” (“he sport”) or “le dort” (“the sleeps”). Since direct transitive verbs were excluded, the pronoun-verb pairing was ungrammatical even when considered as part of a larger sentence (with a direct transitive verb such as “manger” (“eat”), phrases such as “il le mange” would be grammatical).

We excluded target words starting with a vowel, because in this case the determiner “le” would have had to be elided to “l’”. We also excluded mass nouns, for example “pétrole” (“fuel”), because they cannot be utilized with the indefinite determiner “un”; and impersonal verbs (for example “rain”) which could not be conjugated with the pronoun “on” in French.

### ***Procedure***

Task, stimulus presentation, timing and procedure were exactly as in experiment 2 (see Figure 5).

During the forced-choice test (visibility task), participants were asked to guess whether the word presented before the target was a determiner or a pronoun. They were informed that the target grammatical category was incongruent with the prime grammatical category 50% of the time. Each trial comprised the same sequence of masks and stimuli as in the experiment but the target stayed on screen for 500 ms. In addition, just after the target, the words “PRONOM (il, on)” and “DETERMINANT (le, un)” were randomly presented left and right of fixation. Participants responded by pressing the button on the side of the response they selected. The two alternatives remained on screen until a response was made.

In the final repetition-priming block, noun and verb targets were replaced by the four words "il", "le", "un" and "on". The participant's task was to classify them into "determiner" versus "pronoun" categories (randomly assigned to right versus left buttons, counterbalanced across participants).

Each participant first performed the main task, including a training block of 60 trials and 8 blocks of 60 trials (with all possible pairings of primes and targets presented twice), then two blocks of the forced-choice test (60 trials each).

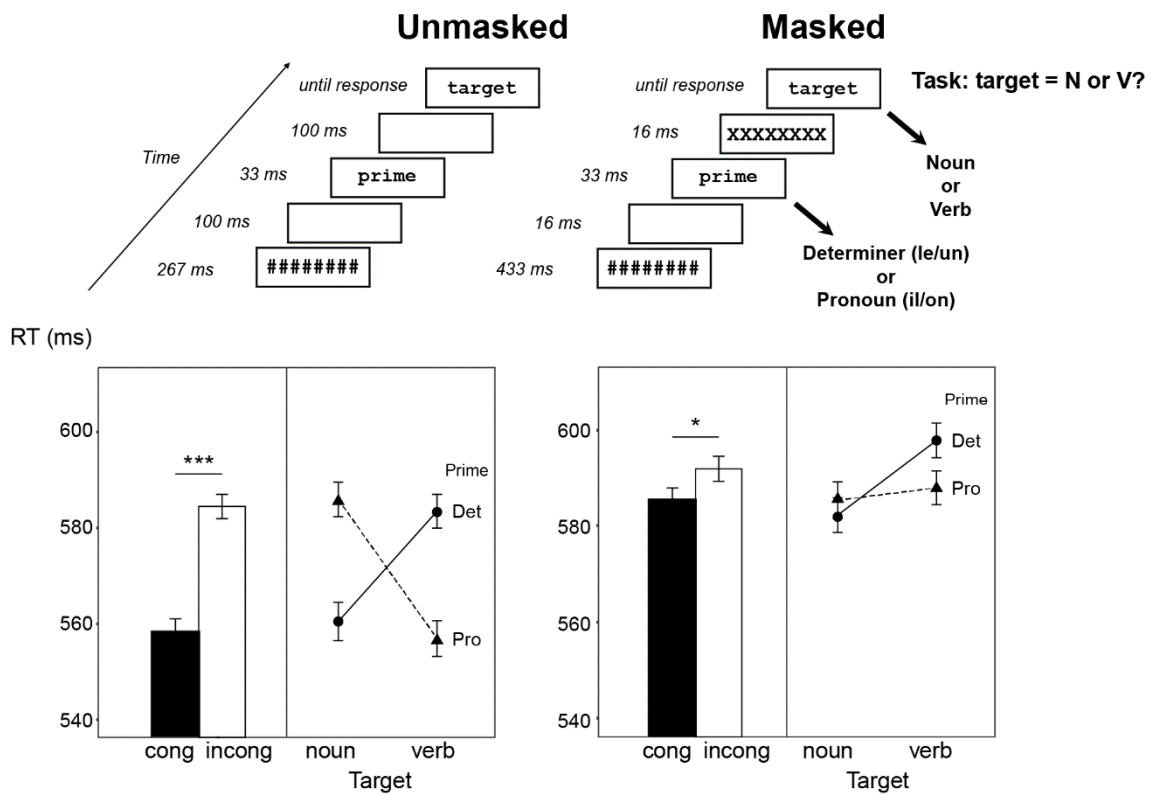


Figure 5. Procedure and results of experiment 3. Participants classified target words as nouns or verbs, each of which was preceded by a masked or unmasked determiner or pronoun prime. At the bottom, barplots show reaction times for congruent (black bars) and incongruent (white bars) trials, lineplots show reaction times as a function of prime category (Det = determiner, solid line; Pro = pronoun, dashed line) and target category. Error bars represent one SEM. \*\*\* =  $p < 0.001$ ; \* =  $p < 0.05$ .

## Results

### *Behavioral priming in response times*

Overall error rate was 5% (range 2-10%). We performed an analysis of variance (ANOVA) on median correct RTs during the grammatical categorization task, with the same exclusion criteria as above, and factors of visibility (masked/unmasked), target category (noun/verb), and prime category (determiner/pronoun). This revealed a main effect of visibility (masked vs. unmasked;  $F_{1,15} = 25.11$ ,  $p < 0.001$ ): responses were 17 ms faster overall in the unmasked condition (572 ms versus 589 ms). There was no main effect of the category of the target ( $F_{1,15} = 0.42$ ,  $p = 0.53$ ) and of the prime ( $F_{1,15} = 0.66$ ,  $p = 0.43$ ). Crucially, a target category  $\times$  prime category interaction revealed a syntactic priming effect (grammatical pairing: 572 ms; ungrammatical pairing: 588 ms, difference: 16 ms,  $F_{1,15} = 37.13$ ,  $p < 0.001$ ). A triple interaction with visibility ( $F_{1,15} = 12.59$ ,  $p = 0.003$ ) indicated greater priming in the unmasked compared to the masked condition. Strong syntactic priming was found in the unmasked condition (559 ms versus 585 ms, difference: 26 ms,  $F_{1,15} = 36.05$ ,  $p < 0.001$ ).

Under masked condition, the effect was reduced and did not reach classical two-tailed significance. However, the direction of the effect could be predicted, either from data from the unmasked trials in the present experiment, from data from previous experiments in the present paper, or from past research: primes that bias subjects towards a certain decision facilitate subsequent response times for that decision, and this phenomenon, which is highly replicable (as reviewed e.g. by (Kouider & Dehaene, 2007)), is predicted by models of decision-making as evidence accumulation (e.g. Vorberg et al., 2003).

Here, therefore, grammatical pairings were predicted to be processed faster than ungrammatical pairings. One-tailed tests supported this prediction: masked syntactic priming was significant in a one-tailed test (585 ms versus 592 ms; 7 ms in the predicted direction,  $F_{1,15} = 3.99$ , one-tailed  $p = 0.032$ ) (see Figure 5). The size of the syntactic priming effect was similar to the category priming in experiment 2, under both masked and unmasked conditions (unmasked: 26 ms vs. 18 ms, Welch  $t_{32,3} = -1.24$ ,  $p = 0.23$ ; masked: 7 ms vs. 7 ms; Welch  $t_{31,3} = 0.038$ ,  $p = 0.97$ ).

### ***Prime visibility***

Measures of  $d'$  values for each participant confirmed that they failed to consciously perceive the category of the primes in the masked condition (52,1% correct,  $d' = 0.12$ ,  $t_{15} = 1.83$ ,  $p = 0.087$ ), whereas they could do so in the unmasked condition (96,6% correct,  $d' = 3.4$ ,  $t_{15} = 31.95$ ,  $p < 0.001$ ). There was no significant correlation between the size of the priming effect and prime visibility in the masked condition ( $t_{14} = 1.27$ ,  $p = 0.23$ ), but the intercept failed to reach significance (3.5 ms,  $t_{14} = 0.83$ ,  $p = 0.42$ ).

### **Discussion**

Our third experiment explored syntactic priming, defined as the ability for a word to prime a target word belonging to the grammatical category that should normally follow it in a grammatical sentence. We obtain a significant syntactic priming under unmasked and masked conditions (respectively of 26 ms and 7 ms). Given the controls we imposed on the stimuli, these priming effects cannot be attributed to other factors such as orthographic, phonological, semantic, or morphological priming. Automatized stimulus-response mapping is also excluded, because neither the masked nor the unmasked primes were ever used as targets. Because few masked primes were used, a subliminal action-trigger hypothesis could be invoked (Kunde et al., 2003), but this possibility was excluded by our experimental design: masked primes were never used as targets, had never been consciously perceived nor categorized during the experiment, and did not even share the same grammatical category as the targets. Therefore, unlike in experiments 1 and 2, priming could no longer be caused by a repetition of the target categories. Finally, on masked trials, participants were unable to consciously perceive the primes and were at chance in discriminating their grammatical category.

We therefore conclude that an irrelevant word can prime the syntactic categorization of a subsequent noun or verb, when those two words form a grammatical constituent. This effect, which we term “syntactic priming”, was very strong for unmasked primes, and was marginal but significant in the predicted direction for masked primes. Furthermore, it was similar in size to the grammatical category priming observed in experiments 1 and 2, suggesting that categorical and syntactic priming are of comparable size.

Interestingly, a similar coexistence of categorical and predictive priming was also observed for movements: two photographs of movement were subsequently presented and

yielded subliminal priming when they depicted two similar movements or when reflecting the natural movement order (Güldenpenning, Koester, Kunde, Weigelt, & Schack, 2011; Güldenpenning, Kunde, Weigelt, & Schack, 2012).

Regarding the framework we proposed, these results support the existence of a third influence on syntactic categorization: beyond word ending cues and syntactic category repetition, the syntactic context formed by the preceding words indeed exerted a strong influence on the retrieval of the syntactic features of the target word. Before discussing this finding further, we replicate and extend it.

## **Experiment 4**

The syntactic priming observed in experiment 3 is compatible with the hypothesis that abstract syntactic rules such as “a determiner precedes a noun phrase” are applied unconsciously. However, an alternative explanation based on transition probabilities cannot be excluded. According to this interpretation, priming would result merely from the fact that grammatical combinations of words are more frequent than ungrammatical ones in natural language, and that adults and even infants are sensitive to such transition probabilities (Thompson et al., 2007). Thus, the difference in RTs between grammatical and ungrammatical pairs might only reflect a difference in transitional probability (do note, however, that this interpretation cannot explain the results of experiments 1 and 2, where all pairs were ungrammatical).

To address this problem, and to further expand our studies of syntactic priming, we designed another experiment in which two syntactic features were orthogonally contrasted: grammatical category and grammatical number (singular or plural). With this new design, we could investigate the distinct contributions of two forms of grammatical agreement: the syntactic relationship between prime category and target category (e.g. determiner noun) and their agreement in number (e.g. singular followed by singular). Because these factors were orthogonally manipulated, there were prime-target pairs that violated syntactic category relationships but agreed in grammatical number, such as “il reptile” (roughly translated as “he reptile”), and pairs that fitted in terms of categories but violated number agreement, such as “des reptile” (“some reptile”). This feature of the design allowed us to study the presence of two orthogonal priming effects (by syntactic category and by number), as well as their presence even in ungrammatical prime-target word pairs. If, as argued by many syntactic theories (as

reviewed e.g. by Sportiche et al., 2013), grammatical number is a stand-alone feature shared by many word categories, then one might expect priming whenever this feature is shared between two words, even these words do not form a grammatical phrase. Crucially, such feature-based priming would not be explainable by transition probabilities, because such probabilities are very close to zero for ungrammatical word pairs.

## **Material and methods**

### *Participants*

Twenty-seven right-handed native French speakers (12 males; mean age 23.7 year; range 19-31 year) were tested. Three participants were excluded: one had an error rate exceeding 10%, one had a mean reaction time of over 800 ms, and one had a reaction time variance of 300 ms.

### *Stimuli*

Prime words were either a determiner, singular “un” (“a”) or plural “des” (“some”), or a 3<sup>rd</sup> person personal pronoun, singular “on” (pronoun “one”) or plural “ils” (“they”). Target words were almost identical to experiment 3. Some stimuli were changed because we excluded words starting by the letter “d” to avoid orthographic priming by “des”, verbs that were homographs or near-homographs of other words in their plural forms (for instance the verb “persiste” was excluded because it is written “persistent” in the present plural, which looks like the adjective “persistant” in French); and nouns or singular verbs that ended in “ent” (for instance “sergent” or “provient”) because they could be confounded with plural verbs.

There were 120 targets in total: 30 French regular countable masculine nouns, either singular or plural, and 30 verbs conjugated in the 3<sup>rd</sup> person present, either singular or plural. Thus, these targets formed 30 quadruplets of 4 words, for instance “cortège” (“procession”), “cortèges” (“processions”), “coopère” (“cooperates”) and “coopèrent” (“cooperate”). These words were matched in orthography, ending, number of letters (mean 7.5; range 5-12), and frequency in French (mean 14.1 per million; range 1.31-252). We again excluded words homophones or homographs of words from other grammatical categories, words with a strong emotional valence, and nouns derived from verbs. Primes also formed couples (“on/un” and “ils/des”) that were similar in orthography, number of letters, and frequency (mean 7451.2 per million, range 3075-12088).



Participants all saw all combinations of the 120 target words (30 singular and 30 plural nouns and 30 singular and 30 plural verbs) and the 4 prime words. These combinations could be congruent for syntax and number (e.g. “un reptile”), congruent for syntax but not for number (“des reptile”), incongruent for syntax but congruent for number (“on reptile”) or incongruent for syntax and number (“ils reptile”). Note that all of these trial types were equally frequent and were, on average, composed of exactly the same prime words and target words. Only one of them was grammatical.

### ***Procedure***

Task, stimulus presentation and procedure were almost identical to experiment 3 (see Figure 6). To avoid any contamination by stimulus-response automatization, participants first performed the noun-verb categorization task with masked trials only, then the visibility task, and finally the task with unmasked trials only.

Each participant first performed a training block of 60 masked trials, then 5 blocks of 96 masked trials, 2 blocks of forced-choice task (64 trials each), and finally 5 blocks of 96 unmasked trials.

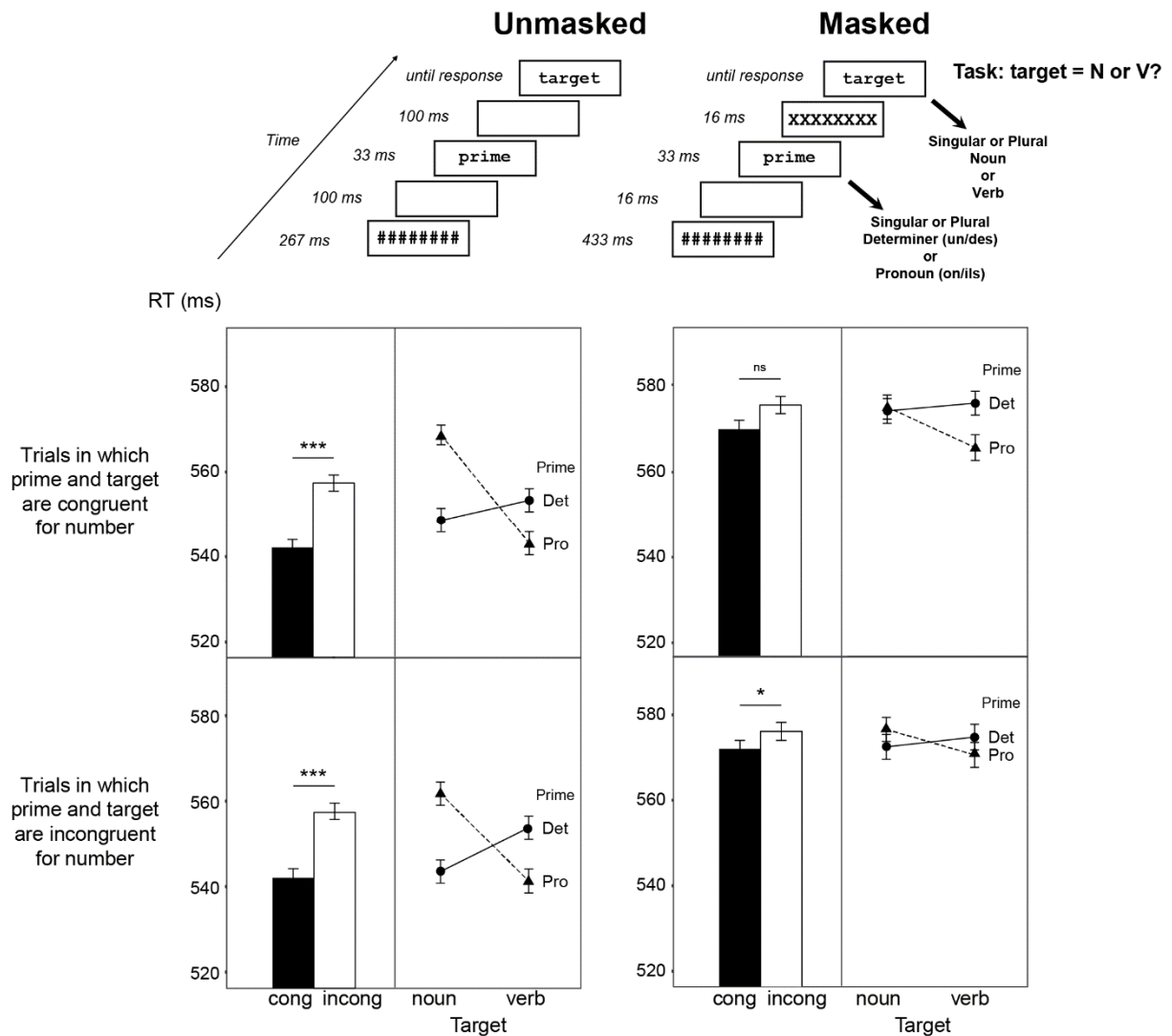


Figure 6. Procedure and results of experiment 4. Participants classified target words as nouns or verbs, each of which was preceded by a masked or unmasked determiner or pronoun prime. Same format as Figure 5. Error bars represent one *SEM*. \*\*\* =  $p < 0.001$ ; \* =  $p < 0.05$ .

