



Use of pupillometry in the assessment of listening effort : a methodological approach

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Use of pupillometry in the assessment of listening effort: a methodological approach

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“Les femmes, je le sais, ne doivent pas écrire, j’écris pourtant.”

Marceline Desbordes-Valmore

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Abstract

Our everyday listening environment is a complex acoustic mixture that needs to be processed and filtered in order to access relevant auditory information. Cognitive resources are then required for the selective processing of a particular sound stream, and simultaneous filtering of irrelevant information. The engagement of these cognitive resources to understand an auditory message, leads to listening effort, especially in noisy environments. Listening effort has been investigated in the last two decades, using a large panel of methods. The work of this thesis aims at bringing new insights on the investigation of listening effort, first with the use of pupillometry, then based on the complementarity of different measures (subjective, behavioral and objective). A methodological investigation was first conducted on pupillometry data recorded during a word-in-noise task, among older hearing-impaired patients, with and without hearing-aids. Several analysis methods were compared, including different normalization techniques, baseline periods, and baseline durations. While the different normalization methods and baseline durations showed similar results, the choice of the baseline period turned out to have a crucial influence on conclusions. Indeed, anticipatory, pre-stimulus cognitive processes, such as attention mobilization were observed on pupil dilation when the baseline period was the most anterior, relative to the stimulus onset. The differences in pupil dilation were observed even at perfect intelligibility, highlighting the relevance of pupillometry as an objective measure of listening effort. The second axis of this work focused on the results of empirical studies in which several measures, including pupillometry, were concurrently used to assess listening effort. Empirical studies were conducted (1) in older hearing-impaired patients using subjective measures of effort and pupillometry during a word-in-noise task, (2) in normal-hearing young adults using pupillometry and scalp electroencephalography during a discrimination in noise task. The lack of correlation between self-assessed difficulty of the task and pupil responses in hearing-impaired listeners, suggests that the two measures address different aspects of effortful listening. Pupil responses allowed for the observation of anticipation processes, even at perfect intelligibility, while subjective measures described the overall perceived effort during the task. In normal-hearing young adults, the

modulations of the cortical responses observed thanks to electroencephalography, were linked to the processing of the stimulation and the inhibition of the irrelevant sound source during discrimination. Pupillary responses, recorded simultaneously, brought information on participants' arousal state during the task. Results of both studies then suggest that the different measures complement each other, and that their combination can help for the understanding of the different cognitive processes involved during effortful listening. Overall, this PhD work brings insights on the use and processing of the pupillometric signal to explore listening effort. It also underlines the relevance of the use of pupillometry and its contribution for the study of listening effort, among distinct populations. Finally, it shows the complementarity of subjective and objective measures during the assessment of listening effort, supporting the idea that it is a multidimensional construct.

Keywords: Listening effort, Auditory perception in noise, Auditory selective attention, Cognitive activity, Arousal, Pupillometry, Electroencephalography, Older hearing-impaired patients

Résumé

Etude de l'effort d'écoute par pupillométrie: une approche méthodologique

Notre environnement sonore quotidien est un mélange acoustique complexe, qui doit être traité et filtré, pour accéder aux informations auditives pertinentes. Les processus simultanés de sélection d'un son en particulier et d'inhibition de l'information non pertinente, nécessitent donc des ressources cognitives. Le déploiement de ces ressources pour comprendre un message sonore induit donc un effort d'écoute, et plus particulièrement dans les environnements bruyants. Depuis deux décennies, l'effort d'écoute a été étudié via un important panel de méthodes. Le travail de cette thèse a pour but d'apporter de nouvelles perspectives à l'étude de l'effort d'écoute, dans un premier temps par l'utilisation de la pupillométrie, puis en s'appuyant la complémentarité de différentes mesures (subjectives, comportementales et objectives). Une étude méthodologique a d'abord été menée sur les données de pupillométrie enregistrées pendant une tâche de reconnaissance de mots dans le bruit, chez des patients âgés malentendants, avec ou sans leur aide auditive. Plusieurs méthodes d'analyse ont été comparées, dont différentes techniques de normalisation, périodes de ligne de base et durées de ligne de base. Alors que les différentes méthodes de normalisation ainsi que durées de ligne de base ont donné des résultats similaires, le choix de la période de ligne de base a eu une influence déterminante sur les conclusions de l'étude. En effet, des processus cognitifs d'anticipation, liés à la mobilisation de l'attention avant la présentation des stimuli, ont pu être observés sur la dilatation pupillaire, lorsque la période de ligne de base était la plus antérieure à la présentation des mots. Ces différences de dilatation pupillaire ont pu être observées même lorsque l'intelligibilité était parfaite, soulignant la pertinence de la pupillométrie comme mesure objective de l'effort d'écoute. Le deuxième axe de cette thèse se concentre sur les résultats d'études empiriques, dans lesquelles plusieurs mesures permettant d'appréhender l'effort d'écoute, dont la pupillométrie, ont été conjointement utilisées. Les études empiriques ont été menées (1) chez les patients âgés malentendants en utilisant des mesures subjectives de

l'effort d'écoute et la pupillométrie pendant une tâche de reconnaissance de mots dans le bruit, (2) chez les jeunes adultes normo-entendants en utilisant la pupillométrie et l'électroencéphalographie de scalp pendant une tâche de discrimination dans le bruit. L'absence de corrélation entre les scores d'auto-évaluation de difficulté de la tâche et les réponses pupillaires chez les patients malentendants suggère que les deux mesures évaluent différents aspects de l'effort d'écoute. Les réponses pupillaires permettent d'observer des processus d'anticipation, alors que les mesures subjectives décrivent l'effort global perçu pendant la tâche. Chez les jeunes adultes normo-entendants, les modulations des réponses corticales observées grâce à l'électroencéphalographie, étaient liées au traitement de la stimulation et à l'inhibition de la source sonore non pertinente pendant la discrimination. Les réponses pupillaires, enregistrées simultanément, ont apporté des informations concernant l'état de vigilance des participants pendant la tâche. Les résultats de ces deux études suggèrent donc que les différentes mesures se complètent, et que leur combinaison aide à la compréhension des divers processus cognitifs impliqués dans l'effort d'écoute. Dans l'ensemble, ce travail de doctorat apporte de nouvelles connaissances sur l'utilisation et le traitement du signal de pupillométrie. Il souligne également la pertinence et les contributions de la pupillométrie dans l'étude de l'effort d'écoute. Enfin, il montre la complémentarité des mesures objectives et subjectives dans l'étude de l'effort d'écoute, appuyant l'hypothèse que l'effort d'écoute est multidimensionnel.

Mots-clés: Effort d'écoute, Perception auditive dans le bruit, Attention sélective auditive, Activité cognitive, Vigilance, Pupillométrie, Électroencéphalographie, Patient âgé malentendant

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Chapter 1

Theoretical background

1.1 Auditory perception in humans

Humans, like any other living creatures, were given sensory systems (vision, audition, smell, taste and touch) to interact with their environment throughout life. By these different systems, information is received and processed to apprehend, understand and adapt to the environment. Perception (from the Latin *perceptio*, meaning gathering) is this specific act of combining and interpreting external information to understand our environment. Therefore, auditory perception is the ability to perceive our sound environment. In the present section, I will briefly define sound as a physical entity, before presenting the human auditory system and different techniques to explore auditory perception.

1.1.1 Physics of sound

Where does sound come from ? Sound comes from successive waves of pressure increase and pressure decrease in the air. Sound is then a vibration that propagates through the air as an acoustic wave. These oscillations in pressure can occur at different rates, measured in Hertz (Hz) (corresponding to the number of oscillation cycles per second), defining the frequencies of the sound. Humans can perceive sounds that range from 20 to 20 000 Hz. These pressure variations can also have different amplitudes, defining the intensity of the sound, measured in decibel (dB). Sounds that are composed of multiple waves of different frequencies are called complex sounds, the lowest frequency being called fundamental frequency. A sound can

be considered harmonic when it only contains integer multiples of the fundamental frequency.

Acoustic properties Sounds can be characterized and identified by the human ear thanks to their acoustic properties. Classic properties of the sound include: fundamental frequency, frequency content, intensity, effective duration. Each of these acoustic properties are processed by the ear and brain and therefore have related perceptual properties. Pitch is closely related to the fundamental frequency of the sound and can be perceived as *high* or *low*. High-pitched sounds are linked to high frequencies, low-pitched sound are linked to low frequencies. Loudness is related to the sound pressure level and corresponds to the sensation of intensity, from *quiet* to *loud*. If two sounds are different but have equivalent pitch and loudness (for example, the same note played at equivalent intensity by two different music instruments), they can be differentiated thanks to a specific attribute called *timbre*, related, in part, to the frequency content of the sound. Finally, perceived duration of the sound is directly linked to its length (or its effective duration), *long* or *short*.

1.1.2 Human auditory system

The ear is the main acoustic sensor in humans. Sound and its acoustic informations are first received through the ear before being transmitted to the brain to be processed. The ear can be divided in three parts: the outer ear, the middle ear and the inner ear (see Fig 1.1: Upper). The outer ear is composed of the auricle, which captures sound, and the auditory canal through which vibrations propagate to the tympanic membrane. Vibrations of the tympanic membrane are transmitted to the middle ear by the ossicle chain containing the hammer, anvil and stirrup. They provide amplification of the vibrations between the eardrum and the oval window. Sensors responsible for audition are found in the inner ear, inside the cochlea. The cochlea is an helical structure which holds on its whole length the basilar membrane on which lies the organ of Corti. In this organ of Corti, little sensory cells, called hair cells, are present and responsible for the auditory information transmission to the brain. Indeed, when the hair cells are stimulated, the mechanic signal (vibrations) is turned into an electric signal transmitted to the brain through the auditory nerve.

By the specific anatomy of the cochlea and the basilar membrane structure, its maximal vibration amplitude is located on a different position according to the acoustic frequency. Very high frequencies are captured at its base, while very low frequencies are captured at its end (apex), leading to frequency specialization of hair cells (tonotopic organization) (see Fig 1.1: Lower). This tonotopy remains in the auditory nerve, in which each fiber has its specific frequency.