## Results

### *Behavioral priming in response times*

Overall error rate was 6% (range 3-10%). An analysis of variance (ANOVA) on median correct RTs, with usual exclusion criteria, with factors of visibility (masked/unmasked), target category (noun/verb), prime category (determiner/pronoun), target number (singular/plural), prime number (singular/plural), revealed a main effect of visibility (masked vs. unmasked;  $F_{1,23} = 27.44$ ,  $p < 0.001$ ): responses were 22 ms faster overall in the unmasked condition (551 ms versus 573 ms). There was no main effect of the category of the prime ( $F_{1,23} = 0.71$ ,  $p = 0.41$ ),

the category of the target ( $F_{1,23} = 1.14$ ,  $p = 0.30$ ), the number of the prime ( $F_{1,23} = 0.11$ ,  $p = 0.74$ ), but there was a significant effect of the number of the target ( $F_{1,23} = 174$ ,  $p < 0.001$ ).

Crucially, we observed an interaction of prime category and target category, indicating a significant syntactic priming effect (grammatical pairings: 557 ms, ungrammatical pairings: 567 ms, difference: 10 ms,  $F_{1,23} = 20.7$ ,  $p < 0.001$ ). An interaction with visibility ( $F_{1,23} = 11.57$ ,  $p = 0.003$ ) indicating greater priming in the unmasked compared with the masked condition. Nevertheless, syntactic priming was found in the unmasked condition (544 ms versus 559 ms, difference: 15 ms,  $F_{1,23} = 22.36$ ,  $p < 0.001$ ) as well as in the masked condition (571 ms versus 576 ms, difference: 5 ms,  $F_{1,23} = 5.94$ ,  $p = 0.023$ ).

Interactions with number congruity were not significant, indicating that the size of the syntactic priming effect was not significantly modulated by congruity in grammatical number (all  $F_{1,23} < 0.2$ , all  $p > 0.7$ ). Unmasked priming was present when number was congruent (545 ms versus 560 ms, difference: 15 ms,  $F_{1,23} = 16.53$ ,  $p < 0.001$ ) and when it was incongruent (542 ms versus 557 ms, difference: 15 ms,  $F_{1,23} = 20.70$ ,  $p < 0.001$ ). Masked priming was small but nevertheless present in the predicted direction when number was incongruent (572 ms versus 576 ms, difference: 4 ms,  $F_{1,23} = 3.03$ , one-tailed  $p = 0.048$ ) but did not reach significance when number was congruent (570 ms versus 576 ms, difference: 6 ms,  $F_{1,23} = 2.69$ ,  $p = 0.11$ ) (see Figure 6).

While we thus found a clear effect of the task-relevant variable (grammatical category), the task-irrelevant variable of number did not yield any significant effects. The main interaction of prime number  $\times$  target number, indexing number congruity, was not significant ( $F_{1,23} = 0.516$ ,  $p = 0.48$ ) and the effect did not reach significance either under unmasked or under masked conditions (all  $F_{1,23} < 3$ , all  $p > 0.1$ , differences  $\leq 3$  ms). As mentioned above, the interaction with syntactic priming was not significant, and number priming failed to reach significance both when the grammatical categories were congruent (determiner-noun or pronoun-verb;  $F_{1,23} = 0.121$ ,  $p = 0.73$ ) and when they were incongruent (determiner-verb or pronoun-noun;  $F_{1,23} = 0.510$ ,  $p = 0.48$ ).

### *Prime visibility*

Examination of  $d'$  values suggested that participants were very slightly but significantly able to classify the four primes in the masked condition (54.0% correct,  $d' = 0.215$ ,  $t_{23} = 2.38$ ,

$p = 0.025$ ), and performed at near-ceiling level in the unmasked condition (99.1% correct,  $d' = 3.956$ ,  $t_{23} = 115.94$ ,  $p < 0.001$ ). Furthermore, the Greenwald (Greenwald et al., 1996) analysis revealed no significant correlation between the priming effect and the prime visibility in the masked condition ( $t_{22} = 1.19$ ,  $p = 0.25$ ), but also no significant intercept (1.45 ms,  $t_{22} = 0.60$ ,  $p = 0.56$ ). The fact that, in this part of the experiment, all prime words appeared under both masked and unmasked conditions could have enhanced visibility or induce automatized stimulus-response mapping relative to other experiments. However, only four participants had a  $d'$  significantly larger than zero in the masked condition. Once these participants were excluded, performance in the visibility task dropped to chance level (51.25% correct,  $d' = 0.068$ ,  $t_{19} = 0.96$ ,  $p = 0.35$ ), but a significant masked syntactic priming was still observed ( $F_{1,19} = 5.15$ ,  $p = 0.035$ ).

## Discussion

In experiment 4, we confirmed that a determiner or pronoun can exert a significant syntactic priming on a subsequent noun or verb. The effect was clear under unmasked conditions (with an effect size of 15 ms), which is not trivial given that the prime was entirely irrelevant and presented for a short duration and SOA. The evidence for masked priming was much smaller (effect size of 5 ms) but still significant, including in the critical condition where the prime and target differed in number. Those results fully replicate those of experiment 3, with a similar size. Furthermore, they extend them in one crucial direction: priming effects remained significant when primes and targets failed to agree in number, again under both unmasked and masked condition (with effect sizes of 15 ms and 4 ms respectively). Examples of this critical condition include “on coopèrent” (“one cooperate”), “ils coopèrent” (“they cooperates”), “un cortège” (“a processions”) and “des cortège” (“some procession”), all of which are strongly ungrammatical in French. The fact that syntactic priming remains unchanged in the presence of such grammatical violations indicates that the priming cannot be solely attributed to transitional probabilities, and must reflect genuine processing of grammatical categories.

Under masked condition, the syntactic priming effect failed to reach significance when number was congruent, but one may assume that this was due to a lack of power when analyzing half of the experiment, given that significant syntactic priming was observed on masked trials in experiment 3 (where number was congruent), and on unmasked trials in experiment 4. It is conceivable that the syntactic priming effect would be reduced on number-congruent trials, due

to an interference between the two priming effects, but the fact that the interaction between the two priming effects was non-significant only allows us to conclude that the category priming was no different on number-congruent and number-incongruent trials.

More importantly, we did not find any priming effect based on the congruity in grammatical number between the prime and the target, neither under unmasked nor masked condition. It is remarkable that participants were no faster on grammatically correct trials, where the prime and target agreed in number, than on ungrammatical trials where such agreement was violated. Experiment 4 leaves open two alternative interpretations of this negative result. First, the feature of grammatical number may not be able to induce any detectable priming. This hypothesis is compatible with some previous studies of language production. Using picture-word interference, it was shown that number congruency between a picture and distractors words had no effect on naming (Schiller et al., 2002) while such an effect was previously demonstrated for semantic, phonology and gender congruency (Schiller et al., 2003; Schriefers, 1993; Schriefers et al., 1990). Alternatively, its absence could be due to the fact that number was irrelevant to the task, which required classifying targets as nouns or verbs without paying any attention to their singular/plural status. Indeed, task-induced attention is known to massively affect neuronal tuning in sensory and cognitive areas (Çukur et al., 2013), and masked priming is known to be influenced by top-down effects of task instructions (Ansorge et al., 2013; Dagenbach et al., 1989; Eckstein et al., 2007; Nakamura et al., 2007) and attention (Naccache et al., 2002b).

To separate those two alternatives, we performed an additional experiment (experiment 5) where we kept the stimuli unchanged but made the number dimension relevant to the task.

## **Experiment 5**

Experiment 5 was strictly identical to experiment 4, except that participants were asked to perform a number categorization task, i.e. to determine whether the target words were singular or plural. If grammatical number cannot be subliminally processed, then there should be no number priming effect. If, however, task-irrelevance was responsible for its absence in experiment 4, then by asking participants to focus on number, we should now observe a number-based priming effect in experiment 5. The latter explanation also predicts that syntactic category-based priming should be reduced or even disappear, since grammatical category (determiner versus pronoun, and noun versus verb) was now made irrelevant.

Because grammatical congruity and number congruity were orthogonally manipulated, we could also explore whether number would induce priming on trials in which syntax was incorrect. In agreement with considerable research in cognitive linguistics (Sportiche et al., 2013), the model presented in Figure 1 hypothesizes that syntactic word processing culminates in a representation of words as a list of grammatical features. If grammatical number is such a free-floating syntactic feature, shared between all of the categories of words used here (determiners, pronouns, nouns and verbs), then we would predict that priming based on grammatical number should be observed in all conditions, irrespective of grammatical category or even of the grammaticality of the word pair.

## **Material and methods**

### ***Participants***

Twenty-four right-handed native French speakers (10 males; mean age 23.6 year; range 18-30 year) were tested. No participant was excluded.

### ***Stimuli and Procedure***

Stimuli and procedure were identical to experiment 4. Only the task was changed: participants were asked to determine as quickly as possible the grammatical number of the target word (singular or plural), with the usual bimanual response (see Figure 7). Also, to better evaluate prime visibility and avoid automatized stimulus-response mapping, the visibility task was split in two blocks. The visibility task on masked stimuli was performed just after the masked block of the main task, and the visibility task on unmasked stimuli was performed at the end of the experiment, after the unmasked block of the main task. During this task, after the prime and target presentation, the words “PLURIEL (ils, des)” and “SINGULIER (un, on)” appeared randomly right and left of fixation, and participants selected one of these two responses.

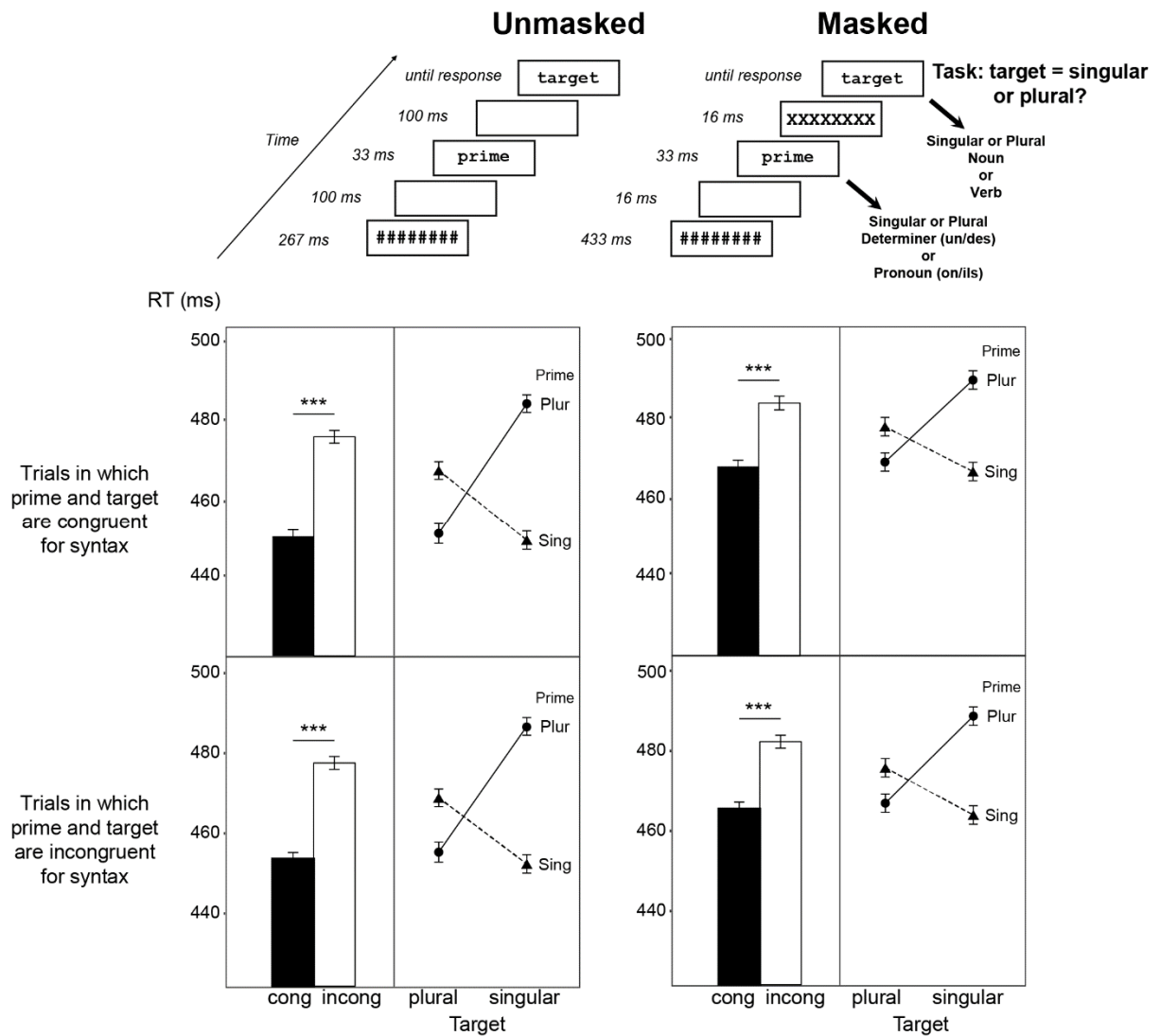


Figure 7. Procedure and results of experiment 5. Participants classified target words as singular or plural, each of which was preceded by a masked or unmasked singular or plural prime. At the bottom, barplots show reaction times for congruent (black bars) and incongruent (white bars) trials, lineplots show reaction times as a function of prime number (Plur = plural, solid line; Sing = singular, dashed line) and target number. Error bars represent one SEM. \*\*\* =  $p < 0.001$ ; \* =  $p < 0.05$ .

## Results

### *Behavioral priming in response times*

Overall error rate was 6% (range 2-10%). An analysis of variance (ANOVA) median correct RTs, with usual exclusion criteria, during the number categorization task revealed a main effect of presentation type (masked vs. unmasked;  $F_{1,23} = 7.11$ ,  $p = 0.011$ ): responses were 10 ms faster overall in the unmasked condition (465 ms versus 475 ms). There was no main

effect of the category of the prime ( $F_{1,23} = 0.02$ ,  $p = 0.88$ ), the category of the target ( $F_{1,23} = 0.18$ ,  $p = 0.67$ ), the number of the target ( $F_{1,23} = 1.59$ ,  $p = 0.22$ ), but there was a significant effect of the number of the prime ( $F_{1,23} = 41.6$ ,  $p < 0.001$ ).

A prime number  $\times$  target number interaction revealed a main effect of number priming (congruent 460 ms versus incongruent 480 ms, difference: 20 ms,  $F_{1,23} = 139.7$ ,  $p < 0.001$ ). A triple interaction with visibility ( $F_{1,23} = 6.56$ ,  $p = 0.018$ ) indicated greater priming in the unmasked compared with the masked condition. Indeed, a strong number priming effect was found in the unmasked condition (452 ms versus 477 ms, difference: 25 ms,  $F_{1,23} = 114.7$ ,  $p < 0.001$ ). This effect was present whether the prime-target categories were grammatical (determiner-noun or pronoun-verb; 25 ms effect;  $F_{1,23} = 120.2$ ,  $p < 0.001$ ) or ungrammatical (determiner-verb or pronoun-noun; 24 ms effect;  $F_{1,23} = 49.79$ ,  $p < 0.001$ ).

Crucially, number priming was also found under masked condition (467 ms versus 484 ms, difference: 17 ms,  $F_{1,23} = 45.30$ ,  $p < 0.001$ ). This effect was present on grammatical (16 ms effect;  $F_{1,23} = 19.78$ ,  $p < 0.001$ ) and ungrammatical trials (16 ms effect;  $F_{1,23} = 36.04$ ,  $p < 0.001$ ) (see Figure 7). There was no interaction, indicating that the size of the number priming effect was not significantly affected by the congruity in grammatical categories (unmasked trials:  $F_{1,23} = 0.11$ ,  $p = 0.75$ ; masked trials:  $F_{1,23} = 0.05$ ,  $p = 0.83$ ).

Importantly, although the stimuli were identical to experiment 4, we now failed to observe any syntactic priming based on grammatical category in any conditions of experiment 5: the prime category  $\times$  target category interaction was not significant globally ( $F_{1,23} = 0.13$ ,  $p = 0.72$ ), neither on masked (-3 ms effect size;  $F_{1,23} = 2.72$ ,  $p = 0.11$ ) nor on unmasked trials (-2 ms effect size;  $F_{1,23} = 2.02$ ,  $p = 0.17$ ). A direction comparison indicated that the size of the number priming effect was significantly larger in experiment 5 compared to experiment 4 (unmasked: 25 vs. -3 ms, Welch  $t_{45.19} = 9.08$ ,  $p < 0.001$ ; masked: 17 vs. 1 ms; Welch  $t_{41.49} = 5.14$ ,  $p < 0.001$ ), while the reverse was true for the syntactic priming effect (unmasked: -3 vs. 15 ms, Welch  $t_{31.06} = -3.80$ ,  $p < 0.001$ ; masked: -3 vs. 5 ms; Welch  $t_{44.77} = -2.93$ ,  $p = 0.005$ ). Finally, number priming in experiment 5 was stronger than syntactic priming in experiment 4 in the unmasked condition (Welch  $t_{41.62} = 2.38$ ,  $p = 0.022$ ) and the masked condition (Welch  $t_{44.39} = 3.64$ ,  $p < 0.001$ ).



### ***Orthographic contribution to number priming***

In French, plural is marked by the morpheme “-s” for nouns, determiners, and pronouns. Only for verbs is a different morpheme used, i.e. “-ent” in the 3<sup>rd</sup> person plural present as used here. Thus, part of the number-priming effect could conceivably arise from the repetition of the terminal letter “s” from prime to target, i.e. an orthographic rather than a grammatical priming effect. However, if orthography was the main source of this effect, then priming should be reduced for verbs relative to nouns, since plural verbs do not end in “-s”. Crucially, under masked condition, we did not find any difference in the size of the number priming effect for verb versus noun targets ( $t_{23} = 1.13$ ,  $p = 0.27$ ): the number priming effect was 18 ms for noun targets and 15 ms for verb targets, and both effects were significant (noun:  $F_{1,23} = 36.98$ ,  $p < 0.001$ ; verb:  $F_{1,23} = 26.46$ ,  $p < 0.001$ ). Therefore, the observed number priming effect could not be explained by orthographic priming.