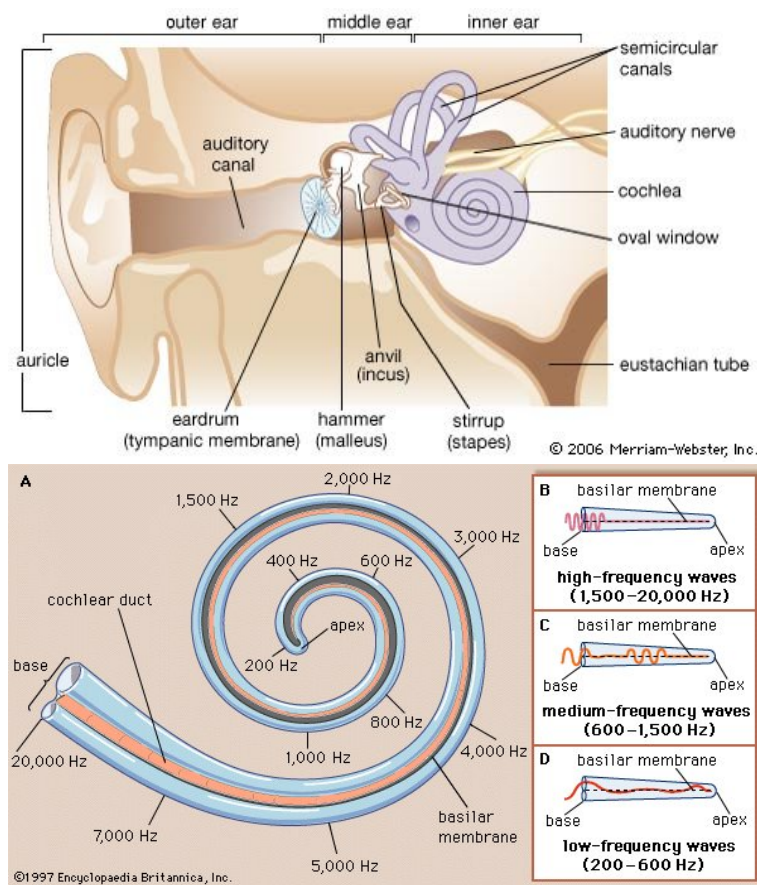


FIGURE 1.1: Upper: Human ear structure.
Lower: Cochlea organization and hair cells frequency specialization
From Encyclopaedia Britannica,
<https://www.britannica.com/science/ear>

The auditory nerve then passes the information to the ipsilateral (same side as the stimulation) cochlear nuclei (dorsal and ventral), before reaching the contralateral (opposite side of stimulation) superior olivary nuclei (see Fig 1.2). At this stage, spatial information about the stimulus can be processed by evaluating intensity and

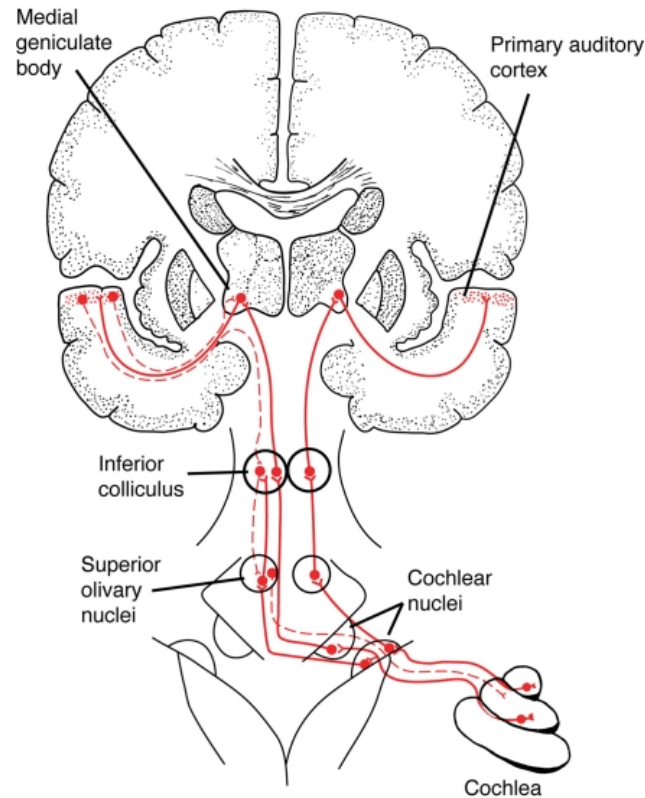


FIGURE 1.2: Simplified representation of auditory pathways through human auditory system (from the cochlea to the auditory cortex). Solid red lines represent ascending auditory pathways, dashed red lines represent descending auditory pathways (represented on one side only). From Patel and Iversen (2007).

arrival time differences between the two ears. Information then transit to the inferior colliculus in the midbrain. Information is transmitted from inferior colliculus to auditory cortex, via the thalamus including medial geniculate body, through three pathways. One pathway from central inferior colliculus to the thalamus and primary auditory cortex with tonotopic organization, two from the inferior colliculus to the thalamus and secondary auditory cortex. While one pathway is strictly auditory, others are multisensory and process combined somato-sensory information. Primary auditory cortex is located in the Heschl's gyrus in the superior part of the temporal lobe. It also has a tonopic organization that allows a precise representation of sounds frequency. Auditory information goes on then to secondary and associative cortical areas, ending its way according to stimulus complexity and relevance.

In addition to ascending (also called *afferent*) pathways, from cochlea to cortex (presented just before), the human auditory system contains descending (or *efferent*) pathways, from cortex to cochlea. Input from the auditory cortex is received by the

superior olivary complex via the inferior colliculus, and terminates its way in the olivocochlear system, linking nuclei of the superior olivary complex to the cochlea and auditory nerve (Guinan, 2006; Rasmussen, 1946). The olivocochlear system consists of the lateral olivocochlear system, which innervates auditory-nerve fibers, and the medial olivocochlear (MOC) system, which terminates onto the cochlear outer hair cells.

Both ascending and descending systems contribute to auditory information processing. Ascending pathways (see Fig 1.2) have been associated with acoustic features representations or sound spacialization for instance. Descending pathways (see Fig 1.2) are involved notably in the detection of behaviourally relevant stimuli in goal-directed attention or noise reduction (Andéol et al., 2011; Lopez-Poveda, 2018; Micheyl and Collet, 1996; Suga, 2008). Indeed, top-down inputs from the higher centers reaching the brainstem and medial olivocochlear (MOC) neurons of the olivocochlear bundle can, in turn, modulate the outer hair cells. This modulation leads to the inhibition of cochlear responses by decreasing the gain of the cochlear amplifier (Guinan, 2006). In noisy environments, MOC activation enhances responses to transient sounds by inhibiting responses to the background noise (Guinan, 2006).

1.1.3 How to explore auditory perception?

Many complex mechanisms occur during sound recognition, music perception or hearing in noise for instance. To complete specific auditory tasks, crucial cognitive mechanisms are involved such as attention or memory. Auditory perception can be then represented with different levels of processing (low to high), each with a specific function and interacting with each other. Processes involved in auditory cognition can be explored through two main angles: with psychophysics and cognitive psychology using behavioural measurements, with psychophysiology using techniques exploring the physiological bases of these processes.

Psychophysics and cognitive psychology When a modification appears in our environment, sensory responses are induced by the specific changes. The main objective of psychophysics is to determine the link between a specific stimulation and its

resulting sensation or perception using behavioural responses. In the auditory domain, psychoacoustics aims at measuring auditory sensations triggered with acoustic stimulations. Many processes have been investigated in this domain such as absolute thresholds (leading to audiometry, the most common technique to evaluate hearing acuity), pitch and intensity discrimination, masking, auditory localization, or auditory perception in noise (Moore, 2012). Cognitive psychology of audition uses behavioral measures (including performance during a task or reaction times for instance) to infer representations of the mental processes involved in auditory perception.

Psychophysiology To explore the physiological bases of the processes involved in auditory cognition, several techniques investigating physiological activity at different levels can be used, including among others:

- Pupillometry: the recording of pupillary responses (or pupil dilation), expressing autonomic nervous system's activity;
- Functional Near-infrared Spectroscopy (fNIRS): the recording of cortical hemodynamic activity in response to neural activity using near-infrared light;
- Electroencephalography (EEG): the recording of electrical activity on the scalp, due to the combination of neurons electric activity;
- Magnetoencephalography (MEG): the recording at the scalp level of magnetic fields produced by electric currents in the brain;
- Functional Magnetic Resonance Imagery (fMRI): the recording of brain activity by detecting changes in blood flow. Contrary to fNIRS technique, fMRI provide a whole brain measurement with high-resolution activation maps, but remains far less practicable than fNIRS due to MRI scanner constraints.

The combination of these methodologies have allowed throughout the years, a more precise determination and representation of how auditory signals are processed along the auditory pathway, from the ear up to the brain.

1.2 Listening effort

Everyday listening environments are complex acoustic mixtures that need to be processed and filtered in order to get access to relevant auditory information, for instance, when you are having a conversation with a colleague at the cafeteria with a lot of background noise covering his/her voice. In these common situations, the brain sets up all of the necessary operations that allow selective processing of a particular sound stream and simultaneous filtering of irrelevant information. These complex operations fall within the concept of *listening effort* that has received increasing interest in the past decades in hearing research and is crucial for the adaptation to our auditory environment.

1.2.1 Definition

The Oxford English Dictionary defines *listening* and *effort* as "giving one's attention to sound" and "physical or mental exertion" respectively (Oxford English Dictionary, 2006). As it has often been defined as "the attention and cognitive resources required to understand speech" (Anderson Gosselin and Gagné, 2011; Fraser et al., 2010; Hicks and Tharpe, 2002; Picou, Ricketts, and Hornsby, 2011), McGarrigle et al. (2014) proposed a dictionary based definition and extended it to all auditory messages. Their proposed definition becomes: "the mental exertion required to attend to, and understand an auditory message". However, Rönnberg et al. (2014) commented on this definition and argued that it was too simplistic, calling it a "good layman's definition", because it was not capturing all cognitive mechanisms involved in mental exertion, leading to incomplete understanding of effortful listening. To understand the point of Rönnberg et al., investigations into the processes involved in listening effort must be developed. The following section will then focus on cognitive mechanisms playing a key role in listening effort.

1.2.2 Processes involved in listening effort

Auditory selective attention

When confronted with complex stimulation and thus incoming complex sensory information, one needs to focus on relevant input, giving less priority on distracting