### ***Prime visibility***

Measures of  $d'$  values indicated that participants were unable to consciously categorize the primes in the masked condition (51.3% correct,  $d' = 0.07$ ,  $t_{23} = 0.94$ ,  $p = 0.36$ ), whereas they could do so in the unmasked condition (97.3% correct,  $d' = 3.69$ ,  $t_{23} = 38.53$ ,  $p < 0.001$ ). There was no significant correlation between the priming effect and the prime visibility on masked trials ( $t_{22} = 0.74$ ,  $p = 0.47$ ), and the intercept of this regression was significant: 16.2 ms,  $t_{22} = 6.12$ ,  $p < 0.001$ ).

### **Discussion**

Experiment 5 demonstrated that prime-target congruity in grammatical number could induce a strong priming effect under both unmasked and masked conditions (25 ms and 17 ms respectively), provided that the task required participants to focus on this grammatical dimension. For instance, the noun “reptile” was categorized faster as singular when preceded by the singular determiner “un”, and even by the singular pronoun “on”, than by the plural determiner “des” or the plural pronoun “ils”.

The emergence of a strong effect of grammatical number was accompanied by the disappearance of any category-based syntactic priming effect, under both unmasked and masked condition. For instance, there was no longer any significant RT difference between the grammatically correct “des reptiles” (“some reptiles”) and the grammatically incorrect “ils

reptiles” (“they reptile”). Thus, task demands radically altered the pattern of grammatical priming, as confirmed by direct statistical comparisons of experiments 4 and 5. This aspect of our findings agrees with previous findings by Ansorge et al. (2013) for grammatical gender (feminine/masculine) in German. Gender agreement triggered a behavioral priming effect between a determiner and a noun when the task required determining the gender of the target. However, such gender priming disappeared when participants performed a task unrelated to gender.

The absence of a behavioral priming effect need not indicate that lexico-syntactic representations were not activated, only that this activation did not propagate all the way to the decision system. Indeed, a study using electroencephalography recordings during a naming task showed that incongruity between the picture and a classifier (a syntactic feature comparable to grammatical gender) elicited a N400 component without affecting naming latencies (Wang et al., 2018). Indirect evidence of such an activation is provided by experiments using German or Dutch, where gender governs the selection of a determiner: in this case, gender congruency had a significant influence on behavior when the task was to choose the appropriate determiner (Schiller & Caramazza, 2003).

Another important aspect of our results is that grammatical number caused priming even between words that did not constitute a well-formed grammatical phrase (as also reported by Ansorge et al., 2013 for grammatical gender). Thus, a plural determiner primed a plural verb, and a plural pronoun primed a plural noun, even though these word combinations are ungrammatical in French. Those findings support the hypothesis that, during reading, syntactic features such as singular or plural are quickly extracted and encoded independently from each other. The presence of priming indicates that the feature of “plurality” is encoded in a format which is similar for the four categories of words tested here. This is remarkable given that this feature is realized orthographically in a very different manner, namely the addition of a terminal “s” on nouns and pronouns; a lexical change (e.g. “un” versus “des”) for determiners; and the addition of a morpheme “-ent” for verbs. The observed priming must have occurred at a level of representation abstract enough to be shared by all these words, in spite of their superficial differences. Moreover, in French, the pronoun “on” is grammatically singular but it is mostly used in informal language in place of “we”, and therefore semantically refers to plural. This argument suggests that number priming in this experiment could not be imputed to the semantic aspects of plural.

Overall, our results strongly argue in favor of a level of syntax processing in the brain that encodes abstract syntactic features such as “singular”, “plural”, and probably also “feminine”, “masculine”, etc. (Ansorge et al., 2013). Still, it was previously suggested that conceptual number (i.e. unique versus multiple) influences grammatical number processing (Nickels et al., 2015). As mentioned above, activations of such representations are not excluded by the absence of behavioral effects (Wang et al., 2018) and deserve further exploration.

## **General discussion**

Across five experiments, we repeatedly observed that the repetition of a syntactic feature from a prime word to a target word could induce both conscious and subliminal priming; and we used this phenomenon to probe our hypothetical framework for the extraction of syntactic features from written words (Figure 1). We studied four different types of priming: grammatical category priming, priming by pseudo-morphological ending, syntactic priming, and number priming. In experiments 1 and 2, we demonstrated that a prime belonging to a given grammatical category could accelerate the processing of a target belonging to the same grammatical category (grammatical category priming). Word ending was a strong cue to grammatical category and was also able to induce priming, at least for fast responses (for instance, after a prime with an ending typical of French verbs, responses were given faster to a verb target than to a noun target). In experiments 3 and 4, we then showed that a prime word belonging to a given grammatical category (e.g. determiner) could prime a target word belonging to a distinct but grammatically appropriate category (e.g. noun). We showed that this syntactic priming effect involves more than mere transitional probabilities (Thompson et al., 2007), because determiners prime nouns and pronouns prime conjugated verbs even when the words are incongruent for grammatical number, and therefore their transition probability is close to zero. Finally, in experiment 5, we observed that a word could prime another word simply by sharing the same grammatical number (singular or plural), even if the prime-target pair was ungrammatical. This number-priming effect was only observed, however, when the task was a number categorization task (experiment 5) but was absent when it was a grammatical categorization task (experiment 4). Conversely, syntactic priming was only present when the task was a grammatical categorization task (experiment 4) and vanished when it was a number categorization task (experiment 5).

Our study extends previous results which demonstrated that semantic, orthographic, phonological, and morphological features of words can be subliminally processed (Dehaene et al., 1998; Gaillard et al., 2006; Giraud & Grainger, 2001; Kouider et al., 2007; Naccache et al., 2005; Van den Bussche & Reynvoet, 2007; van Gaal et al., 2014; Yeh et al., 2012). It confirms that the repetition of syntactic features such as grammatical category and number can induce priming, as previously proposed for gender (Ansorge et al., 2013), verbal inflection patterns (Deutsch et al., 1998), and verb transitivity (Iijima et al., 2014).

Crucially, our results prove that a single word may induce different types of priming: we observed syntactic category priming when participants classified the targets as nouns versus verbs, and number priming when they classified them as singular versus plural. This finding supports linguistic theories which postulate that each word is associated with a set of syntactic features (category, number, etc.) (Sportiche et al., 2013), each of which may be shared with other words. Linguists denote this level of representation using binary features (e.g. +singular; +noun; etc.). Our experiments can be construed as a demonstration of the psychological reality of this abstract linguistic construct. They suggest that this level exists and can quickly be accessed from a written word, with or even without consciousness.

Our experiments were designed, not only to probe the validity of the construct of syntactic features, but also to test a model of the cognitive architecture by which they are extracted from written words (Figure 1). We proposed that this architecture is organized into two distinct pathways, each organized to exploit a distinct source of information about syntactic features. On the one hand, a fast pseudo-morphological route examines word endings for the presence of known grammatical morphemes that index syntactic features such singular vs plural, word categories, verb tense, etc. (e.g. French words ending with “-er” tend to be verbs; those ending in “s” are likely to be plural; etc). On the other hand, a syntactic lexicon indexes the genuine syntactic status of each word (e.g; “boulangier” is actually a noun; “bus” is actually singular; etc).

The results of experiments 1 and 2 confirmed the existence of those two pathways toward syntactic category, because we found two distinct and orthogonal priming effects arising respectively from pseudo-morphological information and from lexical information. Those effects occurred under both conscious and unconscious conditions. Our results therefore suggest that both routes can be activated unconsciously and in parallel. Furthermore, analyses of the impact of SOA and of the difference between short and long RTs suggested that the

lexical route may operate at a slower pace, yet with a strength ultimately capable of overriding the initial hunch provided by the pseudo-morphological route.

As also suggested by previous experiments (Rastle et al., 2004), we thus propose that each incoming word is submitted to a rapid but shallow analysis which decomposes it into tentative morphemes (e.g. *boulang*er = *boulang*+*er* = “verb”), and which is later validated or rejected based on lexical information. Do note that we only tested this dual-route model in experiments 1 and 2, using syntactic category information (noun vs verb) for which word ending cues and genuine category could be orthogonally varied in a large set of words. Two competing routes likely exist for the retrieval of other syntactic features such as singular versus plural, but this is much more difficult to prove, in French at least, because plural is almost always conveyed by a morpheme (e.g. nouns ending with *s* or *x*) rather than by lexical information (irregular plural nouns such as *women* being exceedingly rare in French).

Once conflicts between the two routes are resolved, each word is thought to be encoded by the list of its syntactic features. The last key hypothesis of the model in Figure 1 is that those features then drive syntactic parsing and lead to syntactic expectations about subsequent words. For instance, a determiner induces the expectation of a noun phrase. In experiments 3 and 4, we tested this hypothesis by evaluating whether a determiner primes a noun, and a pronoun a verb, even when those pairings are arbitrary and render the prime entirely irrelevant to the target-based task. We again observed a strong conscious priming effect as well as a smaller unconscious priming effect. Therefore, our study goes beyond previous experiments demonstrating that a subliminal word can be integrated into a conscious syntactic context (Batterink et al., 2013; Hung et al., 2015): in the present experiments, the converse occurs, i.e. a subliminal word induces a syntactic context that influences the processing of a subsequent conscious word. Rabagliati et al. (2018) recently contested that multiple words could be subliminally combined during continuous flash suppression (CFS; Axelrod et al., 2014; Sklar et al., 2012; van Gaal et al., 2014). Our claim, however, bears on visual masking rather than CFS, and is also much more modest: we merely provide replicable evidence for unconscious processing at the earliest stages of syntactic analysis, whereby the syntactic features of a single unconscious word are extracted and their compatibility with a single upcoming conscious word is evaluated.

Importantly, those effects were found to be task-dependent in experiment 5: once participants focused their attention on the singular/plural decision task, priming by syntactic

category (i.e. determiner-noun and pronoun-verb) entirely vanished. The fact that short-latency priming, including subliminal priming, can vary with the participant's task is now a well-established fact (e.g. Naccache et al., 2002b). This finding fits squarely within the evidence-accumulation framework for decision making and extends this hypothesis to decisions based on syntactic features: when participants prepare for a specific task, they set up two accumulators, one for each of the possible responses (e.g. singular vs plural), and priming then reflects the initial accumulation of evidence arising from the prime word and its replacement by subsequent evidence about the target (Dehaene, 2011; Vlassova et al., 2014; Vorberg et al., 2003). This framework readily explains why information which is orthogonal to the task-relevant dimension (e.g. whether the target is a noun or a verb) has no influence on response time: this information is simply never "read-out" by the decision-making process.

Importantly, the absence of any category-priming effect in RTs in experiment 5 does not imply that syntactic category information was not automatically activated. On the contrary, experiments 3 and 4 suggest that, even when participants focus entirely on whether the target is a noun or a verb, the syntactic category of the prime (determiner or pronoun) automatically interferes, even though it is irrelevant and subliminal. Thus, we tentatively surmise that the syntactic-category congruity of the prime and target words was probably automatically computed even in experiment 5, but that this computation did not have any detectable effect on RTs. One way to test this hypothesis could be to record event-related potentials: we would predict the automatic emission of a violation response such as a left anterior negativity (LAN; see e.g. Batterink et al., 2013) when the prime and target do not form a grammatically valid pair.

In the future, brain imaging could also help objectify the two routes postulated in our model, by examining whether they relate to distinct cerebral areas and their connections. Hypothetically, the morphological analysis of written words could take place in the anterior sector of the visual word form area in the left occipito-temporal sulcus (Cohen et al., 2000; Dehaene, Naccache, et al., 2001) while grammatical category retrieval could involve the left superior temporal gyrus (Friederici, 2002, 2012) or the left posterior temporal gyrus (Snijders et al., 2009). Whether the "syntactic lexicon" can be localized to one or several cerebral areas, however, remains unknown. Some fMRI experiments that reported a broadly distributed set of regions for syntactic features have contrasted grammatically correct versus incorrect expressions (Carreiras et al., 2015; Molinaro et al., 2013), raising concerns of a potential

confound between syntactic priming and grammatical violation detection. The fact that, in our study, priming emerges from the repetition of syntactic features even within ungrammatical expressions opens the possibility of disentangling these two effects in order to ultimately isolate the areas involved in the syntactic lexicon.

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# General Discussion

## Summary of the thesis

In this work, we aimed to investigate non-conscious processing and conscious access mechanisms, in particular the role of attention, using schizophrenia as a paradigmatic example of abnormal conscious access.

We first reviewed empirical findings regarding conscious access in schizophrenia (chapter 1). An elevated consciousness threshold has been repeatedly observed in patients with schizophrenia using backward masking (Butler et al., 2003; Charles et al., 2017; Del Cul et al., 2006; Green et al., 2011; Herzog et al., 2013), inattention blindness (Hanslmayr et al., 2013) and attentional blink (Mathis et al., 2012) paradigms. According to the global neuronal workspace (GNW) theory of consciousness, conscious access starts when a relevant piece of information is amplified by attention. It triggers sustained cerebral activity in disseminated cerebral regions interconnected by long-range neurons. This phenomenon, termed as ignition, is thought to render the information accessible to introspection and reportable to others. The GNW model therefore predicts that an abnormal attentional amplification or connectivity within the neuronal network should disrupt conscious access without impacting subliminal processing. Our review draws a link between the extensive literature on the neural basis of consciousness and experimental studies on patients with schizophrenia, showing that they exhibit neurophysiological disturbances, including dysconnectivity, abnormal neural oscillations, glutamatergic and cholinergic dysregulation.

Then we explored two main hypotheses to explain abnormal consciousness threshold in schizophrenia. First, we examined whether cerebral connectivity played a role in conscious access (chapter 2). Importantly, we assumed that dysconnectivity in psychiatric population may induce an elevated consciousness threshold but also that slight fluctuations of connectivity in the general population would correlate with minor variations of consciousness threshold. We found that patients with psychosis, i.e. patients with schizophrenia and with bipolar disorder associated with psychotic features, had an elevated consciousness threshold. Connectivity was measured with diffusion MRI-based tractography and generalized fractional anisotropy (gFA) of interhemispheric and postero-anterior long-distance bundles was correlated to the consciousness threshold across subjects. A causal mediation analysis suggested that a reduced



gFA did not induce psychotic symptoms directly, but only through its effect on the consciousness threshold. Crucially, the bundles that were not supposed to belong to the global neuronal workspace did not significantly correlate with the consciousness threshold.

In a second study (chapter 3), we examined whether attentional amplification was impaired in schizophrenia. Healthy controls and patients' cerebral activities were recorded with electroencephalography while they were attempting to perceive a digit masked with variable delays (SOA) or performing a distracting task and thereby not paying attention to the digit. No difference was observed between patients and controls in potentials evoked by the digit during the distracting task. In particular, cerebral activity similarly increased with SOA in the two groups, suggesting that bottom-up processing was preserved in the patients group. By contrast, an abnormal P300 was observed in patients for long SOA under the attended condition, indicating that some but not all top-down amplification processes were impaired. Again, in this study, subliminal processing, be it due to short SOA or inattention, seemed to be preserved in schizophrenia.

These two studies support some of the proposals we made in the literature review (chapter 1) regarding the mechanisms that could account for a dissociation between conscious and non-conscious processing in schizophrenia. Still, the putative link between elevated consciousness threshold and psychotic symptoms needs to be probed. In a third project, we aim to test this hypothesis using ketamine. Ketamine is a noncompetitive NMDA receptor antagonist that is used in medicine as an anaesthetic agent. When administered at low doses, ketamine can induce reversible psychotic symptoms such as delusional ideas (Krystal et al., 1994; Lahti et al., 2001; Pomarol-Clotet et al., 2006), thereby providing a pharmacological model of psychosis (Corlett et al., 2007, 2016). Interestingly, we supposed that psychotomimetic effects of low doses of ketamine may be related to a slight disruption of consciousness causing a dissociation between conscious and unconscious processing similar to that observed in patients with schizophrenia. In chapter 4, we present a behavioural pilot study on healthy controls, in which we manipulated bottom-up and top-down processing, and could simultaneously obtain masking and attentional blink effects. This paradigm aims to be with electroencephalographic recordings in order to examine whether and how low doses of ketamine eliciting psychotic symptoms impair conscious access.

The study presented in chapter 2 suggested that an elevated consciousness threshold may favour the advent of psychotic symptoms but the cognitive mechanisms underlying this

putative causal effect remain unclear. Recent theories about psychosis rest upon the predictive-coding framework, according to which perception is the result of a computation between priors and sensory inputs (Friston, 2005; Rao et al., 1999; Spratling, 2017; von Helmholtz, 1867). In particular, it was proposed that hallucinations resulted from an imbalance between priors and sensory inputs (Powers et al., 2016; Powers, Mathys, et al., 2017), while delusions would correspond to a failure to update beliefs according to incoming prediction-error signals (Adams et al., 2013; Fletcher et al., 2009). Overall, according to the predictive-coding framework, conscious perception would be shaped by predictions (de Lange et al., 2018; Panichello et al., 2013). In addition, many studies suggested that the identification and the detection of a stimulus were facilitated by previous knowledge and expectations about it. Therefore, understanding how predictions and consciousness interact may shed light on the pathophysiology of delusions in schizophrenia. In chapter 5, we explored whether ability of healthy controls to discriminate and consciously perceive a stimulus were influenced by its predictability. We presented healthy controls with predictable or stochastic sequences ending by a masked stimulus that could, in case of predictable sequences, confirm or violate expectations. Our results suggested that participants were better able to discriminate stimuli violating their expectations than those confirming their expectations or not associated with expectations (following stochastic sequences). However, no effect was observed on visibility.

In chapter 6, we explored subliminal syntactic priming in healthy controls and show that it could be induced by the repetition of the same grammatical category (e.g. a noun followed by another noun), by the transition between two categories (e.g. a determiner followed by a noun), or by the repetition of a single grammatical feature, even if syntax is violated (e.g. “they lemons”, where the expression was ungrammatical but the plural feature was repeated). The orthographic endings of prime words also provided unconscious cues to their grammatical category. Those results support a theoretical framework for syntactic categorization of written words, in which abstract representations of syntactic features are shared between several categories of words, and can be quickly and unconsciously extracted from written words.