or irrelevant information. This is when selective attention takes action. In the auditory modality, the most famous complex sound environment is the "cocktail party" situation, in which we are confronted to several streams of sounds (as in a real cocktail party with multiple discussions going on, background music, glass or cutlery noise etc). "Cocktail party" situation's investigation thrived in the 1950's (Cherry, 1953; Pollack and Pickett, 1957), especially with Broadbent's work (1958), comparing the brain to a computer with limited resources, unable to process all streams at the same time. Several models for selective attention arose from his work: "early-selection" model and "late-selection" models (see Fig 1.3). The first model comes directly from Broadbent, in which he postulated that attention filters inputs at a lower level where acoustical properties are processed, leaving only relevant information to enter further processing networks. This theory arose from dichotic listening experiments. In these paradigms, participants are exposed to two auditory streams, each presented in one ear and have to focus their attention on one ear while ignoring the other (Broadbent, 1958; Cherry, 1953; Hillyard et al., 1973). First results indicated that participants did not process the stimuli presented in the ignored ear (Broadbent, 1958), leading to the formulation of the "early selection" theory. Later results brought new insights on this theory when studies showed that participants could tell when their own name was presented in the ear they were ignoring (Moray, 1960). This result allowed to nuance the statements of the "early-selection" theory, proving that fragment of the unattended irrelevant stream of information was still processed up to a certain level. An attenuated version of Broadbent's model was then proposed by Treisman (1960). In her model, she proposed that irrelevant inputs are attenuated rather than blocked during attentional filtering. "Late-selection" models for selective attention emerged afterwards. According to these models, filtering happens at late stages of processing, where irrelevant stimuli would be extracted at identification or semantics stage based on comparison with targeted information (Deutsch and Deutsch, 1963; Duncan, 1980). Kahneman, another 20th century psychologist, proposed alternatively a limited-capacity model (Kahneman, 1973) in which he suggested that attention is a limited resource and so, that the complexity of the input influences the degree of processing of the unattended input. His work followed the well-known statement of William James (1890) saying that *we can only attend to one*

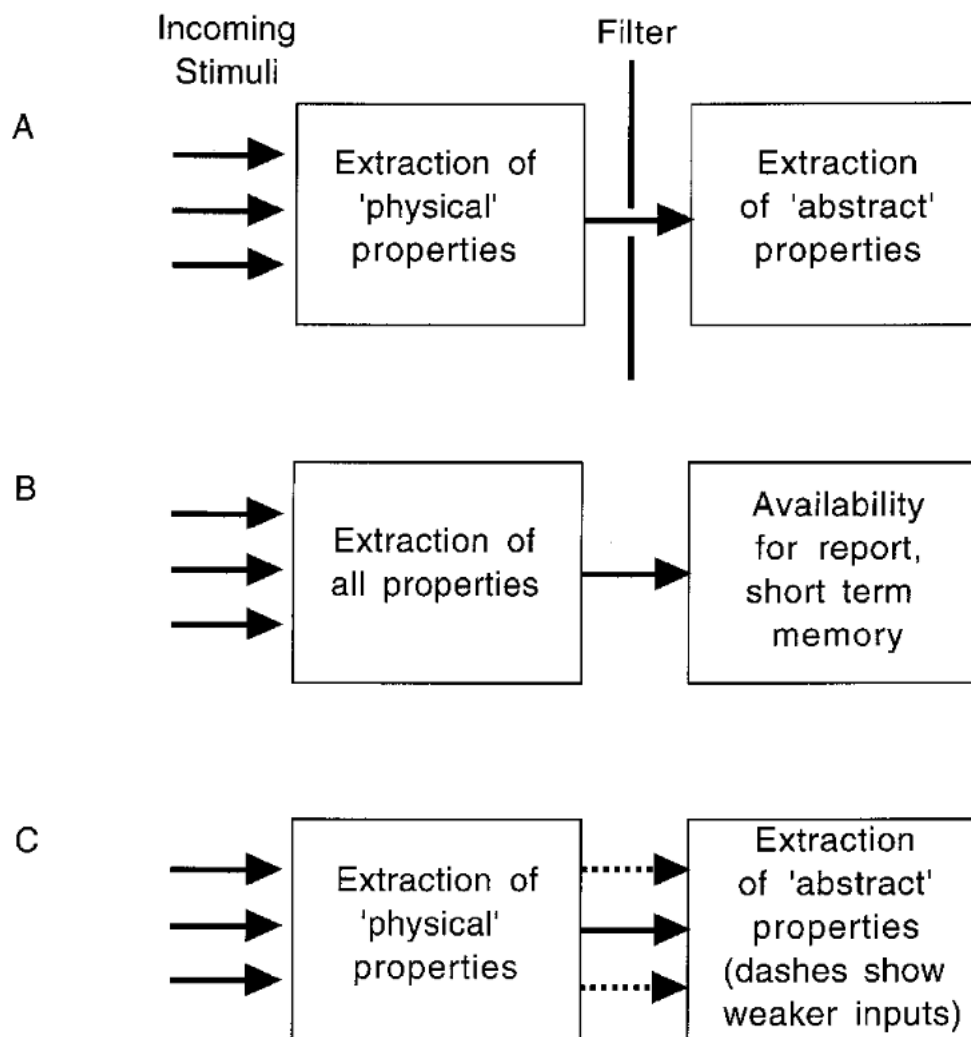


FIGURE 1.3: Schematic representation of models for selective attention. A: Broadbent's (1958) "early-selection" model, B: "late-selection" model (Deutsch and Deutsch, 1963; Duncan, 1980), C: Treisman's (Treisman, 1960) attenuation version of Broadbent's model. Adapted from Driver (2001).

thing at a time. If one is only able to focus at one stimulus at a time, its attention has to be oriented towards a specific input. This process of *attention orienting* was first investigated in the visual domain with the famous Posner task (Posner, 1980), studying attention shifts. Two distinct forms of attention orienting were considered following his work: *Top-down* **voluntary** attention orienting (driven by "internal" factors) involving specific shift of attention (implying relative cognitive effort), and *bottom-up* orienting (driven by "external" factors) involving **automatic** responses to unattended input. These processes of attention orienting apply as well in the auditory modality.