## Implications

### Consciousness access and conscious processing in healthy controls

In part of this work, schizophrenia provided a paradigmatic example of dissociation between conscious and subliminal processing helping us to probe several predictions originated from the global neuronal workspace (GNW) theory of consciousness.

First, in chapter 2, we found that the consciousness threshold was correlated to long-distance connectivity, consistently with the GNW theory according to which conscious access rests upon a large-scale broadcasting of information within the brain so it can be accessed simultaneously by different processors (Dehaene et al., 2011; Dehaene & Naccache, 2001). This result is also in agreement with previous studies in clinical populations, showing that postero-anterior fibres are crucial for awareness (Thiebaut de Schotten et al., 2005; Urbanski et al., 2008), that interhemispheric connection disruption can impair the ability to verbally report or explain one's actions (Gazzaniga, 1967, 2000) and crucially that white matter reduction negatively correlates with consciousness threshold (Reuter et al., 2009). Similarly, studies on anaesthesia suggested that disrupting long-distance connectivity participated to a reversible loss of consciousness, in particular when anaesthesia was induced by ketamine (Blain-Moraes et al., 2014; Bonhomme et al., 2016; Lee et al., 2013; Uhrig et al., 2016; Vlisides et al., 2017; for a review, see: Mashour et al., 2018). Still, other cerebral regions may also play an important role in conscious access, notably the thalamus (Dehaene et al., 2011; Llinás et al., 1998; Ward, 2011).

Second, in chapter 3, we confirmed that accumulation of evidence could occur unconsciously and without attention (Vlassova et al., 2014; Vorberg et al., 2003) and found that top-down attentional amplification probably enhanced cerebral activity by modulating the amount of integrated information per unit of time. Indeed, when masked targets were presented under conditions of inattention, the modulation of cerebral activity by SOA was drastically reduced compared to attention conditions and induced no ignition, but it was still observable for the earliest components. These results suggest that an accumulation of evidence can occur in the absence of attention and is amplified by top-down attention so that it can ultimately translate into a global ignition. The comparison with the patient group provided additional information. First, cerebral activity modulation by SOA was not different between the two groups under attended conditions at short SOA. Given the behavioural dissociation between

impaired conscious and preserved subliminal processing in schizophrenia, these activations may thus be sufficient for the subliminal processing to occur. Moreover, under attended conditions, even at long SOA, P1 and N2 components were not affected in patients, suggesting that top-down attention is not a monolithic process that linearly amplifies all cerebral components. This fits with the hypothesis that, at some steps, a threshold should be crossed in evidence accumulation before the subsequent step starts. In this case, conscious perception may correspond to a particular step in this chain of processes (Dehaene, 2011; Kang et al., 2017; King et al., 2014b; Ploran et al., 2007; Shadlen et al., 2011).

In chapter 5, we found that violations of expectations were better discriminated than absence or confirmation of expectations. This result is at odds with previous studies (Denison et al., 2011; Meijs et al., 2018; Stein et al., 2011) and therefore needs to be further explored and replicated. Still, it emphasizes a putative mechanism by which healthy controls may integrate prediction-error signals to update their conscious representations. Importantly, no effect on visibility was observed. Therefore, this updating by prediction-error may occur unconsciously. Such an enhanced effect of violations probably contributes to learning processes in particular in young infants (Stahl et al., 2017).

Finally, in chapter 6, we extended the knowledge of subliminal processing depth, by showing that syntactic features could also be unconsciously processed, helping categorization of a given word and providing a syntactic context for the subsequent one.

### **Pathophysiology and research in schizophrenia**

Our literature review sheds light on a reproducible dissociation between impaired conscious and preserved unconscious processing in schizophrenia.

The renewed view of psychosis as a consciousness disorder gives tools to understand its symptomatology and its pathophysiology. Schizophrenia is usually described as a protean affection impacting perception, emotion and cognition. Yet, an abnormal conscious access to information parsimoniously may account for many of these manifestations. For instance, many authors evidenced that patients with schizophrenia had an abnormal perception and reckoned that their visual pathways may be altered and lead to impairments in higher-order processes (for a review, see: Javitt, 2009). We assert that perceptual abnormalities in schizophrenia are probably linked to a disruption in conscious access rather than to a deficit in basic perceptual

processes. Similarly, cognitive impairments observed in patients may be restricted to conscious processing. For example, patients were found to be impaired in explicit, but not implicit, learning and memory tasks (Danion et al., 2001, 2005). Besides relating various symptomatic dimensions, our work draws a link between different levels of description of the schizophrenic disease. In particular, observations of reproducible conscious cognitive impairments can be understood in the light of cerebral anatomo-functional abnormalities that had long been established in schizophrenia (e.g. dysconnectivity, abnormal oscillations or P300) and molecular dysfunctions, notably glutamatergic and cholinergic. Importantly, all these hypothetical links coming from the extensive literature on consciousness can be experimentally tested. Empirical data presented in chapters 2 and 3 of the present thesis confirmed that abnormal conscious access in schizophrenia was associated with a dysconnectivity and an abnormal P300. More specifically, results of chapter 3 suggested that some electroencephalographic abnormalities were observable only under attended conditions. Indeed, crucially, our work also aims to emphasize what is preserved in patients and in this chapter, we found that cerebral activity was not different between patients and controls both at short SOA (i.e. for subliminal processes) and under unattended conditions.

Up to now, only few experimental paradigms on schizophrenia took into account the dissociation between conscious and unconscious processing. In particular, in the recent development of computational psychiatry, the distinction between preserved functioning under consciousness threshold and impaired processes above it is lacking. On the one hand, this distinction could account for contradicting results. For instance, in a recent review on computational models of schizophrenia, Sterzer et al. (2018) suggested that priors weights at the lower levels of the hierarchy of representations may not be linearly related to priors weights at the higher levels. Since impairments in patients with schizophrenia are restricted to conscious processing, we suppose that their Bayesian inference deficits arise at the moment where conscious conclusions are drawn. Consciousness threshold could thus constitute a hermetic frontier between "low" (non-conscious) and "high" (conscious) level spaces that could be ruled by different Bayesian computations, and, crucially, differently affected in schizophrenia. On the other hand, the studies on consciousness in schizophrenia, including our work, would probably immensely benefit from computational modelling to be more specific in the description of conscious disruption.

## **Causes and consequences of a disruption of conscious access in schizophrenia**

We developed in the literature review several mechanisms through which conscious access could be disrupted in schizophrenia (chapter 1). In particular, our data underlined two of these mechanisms, namely dysconnectivity (chapter 2) and impairment of top-down attentional amplification (chapter 3), to explain the dissociation between preserved subliminal processing and impaired conscious access. We further suggested that psychotic symptoms may stem from a deficit in conscious access. This idea is consistent with the findings presented in chapter 2. Indeed, we found that patients with bipolar disorder and psychotic features had an elevated consciousness threshold comparable to that observed in patients with schizophrenia. Thus, it appears that psychotic symptoms in bipolar disorder and schizophrenia may rely on common neurophysiological mechanisms. This supports the idea that psychosis is a dimensional symptom which goes beyond psychiatric diagnoses (Allardyce et al., 2007; Stefanis et al., 2002).

Regarding dysconnectivity, the GNW posits that conscious access relies on the broadcasting of information within a large network of interconnected neurons. Abnormal dysconnectivity in the workspace would therefore prevent the sharing of information and disrupt conscious access. Indeed, first, sensory areas might not be properly connected to the rest of the workspace, leading to the observed dissociation between preserved subliminal local processing and abnormal conscious access and the inability for patients to properly amplify sensory information. Global ignition is also supposed to inhibit competing stimuli in order to prevent sustained activity to be destabilized by another simultaneous ignition. Thus, dysconnectivity may hinder this unification process and allow subparts of the workspace to be simultaneously activated without competing or inhibiting each other (Dehaene et al., 2011; Joglekar et al., 2018). This co-activation of several subparts of the GNW could lead to a divided up perception and to symptoms of disorganization such as inappropriate affects and ambivalence. Moreover, abnormally intense activation of sensory areas while other subparts of the workspace are coding for self-generated representations might give to the patients the impression that endogenous representations come from the external environment. Hallucinations, feeling of thought insertion or delusions of control could therefore arise from the misattribution of self-generated thought or action to an external cause, or, on the contrary, patients could experience a feeling of omnipotence if external information is considered as coming from the self. Consistently, many studies evidenced that hallucinations were associated

with cerebral dysconnectivity (Amad et al., 2014; Benetti et al., 2015; Lawrie et al., 2002; Mechelli et al., 2007; Vercammen et al., 2010).

Regarding the amount of information accessing the GNW, two hypotheses can be made. First, because of dysconnectivity or attentional impairment, only few information may access the GNW that would thereby contain less information and could even sometimes be empty. Alternatively, because of an inability to select relevant information or a disinhibition due to the GNW fractioning, the workspace may be saturated by irrelevant external stimuli that would prevent other information from entering and create a bottleneck (Marti et al., 2012; Sigman et al., 2005). Finally, the GNW may also be saturated by internal representations if the balance between externally driven and endogenously generated representations is upset. In any case, these abnormalities in the fluidity of the stream of consciousness could manifest by thought disorders such as thought blocking (brutal interruption in the middle of a train of thought) or derailment (change of the frame of reference or of topic from one idea to the next).

Finally, one of the most difficult points is to account both for the emergence and the fixity of delusions. Indeed, the breach in internal representations that allows a delusional idea to take root should theoretically let other subsequent ideas replace it. On the contrary, patients with psychosis are usually deluded and overwhelmed by the same delusional themes, and when in place, these ideas are unshakeable. Among the above proposals, the fractioning of the GNW into subparts because of dysconnectivity may explain the occurrence of hallucinations but not their stability. Similarly, delusion fixity may result from the saturation of the GNW by the delusional ideas but this mechanism does not explain how they initially took hold.

We previously argued that a wider gap between conscious representations and unconsciously processed incoming stimuli could favour psychotic symptoms (see chapters 1, 2 and 3). An elevated consciousness threshold would severely alter the amount of information entering consciousness, and the few random sensory information bursting into consciousness may thus be overweight, creating a subjective feeling of aberrant salience (Kapur, 2003). Moreover, as unconscious processing is preserved, it would continue to implicitly guide behaviour, and fuel intuitions that the patient can neither consciously explain nor link to its conscious perception. This strange overall situation would urge the patient to forge explanations, that may culminate in delusional ideas. Since those conscious constructions would be partly disconnected from the external environment (because of the deficit in conscious access), delusional beliefs would remain stable in the face of contradictory evidence. Even

when crossing the threshold of consciousness, disconfirmatory evidence would mainly appear as bizarre and may foster further delusions rather than question internal representations.

Moreover, delusions are not only conscious representations that remain stable in spite of contradictory evidence. They are frequently accompanied with an intense emotional subjective experience, and an enhanced sensitivity to contradiction that sometimes leads to ideas of persecution. These clinical features may suggest that patients' conscious representation and conscious access are biased towards a particular type of information.

Results obtained in chapter 5 indicated that healthy controls performed better in discriminating violating stimuli, but also tended to be biased towards violation when stimuli were presented at consciousness threshold. In a previous study in healthy controls, it was shown that emotional information also preferentially accesses consciousness: participants presented with masked words better performed in a naming task and had a higher subjective visibility when the words had a negative emotional semantic content than when they were neutral (Gaillard et al., 2006).

In patients with schizophrenia, whether violating and emotional information preferentially accesses consciousness or biases conscious representations is unknown. However, it is possible that a deficit in conscious access results at first in a wider grey area where external stimuli are less perceptible and more ambiguous. Following the results of chapter 5, patients in early psychosis may infer that this ambiguous information is more likely to be violating information. Such a bias towards violating stimuli may decrease patients' capacity to stabilize an internal model, which is compatible with results obtained in healthy controls administered with ketamine (Vinckier et al., 2015). Speculatively, if a similar bias exists for emotional information when presented at the threshold, patients' conscious content may be biased towards both violating and emotional information and their beliefs could be preferentially updated by incoming information that is surprising and emotionally charged.

Importantly, in chapter 5, we did not observe any positive effect of violation on subjective visibility. Like in healthy controls, updating of conscious representations and adjustments of behaviour according to prediction-error signals in patients may therefore partly occur unconsciously and appear as strange and unmotivated. Alternatively, patients' conscious representations might not be updated at all by these error signals that would unswervingly alert them and appeal for explanations that they cannot provide. Patients would therefore search for



more and more implausible theories in an attempt to dampen these error-signals. Interestingly, such an overloading with conflicting information may induce a feeling of lack of control and make patients more sensitive to coincidences (Whitson et al., 2008). A favoured conscious access to emotional content may colour delusional ideas with a rich and vivid subjective experience, participating to their maintenance (D'Antonio et al., 2015). This intense emotional investment in delusion is generally particularly tangible in the early course of psychosis, at the beginning of relapses and when patients are contradicted by their peers and vigorously defend themselves. In all these situations, expectations are refuted and the internal model is called into question, suggesting that violation processing is accompanied with an important emotional and affective participation. Putatively, the weight of these two factors, i.e. violation and emotion, in delusion, may vary across diseases and patients. In particular, patients with mood disorder and psychotic symptoms, or patients with schizo-affective disorders might have a particularly enhanced conscious access to emotional information, bringing manic-depressive symptoms to the fore.

Still, the fixity of delusions needs to be accounted for. Indeed, such persistence of delusional ideas suggests that, from a moment on, patients' conscious representations stop changing according to violations signals. A possible explanation is that the delusional idea provides a suitable account for the patient's experience, namely a permanent feeling of violation of expectations. In this sense, thinking that others mean us harm, are deliberately contradicting us, or that paranormal events are occurring could satisfactorily explain prediction-error signals. In addition, if the fundamental function of delusions is to provide a powerful theory that explains everything and cannot be contradicted, they naturally swell and enrich their content by absorbing contradictory evidence.

Finally, the disease may progress towards a continuous worsening of conscious access deficit. Information would thus less and less reach consciousness, even though emotional and violating stimuli could still be differently processed. Accordingly, delusion may decrease because prediction-error signals would not access consciousness anymore. Similarly, affective disorganization, characterized notably by emotional numbing, and negative symptoms including withdrawal from social interactions and daily life activities, could result from a considerably reduced access to internal and external information including emotional one. In this sense, patients having schizophrenia in which disorganization is more pronounced than

paranoid delusions (i.e. disorganized or catatonic subtypes of the disease), may have an even more severe deficit in conscious access.

Two additional remarks can be made. First, in this model, we reckoned that delusions are favoured by a deficit in conscious access resulting in a biased update of conscious representations according to violation and emotional information, whereas we assumed that disorganization and negative symptoms would reflect a more serious and chronic disruption of conscious access. This proposal fits the natural evolution of the disease, in which intense delusions become progressively more insidious whilst disorganization and negative symptoms tend to increase, as noted by Bleuler who described schizophrenia as a “dementia praecox” (Bleuler, 1950). However, it also suggests that symptomatic decompensation would correspond to changes in conscious access. Such a prediction is not self-evident, needs to be verified and its pathophysiology explained. Second, we underlined that, in healthy controls, emotional and violating information may preferentially access consciousness compared to neutral or confirming information (chapter 5), and that relevant information was amplified by attentional processing to perform a task (chapter 3). Other parameters probably influence the probability for information to access consciousness. For instance, a stimulus is directed to oneself may be easier to detect (e.g. the cocktail party effect: Cherry, 1953). That is, in case of disruption of conscious access, the content of conscious representation may also be biased towards other specific information. In particular, information directed to oneself may elicit ideas of reference, persecution or megalomania. All these proposals need further exploration.

## **Limits**

Our work has several limits that are discussed in each chapter. Still, general limits worth being highlighted here. First, in all our empirical experiments, we had small sample sizes. In particular, in the study presented in chapter 3, we only had 16 participants in each group. Even if we used Bayesian statistics in an attempt to evidence an absence of difference under unattended conditions, we cannot exclude that some differences could have emerged with a larger sample size. Similarly, in the study presented in chapter 2, we did not have enough power to study differences of connectivity between groups. Second, patient groups are generally more heterogeneous than healthy controls groups. For instance, in the study presented in chapter 2, we chose to split the group of patients with bipolar disorder according to psychotic features but other criteria may have been relevant to create subgroups within these patients or within patients

with schizophrenia. Notably, the duration and the severity of the disease probably impact behavioural measures and cerebral anatomy and functions. An alternative strategy to limit heterogeneity and confounding factors is to study patients' siblings or drug-naïve patients.

Another important limit of our work is the difficulty, not to say the impossibility, to evidence causal relationships. For instance, in chapter 2, dysconnectivity was associated with an elevated consciousness threshold and this association was more pronounced in patients with psychosis. Still, the causal mediation analysis only suggests a causal link between the two (i.e. dysconnectivity would increase consciousness threshold that may in turn favour emergence of psychotic symptoms), based on the respective strengths of their interactions. Similarly, in chapter 3, we observed a disruption of conscious access in condition of attention while no difference is observed under unattended conditions but we cannot prove that conscious access deficit is due to an abnormal attentional amplification. Attentional conditions may only be a particular situation in which such an impairment can be evidenced (i.e. a prerequisite rather than a cause). Studies that intend to explore causality can rely on longitudinal cohorts that allow to tease apart the causal role of several parameters according to the time of their occurrence, or use interventions (e.g. cerebral stimulation or pharmacological administration) in before/after experimental designs.

Finally, many of the results we found were not evidenced earlier, or were even in contradiction with previous findings and therefore absolutely need to be taken with caution and further replicated.

## **Perspectives**

### **Confirming pharmacological models of psychosis**

A way to control for heterogeneity among patients, diachrony, confounding factors associated with the disease and to probe causal effects is to use pharmacological models. Ketamine has largely been used as a pharmacological model of psychosis (Corlett et al., 2007, 2016). Indeed, it can induce reversible psychotic symptoms, including delusional ideas in healthy controls subjects, and bring forward symptoms in patients with remitted schizophrenia (Krystal et al., 1994; Lahti et al., 2001; Lahti et al., 1995; Pomarol-Clotet et al., 2006). Moreover, delusional ideas observed in healthy controls administered with ketamine are associated with aberrant predictions error activations in the prefrontal cortex that are similar to

those observed in patients with schizophrenia (Corlett et al., 2006; Murray et al., 2007). Other subtle alterations observed in schizophrenia, notably in perceptual learning, reasoning, or in ERPs, such as the mismatch negativity, can also be mimicked in normal subjects by the administration of low doses of ketamine (Corlett et al., 2011; Gil-da-Costa et al., 2013; Schmidt et al., 2013; Schwertner et al., 2018; Umbricht et al., 2000; Vinckier et al., 2015). However, recent studies found that oscillation dysregulations induced by ketamine were slightly different from those observed in patients with early and/or chronic schizophrenia (Anticevic, Corlett, et al., 2015; Grent-'t-Jong et al., 2018). Ketamine model of psychosis needs therefore to be further probed.

We intend to use the paradigm of chapter 4 which manipulates masking and attentional blink, in order to explore whether ketamine induces an elevation of consciousness threshold in healthy controls and to study how cerebral activity is affected by ketamine as a function of attentional resources available for the processing of a stimulus. We predict that ketamine would disrupt conscious access through an impairment of top-down amplification (Herrero et al., 2013; Moran et al., 2015; Self et al., 2012; van Kerkoerle et al., 2014; van Loon et al., 2016) and expect to observe an elevation of consciousness threshold under attended conditions, an increased synergistic effect between masking and attentional blink and no impairment in subliminal processing and under unattended conditions. Regarding EEG, a recent literature review found that the P3 component was reproducibly reduced under ketamine, P1 did not seem to be modified by ketamine administration while results were mixed for N1 and N2 components (Schwertner et al., 2018). Ketamine effects on EEG therefore worth being replicated, in particular with a paradigm quite similar to that previously used in patients with schizophrenia.

### **Assessment of conscious access as a clinical tool**

Up to now, no clinical or paraclinical method gives a definite diagnosis of psychosis. Reproducible observations of disruption of conscious access in schizophrenia may thus provide a useful tool in clinic. Indeed, disruption of conscious access has signatures at different levels: patients have robust anomalies in cognitive measures (e.g. elevated consciousness threshold measure and dissociation between conscious and non-conscious processing) and paraclinical results (e.g. dysconnectivity, abnormal oscillations, reduced P3). Accordingly, clinical observations could perhaps be completed with a quick assessment of consciousness threshold using for instance a double staircase paradigm (like in chapter 3). In addition, patients for whom the diagnosis is uncertain could get an EEG recording, searching for a decreased P3.

Interestingly, backward masking deficit was proposed to be a trait-marker of the schizophrenic disease since it was also observed outside acute episodes (Green et al., 1999). Therefore, it could be particularly useful to identify among patients at risk of psychosis those who are more likely to develop the disease (Cannon et al., 2008; Yung et al., 2004). Previous research found that thalamocortical dysconnectivity resembling that seen in schizophrenia was present in at-risk patients and even more pronounced in those who later develop full-blown illness (Anticevic, Haut, et al., 2015). Combining behavioural and paraclinical measures of conscious access to actual tools used in early detection of psychosis would probably increase the predictive accuracy, allowing primary prevention strategies to decrease the rate of conversion to psychosis (Morrison et al., 2004). In the same vein, a vast literature was dedicated to consciousness assessment in vegetative states, providing diagnostic, predictive and follow-up tools (Daltrozzo et al., 2007; Faugeras et al., 2012; King, Faugeras, et al., 2013; King, Sitt, et al., 2013; Monti et al., 2010; Owen et al., 2006; Sitt et al., 2014). More speculatively, the refinement of conscious access impairment assessment in schizophrenia might tease apart different profiles among patients, according to the severity, the subtype or the current state (i.e. stabilized or in an acute episode) of the disease. Such hypothesis fits with the results obtained in chapter 2, showing that the measure of consciousness threshold was correlated with clinical scale scores. Moreover, we suggested above that consciousness threshold for emotional stimuli could guide the diagnosis towards more affective subtypes of psychosis. Such measures may thus be informative for the prognosis, the choice of medication and the follow-up of patients.

Finally, we suggested in chapter 2 that psychosis could be a dimensional symptom going beyond psychiatric diagnoses. This finding questions actual categorical nosography used to classify psychiatric disorders (Allardyce et al., 2007; Henry et al., 2010). Indeed, similar neuronal mechanisms could be involved in psychotic symptoms observed in mood disorders, schizophrenia and even in psychotic manifestations such as hallucinations in the general population (Baumeister et al., 2017; Powers, Kelley, et al., 2017; Stefanis et al., 2002).

### **Modulation of consciousness as a treatment for psychosis**

A better comprehension of the pathophysiology of schizophrenia opens perspectives for its treatment. We have seen that the disruption of conscious access was likely to be underpinned by a dysconnectivity and a NDMA dysfunction. Recently, stimulation techniques aiming to enhance conscious access have been developed. In particular, transcranial direct current stimulation was shown to improve consciousness in patients in minimally conscious state

(Thibaut et al., 2014) and may dampen schizophrenic symptoms when applied to the left dorsolateral prefrontal cortex (Palm et al., 2016; but Fitzgerald et al., 2014). Glycine agonists and glycine transporter inhibitors targeting NMDA dysfunction were also tested in patients, with mixed results (Bugarski-Kirola et al., 2014; Goff, 2014; Heresco-Levy et al., 1999; Tsai et al., 2004; Umbricht et al., 2014; for reviews, see: Howes et al., 2015a; Beck et al., 2016).

Other directions probably worth being investigated. Serotonin and acetylcholine are involved in the transition between awake and asleep states (McCormick et al., 1997) and could also act as potent modulators of NMDA-dependent cortical circuits (Rowland et al., 2010; Smucny et al., 2016). Therefore they could constitute interesting targets for developing new drugs. More specifically, cholinergic neurons were assigned to an important role in regulating ongoing spontaneous activity, notably in the generation of ultraslow fluctuations ( $< 0.1$  Hz) and their synchronicity (Koukoulis et al., 2016) while a moderate level of spontaneous activity seems to be required to correctly process external stimuli (Dehaene et al., 2005). Cholinergic targets, in particular M1 muscarinic receptors agonists showed encouraging effects on negative and cognitive symptoms (Friedman, 2004; Ghoshal et al., 2016; Gibbons et al., 2016; Hopper et al., 2016; Nikiforuk, 2016) and could act through the regulation of ongoing spontaneous activity.

Finally, psychotherapy techniques could take advantage of preserved subliminal processing to help patients. For instance, cognitive remediation could teach them to preferentially use their unconscious skills. In addition, caregivers and relative could be formed to interact with patients using a more implicit form of communication. Other techniques, relying on modified states of consciousness, such as hypnosis and meditation, may also improve cognitive function, attention, and conscious access in patients (Rainville et al., 2002; Zeidan et al., 2010).

## **Conclusion**

In the present thesis, we explored the dissociation between conscious and unconscious processing in patients with schizophrenia and, by doing so, also studied non-conscious processing and conscious access in healthy controls.

We found empirical evidence supporting theoretical proposals formulated by the global neuronal workspace model, notably regarding the role of attention in amplifying accumulation of evidence and of cerebral connectivity integrity to broadcast information throughout the brain.

We also extended knowledge regarding conscious access and subliminal processing in healthy controls, with results suggesting that violations may be easier to process than confirmation when presented at the consciousness threshold, and finding that syntax features could be subliminally processed.

Finally, we discussed clinical and therapeutics implications and made a tentative proposal to explain the complex problem of delusion emergence in schizophrenia in the light of our empirical findings. We proposed that delusional ideas arise because conscious access decreases rendering emotional and prediction-error signals predominant. Such proposal needs to be validated and paves the way to future exciting research where psychiatry meets cognitive neuroscience.







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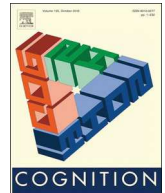
# Annexes

## Unconscious memory suppression

Salvador, A., Berkovitch, L., Vinckier, F., Cohen, L., Naccache, L., Dehaene, S., & Gaillard, R. (2018). Unconscious memory suppression. *Cognition*, 180, 191–199.

<http://doi.org/10.1016/j.cognition.2018.06.023>





## Original Articles

## Unconscious memory suppression

Alexandre Salvador<sup>a,b,c,1</sup>, Lucie Berkovitch<sup>d,e</sup>, Fabien Vinckier<sup>a,b,c,e,f,1</sup>, Laurent Cohen<sup>e,g,h</sup>,  
Lionel Naccache<sup>e,g,h</sup>, Stanislas Dehaene<sup>d,i</sup>, Raphaël Gaillard<sup>a,b,c,\*</sup>

<sup>a</sup> Centre Hospitalier Sainte-Anne, Service Hospitalo Universitaire, Paris, France

<sup>b</sup> Université Paris Descartes, Sorbonne Paris Cité, 12 rue de l'école de Médecine, 75006 Paris, France

<sup>c</sup> INSERM, Laboratoire de "Physiopathologie des Maladies Psychiatriques", Centre de Psychiatrie et Neurosciences, CPN U894, Institut de Psychiatrie GDR 3557 Paris, France

<sup>d</sup> Cognitive Neuroimaging Unit, CEA DSV/I2BM, INSERM, Université Paris-Sud, Université Paris-Saclay, NeuroSpin Center, 91191 Gif/Yvette, France

<sup>e</sup> Université Pierre et Marie Curie-Paris 6, 4 place Jussieu 75005 Paris, France

<sup>f</sup> Motivation, Brain and Behavior Lab, Centre de Neuroimagerie de Recherche, Institut du Cerveau et de la Moelle épinière, Hôpital de la Pitié-Salpêtrière, 47 Boulevard de l'Hôpital, Paris 75013, France

<sup>g</sup> Assistant Publique Hopitaux de Paris (AP-HP), Groupe Hospitalier Pitié-Salpêtrière, Department of Neurology, 47 Bld de l'Hôpital, 75013 Paris, France

<sup>h</sup> Inserm, U1127, CNRS, UMR 7225, Institut du Cerveau et de la Moelle épinière, Sorbonne Universités, UPMC Univ Paris 06, Hôpital de la Pitié-Salpêtrière, 47 Boulevard de l'Hôpital, Paris 75013, France

<sup>i</sup> Collège de France, 11 place Marcelin Berthelot, 75231 Paris Cedex 05, France



## ARTICLE INFO

## Keywords:

Memory

Repression

Unconscious processes

Subliminal perception

Cognitive control

## ABSTRACT

Recent evidence suggests that high-level executive control can occur unconsciously. In this study, we tested whether unconscious executive control extends to memory retrieval and forgetting. In a first experiment, participants learned word-word associations and were trained to either actively recall or forget these associations in response to conscious visual cues (Think/No-Think paradigm). Then, the very same cues were subliminally presented while participants were performing a grammatical gender categorization task on distinct word pairs. Memory retrieval tested a few minutes later was significantly influenced by conscious and masked cues, suggesting that memory recall could be manipulated unbeknownst to the participants. In a second experiment, we replicated these findings and added a baseline condition in which some words were not preceded by masked cues. Memory recall was significantly reduced both when words were preceded by an unconscious instruction to forget compared to the baseline condition (i.e. no cue), and to the unconscious instructions to recall. Overall, our results suggest that executive control can occur unconsciously and suppress a specific memory outside of one's awareness.

## 1. Introduction

Memory suppression corresponds to the voluntary alteration of memory retrieval by conscious cognitive control. This mechanism was first demonstrated by Anderson & Green (2001), with a "Think/No-Think" paradigm modelled on the Go/No-Go task. In the original study, participants first learned a set of word pairs. Then, they were presented with the first word of a pair (hint word) and asked, in response to a visual cue, to either retrieve the associated word (Think trials) or prevent it from coming to mind (No-Think trials). The results showed that executive control could modulate recall: recall could be improved through rehearsal, or deteriorated voluntarily, a phenomenon termed "suppression-induced forgetting" (Anderson & Green, 2001). These

results have been replicated (for a review, see Anderson & Hanslmayr, 2014) and extended to non-verbal memories, using for instance emotional pictures (Depue, Banich, & Curran, 2006; Depue, Curran, & Banich, 2007; Küpper, Benoit, Dalgleish, & Anderson, 2014). Moreover, the neural substrates of this phenomenon have been clarified: fMRI studies indicated that memory suppression may involve top-down modulation of hippocampal activity by the dorsolateral prefrontal cortex (Anderson, Bunce, & Barbas, 2016).

Whether suppression-induced forgetting can be triggered unconsciously remains unknown. Indeed, long-term declarative memory has long been thought to be tightly linked to consciousness (Tulving, 1987). To date, suppression-induced forgetting has always been tested through voluntary and conscious effort to rehearse memories or purge

\* Corresponding author at: Centre Hospitalier Sainte-Anne, Service Hospitalo Universitaire, 1, rue Cabanis, Paris, France.

E-mail address: [raphael.gaillard@normalesup.org](mailto:raphael.gaillard@normalesup.org) (R. Gaillard).

<sup>1</sup> These authors contributed equally to the work.

them. However, recent behavioural and neuroimaging results suggested that a semantic association could be formed through unconscious processes (Reber, Luechinger, Boesiger, & Henke, 2012; vanGaal et al., 2014).

Interestingly, other studies showed that unconscious instructions could modulate high-level executive control processes, such as attention orientation (Jiang, Costello, Fang, Huang, & He, 2006), task-set preparation (Lau & Passingham, 2007; Weibel, Giersch, Dehaene, & Huron, 2013), task switching (Reuss, Kiesel, Kunde, & Hommel, 2011), error detection (Charles, Opstal, Marti, & Dehaene, 2013; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001), conflict adaptation (vanGaal, Lamme, & Ridderinkhof, 2010) and response inhibition (vanGaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008; vanGaal, Ridderinkhof, Scholte, & Lamme, 2010).

Capitalizing on these results, our study aims to test whether high-level executive control processes can unconsciously suppress a previously learned association between two words, i.e. whether suppression-induced forgetting can occur outside of one's awareness.

We designed two experiments that were modelled on the Think/No-Think paradigm (Anderson & Green, 2001), using conscious and masked cues to manipulate memory retrieval. In the first experiment, we investigated whether memory suppression could be induced by masked (unconscious) cues, which had been previously associated with conscious Think/No-Think instructions. In the second experiment, we aimed to replicate our findings with an additional baseline condition, to confirm that masked cues could induce memory suppression over and above the detrimental effect of time.

## 2. Experiment 1

Experiment 1 was designed as an unconscious version of the procedure developed by Anderson & Green (2001). Participants first learned word pairs (hint word – response word). Then, they performed a conscious Think/No-Think task, in which they were presented with a subset of hint words and had to actively remember (Think) or try to forget (No-Think) the associated response words, according to conscious visual shape cues. Afterwards, these conscious trials were intermixed with unconscious trials in which participants performed a distracting task on distinct hint words (a grammatical gender determination task), while the same visual shape cues were subliminally presented. The alternation between conscious and unconscious trials aimed to reinforce the association between shape cues and Think/No-Think instructions, fostering the unconscious Think/No-Think effect. A final test then probed whether participants were able to retrieve response words when presented with the hint words.

The primary aim of this experiment was to test whether masked cues could induce a Think/No-Think effect as previously evidenced in conscious settings (Anderson & Green, 2001). For methodological reasons, our experimental paradigm differs from the original in several aspects. First, in Anderson's experiments, two different methods were used to signal what task participants should perform. One method was to allocate each hint word to the Think or the No-Think conditions and to train participants until they could distinguish these words ("hint training", Anderson & Green, 2001). Alternatively, specific colours could be associated with the Think/No-Think task such the font colour indicated the type of task participants should perform ("colour cueing", Anderson et al., 2004). In our design, we associated shape cues (diamond and square) to Think and No-Think tasks ("shape cueing"). These cues were displayed at the beginning of each trial to indicate to participants whether they should perform a Think or a No-Think task on the subsequent word, which allowed us to then mask these visual cues in the unconscious condition. Secondly, in the original paradigm, a baseline condition was included whereby some words were not presented at all between learning and final recall, allowing active retrieval and active forgetting to be compared to a neutral condition. In Experiment 1, we did not include such a baseline, maximising the Think/

No-Think effect by associating every unconscious trial with a masked cue. However, a comparable baseline condition was added to Experiment 2.

In these experiments we hypothesised that we would observe a Think/No-Think effect with both conscious and masked cues, i.e. that final recall in the No-Think condition would be significantly lower than initial recall, and significantly lower than the Think condition in final recall but not in initial recall performance.

### 2.1. Materials and methods

#### 2.1.1. Participants

Forty-four healthy subjects were recruited through advertising (25 females and 19 males, mean age 24.5 years, range 21–33). All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. No participant took part in both experiments. Participants gave written informed consent before taking part. All methods were carried out in accordance with relevant guidelines and regulations, in particular with the Declaration of Helsinki. No participants were excluded from Experiment 1.