Top-down processes of attention Auditory *top-down* orienting of attention has been investigated via dichotic listening paradigms and bimodal tasks. In the first paradigm, two different auditory streams are presented in each ear of the participant and one stream has to be attended while the other one has to be ignored. Studies using neuroimaging techniques during dichotic tasks showed bilateral activation of auditory cortical areas (Jäncke et al., 2003), while other found activation in the contralateral cortical area (Alho et al., 1999). In bimodal tasks, visual and auditory streams are simultaneously (but with asynchrony) presented to participants. During these tasks, increased activation in cortical areas relevant to attended objects were observed, while activation in sensory areas related to the ignored modality was reduced (Johnson and Zatorre, 2006; Laurienti et al., 2002; Salo et al., 2013). These observations complement the theory that top-down voluntary attention implies processes of facilitation and inhibition, both necessary to select accurately relevant information among complex stimulation (Bidet-Caulet, Mikyska, and Knight, 2010; Chait et al., 2010). During the presentation of concurrent auditory streams, intracranial EEG recordings have also shown facilitation of the attended stream in primary and secondary auditory cortices, while responses to the irrelevant stream were attenuated (Bidet-Caulet et al., 2007). These facilitation and inhibition processes have been shown to be distinct and differentially modulated by cognitive load, notably, inhibition processes are delayed when memory processes are concurrently involved (Bidet-Caulet, Mikyska, and Knight, 2010). Cognitive resources are then clearly needed to activate such attentional mechanisms, inducing, in turn, cognitive effort.

At the peripheral level of the auditory pathway, influence of auditory selective attention have been observed using otoacoustic emissions (OAEs) (Kemp, 1978). As a sound enters the inner ear, the non-linear amplification provided by the contraction of the outer hair cells generates a by-product wave propagated backwards through the middle ear to the outer ear canal, where it can be recorded. OAEs amplitude therefore became a good index of the functioning of the cochlea amplifier in humans via a non-invasive method. Giard et al. (1994) used a selective dichotic listening task (in which pure tones were presented to the participants), and demonstrated that OAEs recorded in one ear presented larger amplitudes when attention was driven on

this ear in comparison to when the stimuli was attended to on the other ear. Unfortunately, Giard's results failed to be replicated in a series of experiments conducted by Michie et al. (1996) two years later. More recently, Francis (2012) introduced a different approach to measure the efferent-induced changes in cochlear responses. He measured MOC efferent activity using continuous click-evoked otoacoustic emission during a sound level discrimination task using 2 tonebursts in the same ear. The results revealed enhanced OAE amplitude changes (indicating larger MOC effect) in the condition of active auditory task in comparison with the equivalent passive listening session. Moreover, the efferent effect was correlated to the difficulty of the task, with a stronger effect associated with lower percentage of correct responses in the discrimination task. This result highlights the effect of the cognitive demands on MOC efferent activity during the task, which was poorly taken into account in the preceding studies, and thus, might stand at the origin of contradictory findings. In multimodal selective attention paradigms, modulations of the otoacoustic emission level were found as well, suggesting an adaptation of sound amplification in the cochlea regarding the modality of interest, with an inhibition of the irrelevant and distracting input during selective attention (Dragicevic et al., 2019; Wittekindt, Kaiser, and Abel, 2014).

Bottom-up processes of attention Even though focusing on specific elements in our environment is required to accurately complete a task, this process needs to be coupled with continuous assessment of task-irrelevant information in case of necessary attention switch. A classic example would be a fire alarm during a specific conversation, you would not want to miss crucial acoustic information alerting a fire and potentially saving your life. Our attention can then be deviated from its original goal and reallocated towards a specific event. Such specific orienting occurs automatically, rather than being voluntary, and comes from *bottom-up* processes of attention (that have been defined in literature as *exogenous orienting* (Most and Simons, 2001; Spence and Driver, 1994)). This automatic orientation can be due to *specific* characteristics of the stimuli: attention is diverted due the particular content of the sound (someone hearing its own name (Moray, 1959; Röer, Bell, and Buchner, 2013), or a mother hearing her own baby's cry (Wiesenfeld, Malatesta, and Deloach,

1981; Young et al., 2017), triggering rapid attention orienting); or *aspecific* characteristics: attention is deviated because of the context in which inherent event occurs (a "B" sound would be highly noticeable if embedded in a sequence of "A" sounds (Escera et al., 1998; Näätänen, 1990)). Moreover, sounds can cause unwanted perturbation by specifically interfering with processes involved during the task, this phenomenon is called *interference-by-process* (Hughes, 2014). This phenomenon has been investigated during short-term recall tasks, in which participants had to recall in order a series of items impaired by the mere presence of sound (during presentation of the series or retention interval) (Ellermeier and Zimmer, 1997; Elliott, 2002; Jones, Madden, and Miles, 1992; Röer et al., 2011). Due to the presence of interference, task performance can be disrupted during recall. Interference can be caused by differences in acoustic features during tones, syllables, vowels or digit recall (Divin, Coyle, and James, 2001; Hughes, Tremblay, and Jones, 2005; Jones and Macken, 1993), or by higher level properties, such as semantic category deviance, during words free recall (Marsh, Hughes, and Jones, 2008).