#### 2.1.2. Procedure

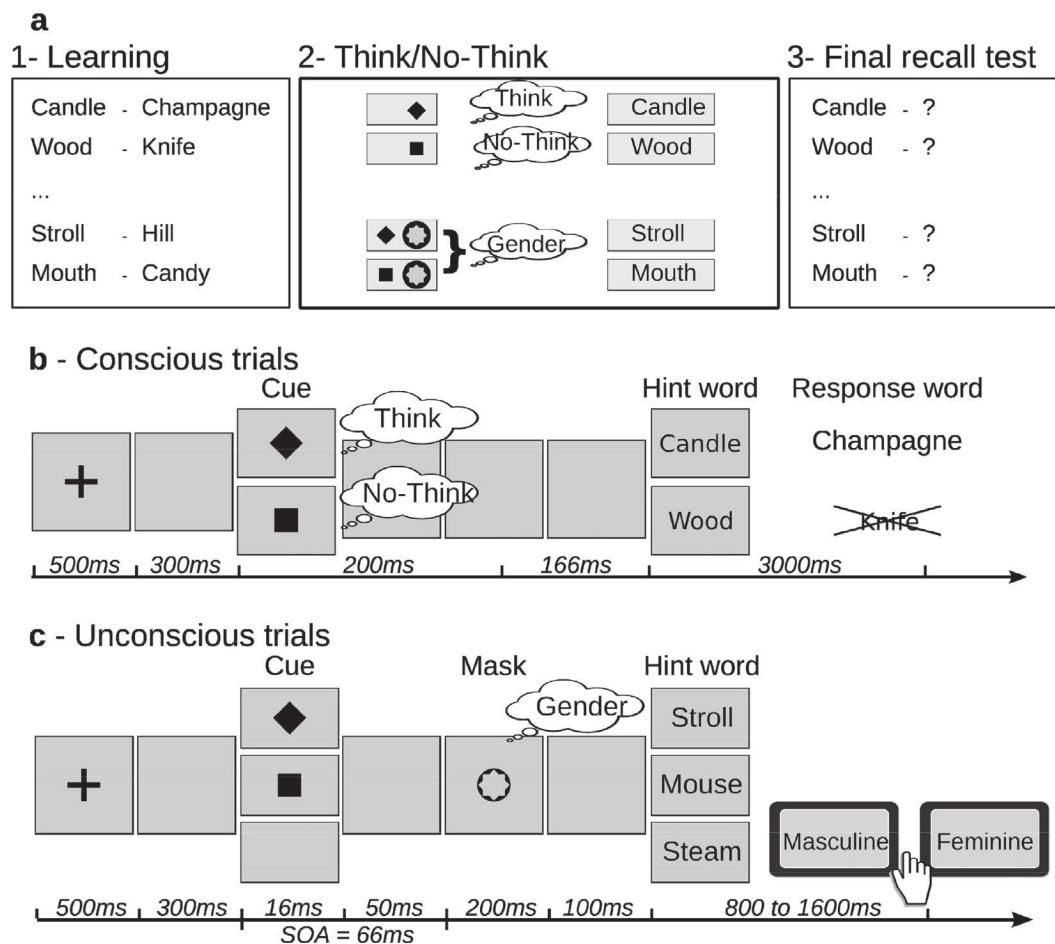
The procedure consisted of three phases: a learning phase, a Think/No-Think phase (comprising a few conscious Think/No-Think trials then intermixed with unconscious Think/No-Think trials), and a final recall test (Fig. 1a).

**2.1.2.1. Learning phase.** First, participants were asked to learn 30 word pairs (composed of a hint word and a response word, e.g. "candle – champagne"). Word pairs were presented in random order and each pair was presented twice. Each word was displayed on screen for 4 s. Hint words were preceded by a 200 ms fixation cross and response words were followed by a 500 ms inter-pair interval. A recall test was then performed: each hint word was displayed for 4 s (e.g. "candle") and participants had to say aloud the corresponding response word (e.g. "champagne"). They could give an answer as soon as the hint word appeared on screen and had 4 additional seconds after it had disappeared to answer, i.e. 8 s in total to answer. No feedback was provided. A new learning phase (maximum 3) started if the minimum of 50% correct answers was not reached. All subjects reached the 50% correct answers criterion after one run of the learning phase, with an average of 80% correct answers.

**2.1.2.2. Think/No-Think phase.** During the Think/No-Think phase, participants were presented with the hint words preceded by Think or No-Think cues ( $n = 760$  trials, 20 trials per target word, 240 conscious trials for 12 word pairs, 240 unconscious trials for 12 word pairs and 280 trials for 6 filler word pairs).

**Conscious Think/No-Think trials.** On conscious Think trials, participants were asked to retrieve the response word associated with the hint word, without saying it aloud. Comparatively, on No-Think trials, subjects were asked to prevent the response word from coming to mind for 3 s, while the hint word was presented on screen. No-Think instructions were unguided: no strategy was proposed to help the participants (Benoit & Anderson, 2012). A visual shape cue, in the form of either a diamond or a square, was presented at the beginning of each trial to indicate which task (Think or No-Think) the participant should perform ("shape cueing"). The association between shapes (diamond/square) and instructions (Think/No-Think) was defined at the beginning of the experiment and counterbalanced across participants. The visual sequence was as follows: fixation cross (500 ms), blank screen (300 ms), shape cue (200 ms), blank screen (166 ms), and hint word (3000 ms) (Fig. 1b).

**Unconscious Think/No-Think trials.** On unconscious trials, participants had to perform a grammatical gender categorization task on the hint words (i.e. determine whether it was feminine or masculine).



**Fig. 1.** Design of Experiment 1. (a) Experiment 1 consisted of three phases: (1) a learning phase, (2) a Think/No-Think phase (detailed in b and c), (3) a final test. (a1) In the learning phase, participants encoded word pairs (hint word – response word), until at least 50% of recall was reached. (b) In the Think/No-Think phase on conscious trials, participants were presented with hint words and had either to recall (Think trial) or suppress (No-Think trial) the corresponding response word. (c) In the Think/No-Think phase on unconscious trials, participants had to indicate as quickly as possible the gender of the hint word. Think and No-Think cues were presented just before the hint word and masked by a ring shape (metacontrast mask) in the unconscious condition. (a3) In the final test phase, participants' ability to retrieve response words was assessed.

Hint words were preceded by the same shape cues as in the conscious phase (i.e. diamond and square) but these cues were masked by metacontrast (Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003), whereby a ring appeared on screen just after the shape cue, closely fitting its contours without touching it, making the shape cue subliminal. Hint words were followed by a go-signal indicating to participants that they could give their answer for the grammatical gender determination task. The go-signal was a dot appearing on screen with a jitter in its position and timing (random position between –200 and +200 pixels above or below the screen centre and random moment between 800 and 1600 ms after the word onset). After the go-signal, participants had to answer as fast as possible by pressing the letter “k” or “d” on a keyboard. The buttons were associated with the “feminine” and “masculine” response at the beginning of the experiment and counterbalanced across participants.

Participants were not informed that masked Think/No-Think cues were presented during these unconscious trials. They were told that the main outcome of these trials was their speed and accuracy in the grammatical gender determination task. Feedback on accuracy and response times was provided every 30 gender trials. On unconscious Think/No-Think trials, the visual sequence was as follows: fixation cross (500 ms), blank screen (300 ms), shape cue (16 ms), blank screen (50 ms), ring metacontrast mask (200 ms), blank screen (100 ms), hint word (800 to 1600 ms), go signal (Fig. 1c). The Stimulus Onset Asynchrony (SOA) for the metacontrast masking was therefore 66 ms.

**Trial order.** Thirty-six conscious trials were first performed. Following this, unconscious trials and conscious trials were intermixed. A minimum of two conscious trials were received between every unconscious trial. To know which task they were required to perform at each trial, participants had to pay attention to conscious visual cues. When they saw a square or a diamond they had to perform a Think/No-Think task (conscious trials), and when they perceived a ring they had to perform a grammatical gender categorization task (unconscious trials).

To investigate the influence of conscious trial instructions on the following unconscious trial, unconscious hint words were divided into two groups: specific hint words were systematically preceded by a conscious No-Think trial, while others were systematically preceded by a conscious Think trial.

**2.1.2.3. Final test phase. Recall test.** After the Think/No-Think phase, participants completed a recall test identical to the one performed at the end of the learning phase.

**Cue visibility assessment.** At the end, participants performed 120 trials of a forced choice test designed to evaluate the visibility of the masked cues. They were told that hidden cues were presented on screen before the metacontrast masking ring, and they were asked to guess whether it was a square or a diamond. The same timing sequence as in the unconscious phase was used (Fig. 1c), except that no hint word was presented. Participants were told that only response accuracy was

**Table 1**  
Initial and final recall rates in Experiments 1 and 2.

	Initial recall rate Mean % (sd)	Final recall rate Mean % (sd)
Experiment 1		
Conscious		
No-Think	80 (21)	77 (20)
Think	80 (21)	83 (19)
Unconscious		
No-Think	79 (25)	75 (28)
Think	83 (23)	81 (23)
Overall		
No-Think	79 (20)	76 (20)
Think	81 (17)	82 (18)
Experiment 2		
Unconscious		
No-Think	78 (22)	67 (24)
Baseline	79 (25)	81 (26)
Think	78 (26)	84 (22)

important, not response speed, and that they had to venture an answer even if they did not see the cue. Discrimination performance was assessed through  $d'$  (Macmillan & Creelman, 2005).

**Questionnaire.** Finally, a post-experiment questionnaire evaluated the frequency of intrusions during the unconscious condition, i.e. the frequency at which response words entered awareness during the grammatical gender determination task on hint words.

### 2.1.3. Materials

**Stimuli.** We built 30 word pairs (hint word – response word) composed of French nouns that were weakly related one to another (e.g. “candle – champagne”, “wood – knife”), while unrelated to other pairs. For each subject, the 30 word pairs were randomly split into 5 sets of 6 word pairs. Four of these sets were associated with a specific Think/No-Think condition (i.e. Conscious Think, Conscious No-Think, Unconscious Think, Unconscious No-Think,  $n = 6$  word pairs for each condition). The remaining 6 word pairs were used as filler word pairs. They were always preceded by conscious cues but not allocated to a Think or a No-Think condition: in half of the trials, they were preceded by a Think shape cue and, in the other half, by a No-Think shape cue. Therefore, participants had to continuously attend to the shape cues to know whether they should perform a Think or a No-Think task (“shape cueing”) and could not only rely on hint words to identify conditions (“hint training”). Each word pair associated with a specific Think or No-Think condition was presented 20 times during the Think/No-Think phase. The randomization process was checked to ensure it did not result in an unbalanced allocation of word pairs to conditions across subjects.

**Apparatus.** The experiment was run on a Linux personal computer running the Psychophysics toolbox (Brainard, 1997) within Matlab. All stimuli were displayed on a CRT monitor with a refresh rate of 60 Hz, in grey on a black background. Participants sat with their head at a distance of 60 cm from the screen, so that the shape cues occupied one degree of visual angle.

### 2.1.4. Statistical analysis

Statistical analyses used standard repeated measure ANOVA, t-tests and linear regressions. The relevant analysis is described in the results section at the time it is first performed. Significance level was  $\alpha = 0.05$ , uncorrected.

All statistical analyses were performed using the “R” statistical software (R Core Team, 2013).

## 2.2. Results

### 2.2.1. Conscious and masked No-Think cues reduce memory recall

A three-way analysis of variance (ANOVA) on recall performance was performed for each participant, with cue type (Think versus No-Think), cue visibility (conscious versus unconscious) and time (initial versus final recall) as within subject factors, and subject as random factor. This analysis revealed a significant interaction between cue type and time ( $F(1,43) = 5.56$ ,  $p = 0.023$ ), while there were no main effects of cue type ( $F(1,43) = 3.67$ ,  $p = 0.062$ ), cue visibility ( $F(1,43) = 0.036$ ,  $p = 0.85$ ) or time ( $F(1,43) = 2.90$ ,  $p = 0.096$ ). A significant interaction between cue visibility and time ( $F(1,43) = 4.3$ ,  $p = 0.044$ ) was observed, but there was no significant interaction between cue type and cue visibility ( $F(1,43) = 0.01$ ,  $p = 0.72$ ), and no triple interaction between cue type, cue visibility and time ( $F(1,43) = 0.47$ ,  $p = 0.498$ ). The effect of cue type over time was therefore analysed irrespective of cue visibility.

Think/No-Think effects were assessed in two different ways: (1) by comparing final versus initial recall performances separately for Think and No/Think conditions, (2) by comparing Think and No/Think recall performances in the final test.

No-Think cues (conscious and unconscious) significantly reduced recall performance in the final test compared to the initial test (76% versus 79%,  $t(43) = 3.10$ ,  $p = 0.003$ ), whereas Think cues did not significantly improve recall performance (82% versus 81%,  $t(43) = -0.42$ ,  $p = 0.67$ ) (Table 1, and Fig. 2b).

In the initial test, there was no significant difference in recall between word pairs that were next allocated to the Think and No-Think conditions (initial recall of 81% and 79% respectively,  $t(43) = 0.86$ ,  $p = 0.39$ ). By contrast, in the final test, a significant difference in recall between the Think and No-Think conditions arose (final recall of 82% and 76% respectively,  $t(43) = 2.75$ ,  $p = 0.009$ ).

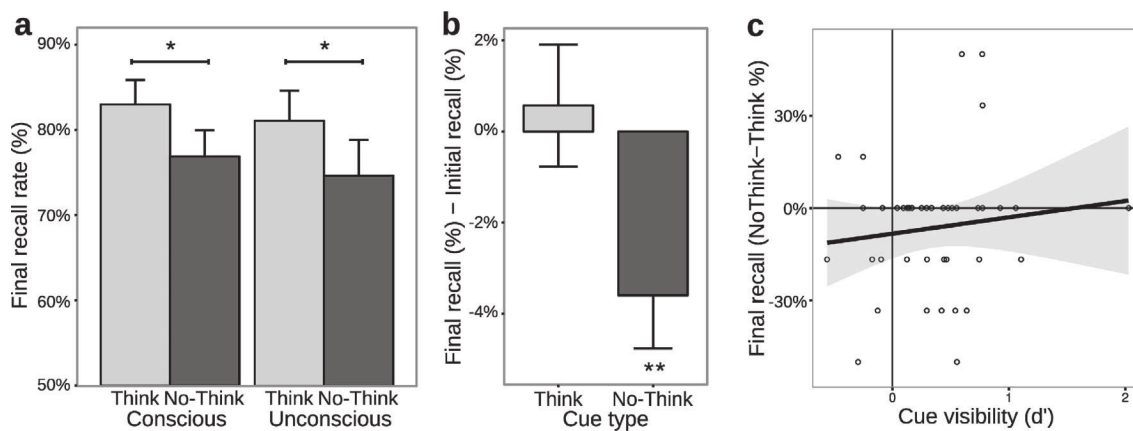
No significant effect of cue visibility was found, however, as an exploratory analysis, we analysed separately conscious and unconscious trials.

For unconscious trials, the two-way ANOVA on recall performance for each participant according to cue type (Think versus No-Think) and time (initial versus final recall) did not reveal a significant Think/No-Think effect (cue type  $\times$  time:  $F(1,43) = 1.92$ ,  $p = 0.173$ ). There was no main effect of masked cue type ( $F(1,43) = 2.77$ ,  $p = 0.103$ ) but a main effect of time ( $F(1,43) = 6.23$ ,  $p = 0.017$ ). Exploratory t-tests showed that unconscious No-Think cues significantly reduced recall in the final test compared to the initial test (75% versus 79%,  $t(43) = 2.90$ ,  $p = 0.006$ ) and final recall was significantly lower with unconscious No-Think cues compared to unconscious Think cues (75% versus 81%,  $t(43) = 2.03$ ,  $p = 0.024$ , single-sided) (Fig. 2a, Table 1).

For conscious trials, in the two-way ANOVA on recall performance for each participant according to cue type (Think versus No-Think) and time (initial versus final recall), the Think/No-Think effect did not reach statistical significance (cue type  $\times$  time:  $F(1,43) = 4.03$ ,  $p = 0.051$ ) nor did the main effect of cue type ( $F(1,43) = 1.22$ ,  $p = 0.27$ ) or time ( $F(1,43) = 0$ ,  $p = 1$ ). Exploratory t-tests showed that final recall was significantly lower with unconscious No-Think cues compared to unconscious Think cues (75% versus 81%,  $t(43) = 2.03$ ,  $p = 0.038$ , single-sided) (Fig. 2a, Table 1).

### 2.2.2. The memory effect is not due to cue discriminability

Discriminability, as assessed by the forced choice test, was very low in the unconscious condition, albeit significantly above zero (hit rate 55.5%,  $d' = 0.35$ ,  $t(43) = 5.01$ ,  $p < 0.001$ ). Crucially, a between-subject regression analysis (Greenwald, Draine, & Abrams, 1996) demonstrated that subjects' ability to discriminate masked cues ( $d'$ ) was unrelated to the cues' effect on memory (No-Think – Think recall performance in the final test) (Fig. 2c). The slope of the regression line was not significantly different from zero (slope = 0.05,  $t(42) = 0.77$ ,  $p = 0.45$ ), indicating that people's ability to discriminate masked cues



**Fig. 2.** Effect of cue type and visibility in Experiment 1. (a) Final recall performance was lower with No-Think cues (black) compared to Think cues (grey) when these cues were consciously visible (left) and masked (right). Error bars represent the standard error of the mean (SEM). (b) Think cues (grey) did not improve overall recall performance (final recall – initial recall, grouping conscious and unconscious trials together), whereas No-Think cues (black) significantly reduced it. Error bars represent the standard error of the mean (SEM). (c) Participants' ability to discriminate masked cues on unconscious trials, as measured by  $d'$ , did not significantly alter cues effect on final recall, and the effect remained significant for people who could not discriminate masked cues (intercept =  $-8\%$ ). The shaded area around the regression lines represents the 95% confidence interval. \* =  $p < 0.05$ , \*\* =  $p < 0.01$ .

did not predict their memory effect. The intercept of the regression was significantly different from zero (intercept =  $-8\%$ ,  $t(42) = -2.08$ ,  $p = 0.044$ ), indicating that people who could not discriminate masked cues still showed an effect on final recall.

To further isolate the inhibition effect in unconscious No-Think trials, we performed a regression analysis (Greenwald et al., 1996) on final versus initial recall performance (final No-Think – initial No-Think performance), as a function of cue discriminability ( $d'$ ). This analysis yielded a similar result with an effect of cues that was unrelated to people's ability to discriminate masked cues (slope =  $0.01$ ,  $t(42) = 0.32$ ,  $p = 0.75$ ). This effect remained significant for people who could not discriminate masked cues (intercept =  $-5\%$ ,  $t(42) = -2.47$ ,  $p = 0.017$ ).

### 2.2.3. Recall performance in unconscious trials was not affected by the preceding conscious trial

Final recall performance for unconscious trials was not influenced by the type of cue presented in the preceding conscious trial. There was no significant effect of conscious Think/No-Think trials on the subsequent unconscious trials (main effect of preceding conscious trial:  $F(1,43) = 0.01$ ,  $p = 0.91$ , interaction between current masked cue type and previous conscious cue type:  $F(1,43) = 0.10$ ,  $p = 0.76$ ).

### 2.2.4. Performance in the grammatical gender determination task

Participants reported a low level of intrusions during the word gender determination task (16.5% based on post-session questionnaires), suggesting that the word gender determination task efficiently drew their attention away from conscious memory task during unconscious trials.

Performance in the word gender determination task did not significantly differ according to unconscious cue type: gender response accuracy was 99.3% and 99.2% with the Think and No-Think masked cues respectively ( $t(43) = -0.53$ ,  $p = 0.60$ ), and reaction time was 365 ms and 361 ms respectively ( $t(43) = 0.43$ ,  $p = 0.67$ ).

## 2.3. Discussion

Experiment 1 showed that a Think/No-Think effect could be induced by conscious and masked shape cues. Crucially, in the unconscious condition, word pairs had never been consciously associated with Think/No-Think instructions.

While the Think/No-Think effect of cues irrespective of cue visibility was confirmed by a significant three-way ANOVA and subsequent  $t$ -

tests, further exploratory ANOVA and  $t$ -tests on unconscious cues separately and conscious cues separately provide further contrasts. The two-way ANOVAs on unconscious and conscious cues separately failed to reach statistical significance, but exploratory  $t$ -tests show a difference in final recall between Think and No-Think cues both for unconscious and conscious trials, when such differences were not present in initial recall. These exploratory results require confirmation to ascertain that unconscious cues taken alone significantly alter recall, which was the object of Experiment 2.

Interestingly, no main effect of cue visibility (conscious versus masked) was observed, whereas a stronger effect in the conscious condition was expected (Dehaene & Changeux, 2011). A possible explanation is that the distracting task performed by participants in unconscious trials may have elicited forgetting through interference (Tomlinson, Huber, Rieth, & Davelaar, 2009), thus strengthening the No-Think effect in the unconscious condition. This hypothesis is supported by the main effect of time which is only observed in the ANOVA restricted to unconscious trials. Moreover, no enhancement of recall was observed in the Think condition between the initial and final recall test. This result is not fully compatible with the previous literature on Think/No-Think effects (Anderson & Huddleston, 2012) and suggests a global detrimental effect of time.

In previous studies, conscious Think and No-Think effects on recall were compared to a baseline condition (Anderson & Green, 2001; Anderson et al., 2004): a subset of words that were not presented between the learning phase and the final test to reflect the pure detrimental effect of time. In this experiment, we did not include such a condition, therefore we could not disentangle an enhancement of recall due to the Think condition from a suppression effect due to the No-Think condition. Moreover, we could not measure the interference effect of the distracting task (Tomlinson et al., 2009) and its interaction with the Think/No-Think cues. Therefore, to confirm that unconscious No-Think cues have a genuine suppression effect on recall performance, we replicated this experiment, including a baseline condition.

## 3. Experiment 2

Experiment 2 was a replication of Experiment 1, which included unconscious baseline trials where no masked cue was presented before the hint word. The aim of this experiment was to reproduce and extend Experiment 1 results, and to prove that masked cues can induce a genuine suppression effect. This experiment was also designed to control for any detrimental effects of time and to rule out interference from

the distracting task in the measured No-Think effect, since the only difference between the unconscious baseline condition and the No-Think condition is the absence/presence of masked cues.

Capitalizing on previous studies and the results of Experiment 1, we did not aim to replicate conscious Think/No-Think effects in this experiment. Instead, conscious trials were used to induce and maintain a strong association between shape cues and Think/No-Think instructions. To this end, conscious hint words were not associated with a specific Think or No-Think task: they were equally preceded by Think and No-think cues. The purpose of this change was to encourage participants to focus on cues in conscious trials and therefore to maximize the Think/No-Think effects in unconscious trials (“shape cueing”). Furthermore, it was not possible to include a baseline in conscious trials equivalent to the baseline designed for unconscious trials. Indeed, presenting a hint word without any conscious cue would have undoubtedly led participants to either think or repress the corresponding response word without any way for us to control this parameter.

We hypothesised that a Think/No-Think effect would occur with masked cues, i.e. that final recall would be significantly lower than initial recall with unconscious No-Think cues, and that there would be a significant difference in final recall performance with No-Think cues compared to both Think cues and baseline, in the absence of any such difference in initial recall performance.

### 3.1. Materials and methods

#### 3.1.1. Participants

Thirty one healthy subjects were recruited through advertising (23 females and 8 males, mean age 24.0 years, range 18–33). All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. No participant took part in both experiments. Participants gave written informed consent before taking part. All methods were carried out in accordance with relevant guidelines and regulations, in particular with the Declaration of Helsinki. One subject was excluded because they did not understand the instructions and stopped the experiment before completion.

#### 3.1.2. Procedure

The procedure consisted of the same three phases as in Experiment 1: a learning phase, a Think/No-Think phase (760 trials, 20 trials per target words: 240 unconscious trials for 12 word pairs and 520 conscious trials for 12 filler word pairs) and a final recall test (Fig. 3).

The learning phase was the same as in Experiment 1, except that word pairs allocated to the conscious condition were presented one additional time (i.e. three times) in order to yield a higher initial recall rate. Thus, participants could do the conscious Think/No-Think task on a maximum number of items.

In both the initial and the final recall test phases, hint words were presented on the screen for 4 s. However, contrary to Experiment 1, participants had to provide their answer before the word disappeared from the screen (i.e. within 4 s versus 8 s in Experiment 1). This change aimed to highlight differences between Think and No-Think in the final recall rate. Two subjects did not reach the minimum recall performance

of 50% after one run of learning phase and were thus presented with word pairs an additional time.

Conscious and unconscious Think/No-Think trials consisted of the same tasks and the same visual time sequence as in Experiment 1, except that an unconscious baseline condition was added. In baseline trials, no shape cue was presented before the metacontrast mask (ring): the diamond and square shapes were replaced by a blank screen (Fig. 3). As in Experiment 1, the Think/No-Think phase started with 36 conscious trials before conscious and unconscious trials were intermixed.

We revealed the presence of masked cues at the end of the experiment and assessed cue visibility (*d'*) using the same procedure as in Experiment 1 (i.e. forced choice on the identity, square or diamond, of the masked shape cue).

#### 3.1.3. Materials

We used 24 pairs of French nouns: a hint word and a response word that were weakly related one to another whilst unrelated to other pairs, as in Experiment 1. Four word pairs were used for each of the 3 unconscious conditions: Think, No-Think, and baseline (for a total of 12 word pairs allocated to the unconscious condition).

Contrary to Experiment 1, in the conscious condition, hint words were not associated with a fixed instruction: they were preceded by a Think shape cue in half of the trials, and by a No-Think shape cue in the other half. That is, we extended to all conscious word pairs what was done on a subset of 6 conscious word pairs in Experiment 1. Consequently, the Think/No-Think effect of conscious shape cues could not be assessed in Experiment 2. The main purpose of this change was to force participants to focus on cues and, by doing so, to maximize Think/No-Think effects in unconscious trials (“shape cueing”). Twelve word pairs were allocated to the conscious condition. As in Experiment 1, each word pair allocated to the unconscious condition was presented 20 times during the Think/No-Think phase. As in Experiment 1, the 24 word pairs were randomly allocated to conditions for each subject, and the randomization process was checked to ensure it did not result in an unbalanced allocation of word pairs to conditions across subjects.

In Experiment 1, preceding conscious trials had no effect on subsequent unconscious trials. Therefore, in Experiment 2, conscious trials were randomized so that each unconscious trial was preceded by the same number of conscious Think and conscious No-Think trials. The computer, screen and programs used to run Experiment 2 were identical that used in Experiment 1 (see Material and methods of Experiment 1).

#### 3.1.4. Statistical analysis

Statistical analysis in Experiment 2 followed the same methods as in Experiment 1, except that we restricted analyses to unconscious trials only. Indeed, in conscious trials, word pairs were not associated with a specific Think or No-Think condition as hint words were equally preceded by Think and No-Think cues.

Effect sizes were computed with Cohen *d* to compare the two experiments.

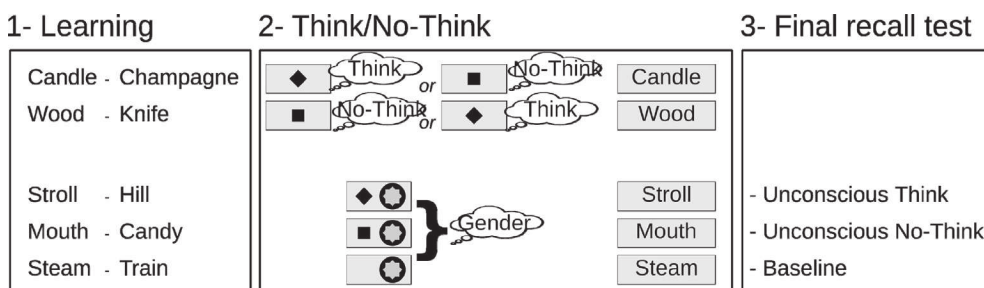
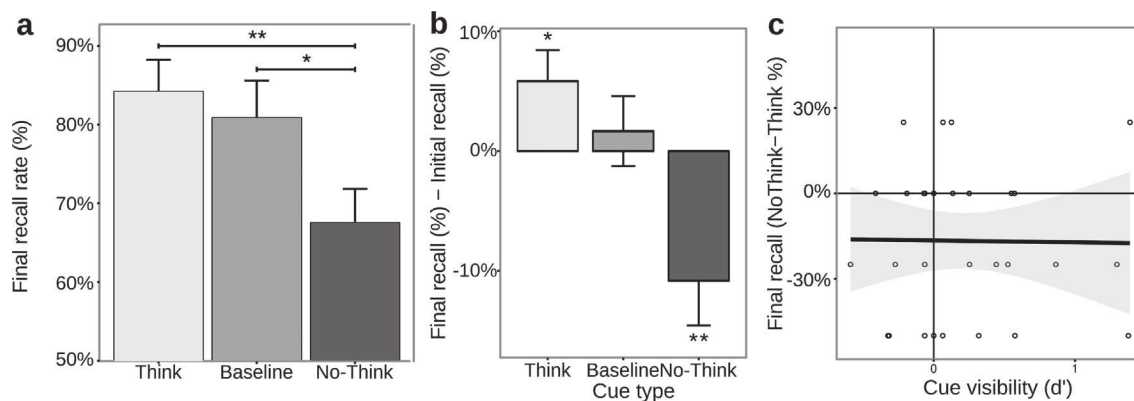


Fig. 3. Design of Experiment 2. A baseline condition was added to the unconscious condition. Therefore, in unconscious trials, either a diamond, a square or a blank screen could be presented before the metacontrast mask (ring). In the conscious condition, all hint words were equally preceded by Think shape cues and No-Think shape cues (i.e. word pairs were not associated with a specific instruction). In the final test, the recall performance was assessed only for the words that were used in the unconscious condition.



**Fig. 4.** Effect of masked cues in Experiment 2. (a) Final recall was lower with No-Think cues (black) compared to Think cues (light grey) and the Baseline condition (dark grey), with no significant difference between Think and baseline conditions. Error bars represent the standard error of the mean (SEM). (b) No-Think cues (black) significantly reduced recall performance (final recall – initial recall), Think cues (light grey) improved recall performance, and recall performance did not significantly change in the baseline condition (dark grey). Error bars represent the standard error of the mean (SEM). (c) The level of cue discriminability, as measured by  $d'$  in unconscious trials did not significantly alter the effect of masked cues on final recall, and the effect remained significant when visibility was nil. The shaded area around the regression lines represents the 95% confidence interval. \* =  $p < 0.05$ , \*\* =  $p < 0.01$ .

## 3.2. Results

### 3.2.1. Masked No-Think cues reduce recall performance compared to Think cues and to baseline

A two-way analysis of variance (ANOVA) on recall performance was performed for each participant, with cue type (Think versus No-Think) and time (initial versus final recall) as within subject factors, and subject as random factor. This analysis revealed a significant interaction between cue type and time ( $F(2,58) = 7.63$ ,  $p = 0.001$ ).

Masked No-Think cues significantly reduced recall performance in the final test compared to the initial test (67% versus 78%,  $t(29) = 2.90$ ,  $p = 0.007$ ). On the contrary, masked Think cues significantly improved recall performance in the final recall compared to the initial test (84% versus 78%,  $t(29) = -2.25$ ,  $p = 0.032$ ). For the baseline condition, no significant difference between initial and final recall was observed (81% versus 79%,  $t(29) = 0.57$ ,  $p = 0.57$ ) (Fig. 4b).

In the initial test, there was no significant difference in recall between words that were allocated to the different unconscious conditions (No-Think: 78%, Baseline: 79% and Think: 78%,  $F(2,58) = 0.02$ ,  $p = 0.98$ ). By contrast, in the final test, a significant difference in recall performance emerged with a main effect of cue type (No-Think: 67%, Baseline: 81% and Think: 84%,  $F(2,58) = 4.65$ ,  $p = 0.013$ ), and final recall performance was significantly lower when words were preceded by both No-Think cues compared to Think cues (difference: 17%,  $t(29) = 3.55$ ,  $p = 0.0013$ ) and baseline (difference: 13%,  $t(29) = 2.08$ ,  $p = 0.047$ ). However, there was no significant difference in recall performance between Think and baseline conditions (difference: 3%,  $t(29) = 0.55$ ,  $p = 0.59$ ) (Fig. 4a and Table 1).

### 3.2.2. The memory effect is not due to cue discriminability

Discriminability, as assessed by the forced choice test, was again very low in the unconscious condition but significantly above zero (hit rate 58.1%,  $d' = 0.21$ ,  $t(29) = 2.23$ ,  $p = 0.033$ ). As in Experiment 1, a between-subjects regression analysis (Greenwald et al., 1996) demonstrated that subjects' ability to discriminate masked cues ( $d'$ ) was unrelated to the cues effect on memory (No-Think – Think final recall performance). The slope of the regression line was not significantly different from zero (slope =  $-0.007$ ,  $t(28) = -0.07$ ,  $p = 0.94$ ), indicating that people's ability to discriminate masked cues did not predict their memory effect. The intercept of the regression line was significantly different from zero (intercept =  $-16\%$ ,  $t(28) = -3.20$ ,  $p = 0.003$ ), indicating that people who could not discriminate masked cues still showed an effect on final recall (Fig. 4c).

To further isolate the inhibition effect, we conducted the same regression analysis for final recall performance in unconscious No-Think trials versus baseline as a function of cue discriminability. Again, the effect of cues was unrelated to people's ability to discriminate masked cues (slope =  $-0.12$ ,  $t(28) = -0.91$ ,  $p = 0.37$ ). The intercept was negative, but failed to reach statistical significance (intercept =  $-11\%$ ,  $t(28) = -1.56$ ,  $p = 0.13$ ).

We repeated the above analysis on final versus initial recall performance for No-Think word pairs, as a function of cue discriminability ( $d'$ ). This analysis yielded a similar result with an effect of cues that was unrelated to people's ability to discriminate masked cues (slope =  $-0.11$ ,  $t(28) = -1.56$ ,  $p = 0.13$ ). The effect of cues remained significant even for people who could not discriminate masked cues (intercept =  $-8\%$ ,  $t(28) = -2.15$ ,  $p = 0.040$ ).

### 3.2.3. Performance in the grammatical gender determination task

Performance in the word gender determination task did not significantly differ according to masked cue type (No-Think: 99.3%, Baseline: 99.5% and Think: 99.4%,  $F(2,58) = 0.21$ ,  $p = 0.81$ ), nor did reaction time (No-Think: 369 ms, Baseline: 394 ms, Think: 365 ms,  $F(2,58) = 2.83$ ,  $p = 0.07$ ).

### 3.2.4. Comparison of effect size in Experiment 1 and Experiment 2

We computed the effect size (Cohen  $d$ ) for the difference between unconscious Think and unconscious No-Think cues in the two experiments. These amounted to 0.25 in Experiment 1 and 0.72 in Experiment 2. An ANOVA on recall performance, with cue type (Think versus No-Think) and Experiment (1 versus 2) as factors showed a significant main effect of cue type ( $F(1,73) = 15.1$ ,  $p < 0.001$ ) but no significant effect of Experiment ( $F(1,72) = 0.15$ ,  $p = 0.7$ ), suggesting that effect size was comparable in the two experiments.

## 4. General discussion

Taken together, the results of this study demonstrate that memory suppression through executive control can be unconsciously triggered on specific memories. Borrowing from Anderson's Think/No-Think paradigm (Anderson & Green, 2001), participants were trained to actively recall or repress word-word associations, in response to conscious visual cues. Then, the very same cues were subliminally presented while participants were doing a grammatical gender determination task on other hint words. Experiment 1 showed that recall performance was significantly lower with No-Think cues compared to Think cues, be they conscious or masked. Crucially, word pairs used in the unconscious

condition were different from those used in the conscious condition, therefore, they had never been preceded by conscious Think/No-Think cues or consciously associated with these instructions.

In Experiment 1, the difference between the Think and No-Think conditions could either be due to a recall enhancement by Think cues and/or to a suppression effect by No-Think cues. Indeed, Experiment 1 did not comprise a baseline condition. Experiment 2 replicated the effect of masked cues on recall performance, and further demonstrated that this includes a suppression-induced forgetting component. Indeed, the recall of word pairs was lower when preceded by masked No-Think cues than in a neutral baseline condition (i.e. no cue). Therefore, the memory suppression effect was independent of any detrimental effect of time, or an interference with the distracting task. Furthermore, other controls ruled out a difference in initial encoding or a residual capacity to discriminate the cues.

In both experiments,  $d'$  values were significantly above zero. As proposed by Greenwald et al. (1996), we therefore performed a regression analysis in order to check whether subliminal priming relies on residual visibility. This method has been discussed using simulations (see e.g. Miller, 2000, but also Greenwald's reply in Klauer & Greenwald, 2000) and is routinely used even when  $d'$  are not significantly different from zero. We showed that the behavioural measures of interest were not correlated to  $d'$  and that the intercepts were significantly different from zero. This result suggests that subliminal cues impact memory independently of participant's ability to discriminate them.

The unconscious memory effect did not significantly differ between Experiment 1 and Experiment 2 although experimental modalities were slightly different, suggesting that this effect is robust and reproducible. Surprisingly, effect size was not significantly different between the masked and the conscious conditions in Experiment 1 (6% difference between Think and No-Think conditions with both conscious and masked cues). Previous work suggested that masked cues had a weaker effect than conscious cues (Dehaene & Changeux, 2011 for a review). However, opposing studies have shown that priming effects could be comparable with low-visibility cues and high-visibility cues (Vorberg et al., 2003). Similarly, electrophysiological studies found that N400 waves associated with semantic processing had the same amplitude under conscious and unconscious conditions in attentional blink and masking paradigms (Kiefer, 2002; Luck, Vogel, & Shapiro, 1996; vanGaal et al., 2014). These contradictory findings are potentially linked to the masking procedure itself. Indeed, Vorberg et al. (2003) used a long stimulus onset asynchrony (SOA) to increase the cue effect, and a long mask duration to maintain a low visibility of the stimulus. Following this procedure in the present experiment (SOA = 66 ms and mask duration = 200 ms), we obtained consistent results, i.e. strong effects of low-visibility cues.