Top-down and Bottom-up interactions As *top-down* and *bottom-up* processes have been mostly investigated separately, Miller et al. (2011) tried to assess their interaction during a video game, using auditory stimuli as distractors. Attenuated brain responses to auditory perturbations were found while increasing video game difficulty (and thus increased *top-down* attention engagement). In light of these results, the two modes of attention seem to interact. In the visual modality, Corbetta et Schulman (2002) reviewed neuroimaging studies on Posner's tasks and identified cortical networks responsible for the control of *top-down* goal-directed attention. Anticipation of an upcoming target during spatial localization leads to consistent activation pattern: the dorsal attention network (DAN). This pattern of activation have also been shown in the auditory modality during spacial attention (Kong et al., 2014; Lee et al., 2013; Smith et al., 2010; Wu et al., 2007). A distinct attention network was also identified during Posner's tasks, but also in *oddball* paradigms, for *bottom-up* attention network: the ventral attention network (VAN), interrupting *top-down* control and enabling attention shift (Corbetta, Patel, and Shulman, 2008; Corbetta and Shulman, 2002; Kim, 2014). These two cortical networks have often been presented

as separate anatomic entities although they happen to overlap, particularly in the lateral prefrontal cortex (PFC) and posterior parietal cortex (PPC) (Corbetta, Patel, and Shulman, 2008; Katsuki and Constantinidis, 2014). The PFC has been associated with facilitatory (Barceló, Suwazono, and Knight, 2000) and inhibitory (Caclin and Fonlupt, 2006) mechanisms of *top-down* control of attention, as well as *bottom-up* attentional orienting (Watkins et al., 2007) and distractor suppression (Suzuki and Gottlieb, 2013). These networks then seem to interact and their implicated area could provide a priority map for stimuli selection based on *bottom-up* and *top-down* factors (Katsuki and Constantinidis, 2014).

Working memory

In a complex acoustic environment, attention mechanisms are engaged but other essential cognitive processes are needed to successfully attend a discourse, or other auditory message. As auditory messages are composed of successive elements changing through time, it is crucial to retain each element to integrate and understand the auditory message in its entirety. In this way, memory plays also an important role to successfully attend auditory information. Memory has been defined as the capacity to acquire, retain, and use information. Human memory has been divided into three main components: sensory memory, short-term/working memory, and long-term memory (Atkinson and Shiffrin, 1968). Sensory memory is the stage during which one can access perceptual information and is directly linked to the processing of information in the perceptual system. Short-term memory refers to the ability to maintain information for a (short) limited amount of time, whereas working memory implies the manipulation in addition to the maintenance of the information kept in memory. Finally, long-term memory is defined as a great capacity storage in which information can be kept for a long amount of time (from hours to a lifetime). During a conversation for instance, all the uttered elements have to be stored and linked to each other in order to completely understand the message and give a consistent and relevant answer. Working memory thus seems to play a crucial role in this situation, even more so if the listening conditions are challenging and auditory messages are degraded. Indeed, the more the message is degraded, the more cognitive resources will be needed to reconstruct the message, leading to cognitive effort.

It should be noted however, that the three memory components are not independent. Sensory memory is essential to the encoding of information into short-term and working memory (Demany and Semal, 2008), and long-term memory representations can impact performance during working memory tasks (Hulme, Maughan, and Brown, 1991).

Working memory became a central component of human cognition in Baddeley and Hitch's pioneer paper (1974). Working memory can be defined as "the retention of information in conscious awareness when this information is not present in the environment, to its manipulation, and to its use in guiding behavior" (Postle, 2006). This definition can be extended with the notion of working memory capacity (WMC) that is finite, such that WM can carry a limited amount of cognitive operations during problem-solving, decision making or language comprehension. Most famous tasks to measure someone's WMC is the *complex span* paradigm (Daneman and Carpenter, 1980) in which lists of items (words, numbers, letters, or sentences for examples) are presented to participants and have to be manipulated then recalled according to certain characteristics. In the *reading span test* for example, participants have to read series of sentences (of varying size) and maintain a running list of the final words, which they are then asked to repeat. Verbal information (final words) thus have to be held in memory while simultaneously processing the new sentence read. The use of such tests revealed that reading span scores were strongly related to spoken communication skills (Daneman and Carpenter, 1980; Just and Carpenter, 1992; Kane et al., 2004), inhibition of irrelevant information (Gunter, Wagner, and Friederici, 2003), accurate selective attention (Conway, Cowan, and Bunting, 2001), the ability to divide attention (Colflesh and Conway, 2007), integration of signal-relevant information (Zekveld et al., 2011, 2012), and the processing of acoustically degraded speech (Ward et al., 2016). Moreover, a study using magnetoencephalography compared the effects of increasing memory load during an explicit memory task and degraded speech understanding, and found a superadditive effect of memory load and acoustic degradation on cortical responses (Obleser et al., 2012). This result suggests that both degraded speech processing and working memory rely on shared limited-capacity resources.

Several models of WM and cognitive resources arose from the 1960's to today,

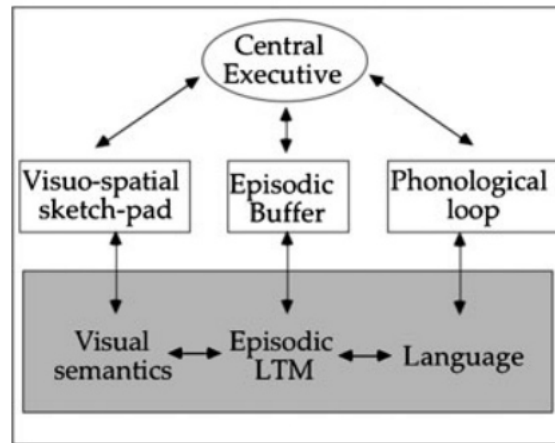


FIGURE 1.4: Baddeley's model of working memory. LTM: Long-Term Memory. Adapted from Baddeley (2012).