Alternatively, the relatively large effect of masked cues we observed might be the result of the peculiar nature of the task. Indeed, we found a low intrusion rate (i.e. thinking about the response word while the instruction is to determine the gender of the hint word) in the unconscious condition (16.5% on average) compared to what is usually found in the conscious version of the Think/No-Think paradigm (60% at the beginning of the procedure and 30% at the end of the experiment, see Levy & Anderson, 2012). Several studies pointed to the importance of intrusions in the inhibition process (Benoit, Hulbert, Huddleston, & Anderson, 2015; Gagnepain, Hulbert & Anderson, 2017; Hellerstedt, Johansson, & Anderson, 2016; Levy & Anderson, 2012). However, intrusions could also induce a paradoxical reinstatement or reinforcement of the memory the subject tries to suppress. The conscious No-Think effect may therefore result from two opposing trends: a high inhibition that is tempered by automatic recall (as reflected by intrusions). By contrast, the unconscious memory effect may arise from a lower but unchallenged inhibitory effect, leading finally to a net effect similar to the one obtained under the conscious condition.

Our results are in line with previous publications suggesting that

inhibition can be induced by subliminal stimuli. These studies demonstrated that cognitive control could be influenced by subliminal priming (Boy, Husain, & Sumner, 2010), error detection processes could proceed without awareness (Charles et al., 2013) and that inhibition, even intentional, could be triggered unconsciously (Parkinson & Haggard, 2014; vanGaal et al., 2010). Moreover, unconscious memory suppression further adds to the strongly debated question of the long-lasting effects of unconscious cues on cognitive processes. In most priming studies, the effect of masked cues sharply decreases with time and vanishes within less than a second (Dehaene & Changeux, 2011). Nonetheless, recent studies suggested that a stimulus subjectively judged as unseen could be maintained in neuronal activity for more than 1 s (King, Pescetelli, & Dehaene, 2016). In addition, subliminal visual stimuli have been shown to affect familiarity judgements (Sweeny, Grabowecy, Suzuki, & Paller, 2009; Voss & Paller, 2009; Voss, Baym, & Paller, 2008) or preference judgement (Kunst-Wilson & Zajonc, 1980) several minutes, hours or days later, and emotional words trigger cerebral changes over several minutes (Gaillard et al., 2007). In the present experiment, the lower recall performance in the unconscious No-Think condition supports the idea that masked cues have a detrimental effect that affects performance several minutes after they were presented (i.e. in the final test). To the best of our knowledge, only one previous study demonstrated a long-lasting detrimental effect of unconscious cues by measuring the attractiveness of masked cues in a reinforcement learning paradigm (Pessiglione et al., 2008).

Finally, working memory has already been demonstrated to be influenced by unconscious effects (Soto & Silvano, 2014; Trübtschek et al., 2017). To ensure that our effects concerned long-term declarative memory processing, we used a large number of word pairs (30 in Experiment 1 and 24 in Experiment 2), far exceeding working memory capacity (Squire & Wixted, 2011).

To summarize, these experiments showed that it is possible to suppress specific memories unbeknownst to participants, in a minimal laboratory setting. As people encounter repeated occasions to recall or repress memories throughout their lifetime, the mechanism described here could explain why one may occasionally experience the inability to recall unwanted memories, while unaware of any conscious will to reject it (Naccache, 2006).

## Acknowledgements

This work was supported by the Fondation pour la Recherche Médicale [grant number FDM20120624489 and 40532] the French program Investissements d'avenir [grant number ANR-10-IAIHU-06] and the Fondation d'entreprise Groupe Pasteur Mutualité. The funding sources had no involvement in study design, analysis, report writing or decision to submit the article for publication. Thanks to Olivia Faull for proofreading the manuscript. Declarations of interest: FV has been invited to scientific meetings, consulted and/or served as speaker and received compensation by Lundbeck, Servier, Recordati, Janssen and Otsuka. None of these links of interest are related to this work.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.cognition.2018.06.023>.

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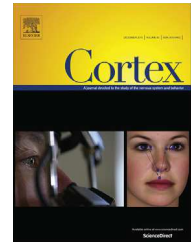
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**Why the P3b is still a plausible correlate of conscious access? A  
commentary on Silverstein et al., 2015**

Naccache, L., Marti, S., Sitt, J. D., Trübtschek, D., & Berkovitch, L. (2016). Why the P3b is still a plausible correlate of conscious access? A commentary on Silverstein et al., 2015. *Cortex*, 85, 126–128. <http://doi.org/10.1016/j.cortex.2016.04.003>



## Commentary

## Why the P3b is still a plausible correlate of conscious access? A commentary on Silverstein et al., 2015



Lionel Naccache <sup>a,b,c,d,e,\*</sup>, Sébastien Marti <sup>f</sup>, Jacobo D. Sitt <sup>c,d</sup>,  
Darinka Trübtschek <sup>f,g</sup> and Lucie Berkovitch <sup>f</sup>

<sup>a</sup> AP-HP, Groupe hospitalier Pitié-Salpêtrière, Department of Neurology, Paris, France

<sup>b</sup> AP-HP, Groupe hospitalier Pitié-Salpêtrière, Department of Neurophysiology, Paris, France

<sup>c</sup> INSERM, U 1127, Paris, France

<sup>d</sup> Institut du Cerveau et de la Moelle épinière, ICM, PICNIC Lab, Paris, France

<sup>e</sup> Sorbonne Universités, UPMC Univ Paris 06, Faculté de Médecine Pitié-Salpêtrière, Paris, France

<sup>f</sup> Cognitive Neuroimaging Unit, CEA DSV/I2BM, INSERM, Université Paris-Saclay, NeuroSpin Center, Gif/Yvette, France

<sup>g</sup> Ecole des Neurosciences de Paris Ile-de-France, France

We read with interest the article by Silverstein and colleagues (Silverstein, Snodgrass, Shevrin, & Kushwaha, 2015) who questioned the putative specificity of the P3b event-related potentials (ERP) component as a neural signature of conscious access to a visual representation. Prior to this new study, numerous empirical reports revealed that a brain response peaking ~300 msec after stimulus onset and maximally distributed over parietal electrodes – the so called P3b – is closely related to subjective visibility (Sergent, Baillet, & Dehaene, 2005; Vogel, Luck, & Shapiro, 1998). These experimental findings provided the bases to develop neuronal and computational theories of consciousness such as the global workspace model (Dehaene & Changeux, 2011; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Dehaene & Naccache, 2001). Silverstein and colleagues used a ‘passive attentive’ version of a masked visual odd-ball paradigm while recording scalp ERPs. In each trial, subjects were presented with either the masked word ‘LEFT’ (in 80% or 20% of trials) or the masked word ‘RIGHT’ (in 20% or 80% of trials). Word frequency was balanced across subjects, who were asked to carefully attend to the masked sequence. Not only were they instructed that this sequence contained a masked word, but

also that: “however implausible it might seem, our prior data suggested that the stimuli would nonetheless be unconsciously perceived and produce brain wave effects – but only if they maintained their attention”. When contrasting ERPs elicited by rare and frequent masked words, Silverstein and colleagues identified a P3b ERP component followed by a late, and sustained, slow wave (LSW). Given that participants subjectively reported the absence of conscious perception of words, and that they performed at chance-level in a stimulus detection task performed after the main experiment, Silverstein and colleagues concluded that a P3b can be observed during unconscious perception. If valid, their interpretation would then simply invalidate the P3b as a possible candidate neural signature of conscious access.

This original and provocative study, however, raises both methodological and conceptual concerns which need to be addressed before one can adopt Silverstein and colleagues’ interpretation.

### 1. A set of methodological problems

The P3b is part of a larger complex of positive deflections – the so-called P300. Of particular importance here, the P3a can be

\* Corresponding author. AP-HP, Groupe hospitalier Pitié-Salpêtrière, Department of Neurology, Paris, France.

E-mail address: [lionel.naccache@gmail.com](mailto:lionel.naccache@gmail.com) (L. Naccache).

<http://dx.doi.org/10.1016/j.cortex.2016.04.003>

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functionally distinguished from the P3b: it is known to occur in the absence of conscious perception (Muller-Gass, Macdonald, Schroger, Sculthorpe, & Campbell, 2007) and even in non-conscious patients (Faugeras et al., 2012). Both the P3a and P3b are positive deflections and occur in similar time windows, but they can nevertheless be separated based on their topographies. The P3b is maximally distributed over parietal electrodes, while the P3a is more frontally distributed. The spatial sampling of the EEG signal is therefore critical to separate these ERPs. Surprisingly, the authors only used 3 midline (Fz, Cz, Pz) electrodes referenced to linked ears, as well as 2 electrodes at the right eye to detect eye movement artifacts. As expected for a P3b component, the effect reported by Silverstein and colleagues was maximal over Pz, but we simply do not have access to the scalp topographies of the ERP effects reported in this work. We agree that there is no intrinsic relationship between the number of electrodes and the quality of a result, but in the context of distinguishing P3b from P3a ERP components this limitation turns into a genuine problem.

In the same vein, one of the most reliable findings in the vast odd-ball literature, is the existence of a N2 and mismatch negativity (MMN) ERP effect occurring before the P3 complex (Tiihinen, May, Reinikainen, & Naatanen, 1994). The apparent absence of such an effect (a small inverse difference is seen in Figure 2) confirms the necessity of sampling brain activity with a richer spatial resolution in order to reliably describe the observed effects.

Moreover, shortcomings in the statistical analyses of the ERPs deserve further discussion. Visual inspection of the ‘effects’ suggests that the effect size reported by Silverstein et al. are not substantially different from fluctuations within the baseline and from other periods of the ERPs (see e.g., Figure 2C). Actually, the authors did not assess significant differences on the entire time course of the ERP but only on predefined time windows. Thus it is impossible to determine whether the reported effects are temporally and spatially precise and specific to the P3b. A better approach would consist in performing non selective sample-by-sample tests, and then identifying temporal clusters during which ERPs significantly differ.

More importantly, although the article by Silverstein et al. opens by asking the fundamental question “How can perceptual awareness be indexed in humans?”, their experimental design is lacking the crucial comparison of the unconscious ‘P3b’ with its conscious equivalent. Rather than using exclusively masked trials, the authors could have added unmasked trials, in order to compare the properties (latency, amplitude and effect size, duration, topography) of conscious and unconscious ERP effects. By doing so previous studies could identify specific components of conscious access (Dehaene et al., 2006). From a theoretical perspective, we previously mentioned and modeled the possibility for a masked stimulus to “evoke transient workspace activity of variable intensity and duration” (see also Figure 1 in Dehaene & Naccache, 2001). Such transient and partial activation of the workspace could appear as brief and small patterns of activity distinct from a large and sustained P3b component. Therefore, without this crucial conscious contrast, it becomes almost impossible to precisely qualify the observed ERP effect.

It is noteworthy that according to our theory, conscious access associated with the P3b is also associated with other signatures (Gaillard et al., 2009) such as: long-range synchrony in theta–alpha–beta band, decrease of alpha power, and late increase of gamma power. None of these neural signatures, complementary to the P3b, are tested here and the nature of the observed ERP effects therefore remains unclear.

Additionally, the interesting use by Silverstein et al. of ‘LEFT’ and ‘RIGHT’ as target words opened the possibility of complementing the results by lateralized readiness potentials (LRPs) analyses. Such analyses proved to be very useful to explore both unconscious and conscious processing of masked primes (Dehaene et al., 1998; Eimer & Schlaghecken, 1998). Unfortunately, the use of only 3 midline electrodes, and the absence of C3/C4 electrodes precluded this interesting complementary approach.

Furthermore, from a Bayesian perspective, we think the authors should have mentioned and discussed more extensively the large set of empirical evidence that their finding seems to contradict: numerous studies conducted in normal controls as well as in many clinical settings (e.g.,: blindsight, visual neglect) support the P3b theory by reporting rich unconscious processing of visual stimuli without any late P3b signature (for a review see Dehaene & Changeux, 2011). This literature, acting here as a strong prior against Silverstein and colleagues interpretation, needs to be addressed.

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## 2. Conscious metacognition of unconscious perceptual processes?

Beyond these notable methodological issues, this article also raises a more profound question. The major difference between this study and previous studies rests in the fact that subjects were told from the very beginning of the presence of masked stimuli, and were instructed to pay attention to them very carefully. Therefore, even if we discard the methodological issues we just raised, and consider that these results are correct, it may be the case that the P3b signature observed here between deviant and standard stimuli corresponds to a metacognitive effect, that is to say to conscious access to the consequence of unconscious processing of masked primes. For instance, a motor effect induced by the processing of the rare ‘LEFT’ prime (or ‘RIGHT’ for other subjects) in motor areas may well lead to conscious access to a subjective confidence information that the prime was deviant or standard. By amplifying subjects’ attention to monitor prime processing, this metacognitive interpretation may well explain the striking pattern of results reported here. Interestingly, a growing empirical evidence demonstrates that a large class of unconscious cognitive processes are strongly influenced by the conscious posture and endogenous attentional allocation (Naccache, Blandin, & Dehaene, 2002). In addition to such an amplification, it might be the case that subject informed of the presence of subliminal stimuli could more easily introspect a form of surprise originating either from perceptual or from motor-related areas (‘LEFT’, ‘RIGHT’). In other words, this study may illustrate conscious access to the downstream effects of an unconsciously perceived stimulus. Interestingly, a recent study using a visual masked priming paradigm

reported that the conflict between masked prime and visible target stimuli modulated two ERP components (Desender, Van Opstal, Hughes & Van den Bussche, 2016): an early N2 component, as well as a late P3 complex. During this experiment, subjects had to perform two tasks on each trial: they first had to respond to the target, and then to introspect the difficulty of the trial. Nicely, introspection of the prime-target conflict elicited by the unconscious processing of the prime was possible, and correlated only with the P3 component. Similarly, in the study by Silverstein and colleagues, one may suppose that the P3b component and the LSW they observed correspond to the conscious introspection of processes elicited by the unconsciously perceived prime.

As a conclusion, if the results reported in Silverstein et al. do correspond to a genuine P3b ERP component (but see our methodological concerns above), they may elegantly illustrate the complex relations prevailing between conscious and unconscious processes, and still not refute the relationship prevailing between conscious access and the P3b ERP component.

## Funding

This work has been supported by the Fondation pour la Recherche Médicale ('Equipe FRM 2015') grant to L.N. and by the 'Recovery of consciousness after severe brain injury Phase II' grant of the James S. McDonnell Foundation.

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Received 16 February 2016

Reviewed 24 March 2016

Revised 29 March 2016

Accepted 1 April 2016

Abstract:

Across a variety of experimental paradigms, an elevated threshold for conscious perception has been observed in persons with schizophrenia. However, even subtle measures of subliminal processing appear to be preserved. In this thesis, we rely on this dissociation between conscious and subliminal processing observed in schizophrenia to examine conscious access mechanisms and non-conscious processing. We first probed the link between cerebral connectivity and consciousness threshold, and found that, in patients with psychosis, dysconnectivity was associated with an elevated consciousness threshold, which may in turn favour psychotic symptoms. We explored how top-down, bottom-up factors and their interaction modulated conscious access in healthy controls and patients with schizophrenia using behavioural and electroencephalography measures. We showed that an accumulation of evidence could occur under unattended conditions but was tremendously amplified in healthy controls for attended stimuli. By contrast, patients with schizophrenia exhibited some impairments of this top-down attentional amplification. To further study this interaction between bottom-up and top-down processing, we then conducted three additional studies in healthy controls. First, we manipulated attentional blink (reflecting top-down processing) and visual masking (capturing bottom-up processing) in preventing conscious access and observed a synergistic effect. We also examined whether predicted events were better processed under low visibility conditions and found that stimuli violating expectations were more easily identified than confirming or random ones. Finally, we conducted behavioural experiments on language, revealing that syntactic features could be subliminally extracted and induce different levels of priming.

Keywords: Consciousness, Schizophrenia, Masking, Attention, Prediction, Syntax

**Traitement non conscient, amplification attentionnelle et accès conscient chez les sujets sains et atteints de schizophrénie**

Résumé :

Une élévation du seuil de perception consciente a été observée chez les personnes atteintes de schizophrénie dans de nombreux paradigmes expérimentaux. Toutefois, des mesures parfois subtiles du traitement subliminal sont préservées chez ces patients. Dans ce travail de thèse, nous nous appuyons sur cette dissociation entre traitement conscient et subliminal dans la schizophrénie pour explorer l'accès conscient et les processus non conscients. Nous avons tout d'abord testé le lien entre connectivité cérébrale et conscience, montrant que la dysconnectivité était associée à une élévation du seuil de conscience chez les patients atteints de psychose, ce qui favoriserait la survenue de symptômes psychotiques. Nous avons ensuite exploré comment les facteurs descendants, ascendants et leur interaction modulaient l'accès conscient chez les sujets sains et atteints de schizophrénie à l'aide de mesures comportementales et d'électroencéphalographie. Nos résultats indiquent qu'une accumulation d'évidence a lieu en l'absence d'attention, et qu'elle est fortement amplifiée chez les sujets sains lorsqu'ils focalisent leur attention sur un stimulus. En revanche, les patients atteints de schizophrénie présentent des anomalies partielles de cette amplification attentionnelle descendante. Pour explorer davantage les interactions entre facteurs descendants et ascendants, nous avons réalisé trois études supplémentaires chez les sujets sains. Tout d'abord, nous avons étudié l'interaction entre clignement attentionnel (reflétant la signalisation descendante) et masquage (traduisant la signalisation ascendante) dans la perturbation de l'accès conscient et avons observé une synergie. Nous avons ensuite regardé si le traitement des événements prévisibles était facilité en condition de faible visibilité et montré que les stimuli violant les attentes étaient plus facilement identifiés que ceux qui les confirmaient ou étaient aléatoires. Enfin, nous avons mené des expériences comportementales sur le langage et observé que les caractéristiques syntaxiques pouvaient être extraites inconsciemment et induire différents niveaux d'amorçage.

Mots clés : Conscience, Schizophrénie, Masquage, Attention, Prédiction, Syntaxe