from linear stage models (representing the flow of information from one stage to the next over the course of time), to the more recent Baddeley's model (2012) (see Wingfield, 2016, for review). Baddeley's model is a multi-component model comprising two domain-specific rehearsal buffers, an episodic buffer and a central executive (see Fig 1.4). The first buffer is a temporary store for visuo-spatial input, and the second buffer is directly related to spoken input as a phonological loop with limited capacity, information in the buffer being maintained through subvocal rehearsal. The episodic buffer, unlike the two others, holds multidimensional representations and bounds features from different sources of long-term memory into "episodes". Finally, these buffers are monitored by a limited-capacity central executive, controlling rehearsal or reordering of items stored. The central executive in this model plays a key role in maintaining attention, decision making and task switching. In this model, WMC is closely linked to the ability to inhibit interference from irrelevant information and to the control of attention, both of which are needed to understand an auditory message in challenging conditions. In the past two decades, Rönnerberg et al. worked on a model to better understand speech comprehension, with similar constructs as Baddeley. Their model, the Ease of Language Understanding (ELU) model, is based on the assumption that WMC has a major influence on language understanding especially under challenging conditions (Rönnerberg, 2003; Rönnerberg, Holmer, and Rudner, 2019, 2021; Rönnerberg et al., 2008, 2013).

Ease of Language Understanding (ELU) model

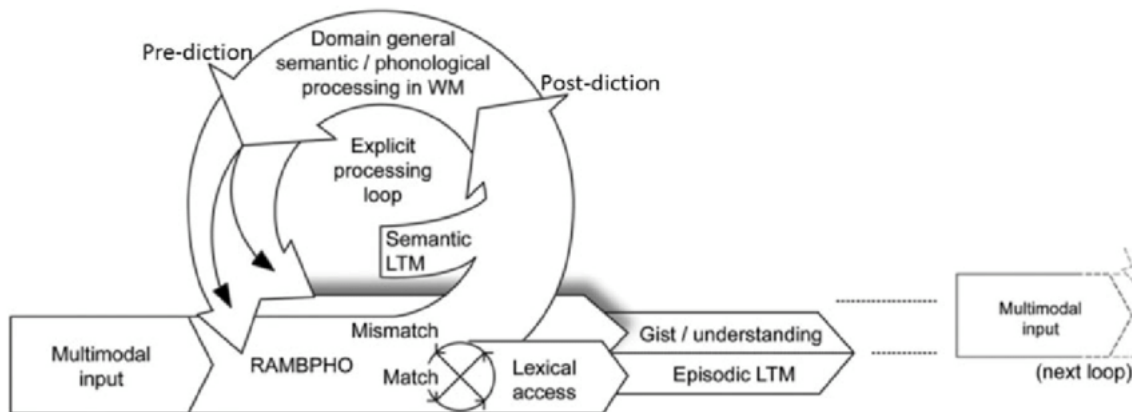


FIGURE 1.5: The Rönnerberg et al.'s ELU model. From Rönnerberg et al. (2019).

Rönnerberg et al.'s ELU model (see Fig 1.5) hinge on the interaction of three memory systems: WM, episodic long-term memory (ELTM) and semantic long-term memory (SLTM) (Rönnerberg, Holmer, and Rudner, 2019, 2021). According to their approach, WM is a central pool in which storage of sensory/semantic information and grammatical processing is flexible: if processing requires lot of resources, less will be available for storage and conversely (Sörqvist et al., 2016). ELTM manages personally experienced episodes labeled in time, space, emotions and context (Tulving, 1983). When someone tries to remember a specific event, the use of relevant sensory-perceptual traces and semantic association is necessary. On the other hand, SLTM is associated with knowledge in a general manner, without personal reference, for instance, vocabulary knowledge, grammar comprehension, or common world knowledge. In their assessment of language comprehension, Rönnerberg et al. stated that processing language input is based on Rapid, Automatic, Multimodal Binding of PHOnological (RAMBPHO) information into a coherent percept independently from the source of phonological information. This binding is assumed to be a rapid mechanism (around 200 ms (Stenfelt and Rönnerberg, 2009)) or otherwise would slow down all subsequent mechanisms. In ideal listening conditions, multimodal RAMBPHO input matches a sufficient number of phonological attributes (i.e., above threshold) in the mental lexicon and lexical access proceeds rapidly and automatically. RAMBPHO may be preset by expectations (modulated by WM) concerning the phonological characteristics of the communicative signal, for example,

the language or regional accent of the communicative partner or by semantic or contextual constraints. When there is a mismatch (as in non-optimal listening conditions), WM “kicks in” to support listening and aid explicit reconstruction, or *post-diction* (Rönnberg, Holmer, and Rudner, 2019; Rönnberg et al., 2010, 2013). The explicit, WMC-dependent, processing loop uses SLTM information to attempt to fill in or infer missing information, which also feeds back to RAMBPHO. This explicit use of WM is assumed in the ELU model to come with increasing effort, with more missed encoding and retrieval from LTM leading to more perceived effort to overcome communication obstacles (Pichora-Fuller et al., 2016; Rudner et al., 2012). While WM plays a keyrole in the reconstruction of misperceived information (post-dictive aspect), it is also involved in the pretuning (or *prediction*) of to-be understood sentences (Rönnberg, Holmer, and Rudner, 2019; Rönnberg et al., 2013). In this process, WM functional role is related to the identification and detection of targets and demands less elaborated processing of input. The output of the system is some level of understanding or gist, which in turn induces a semantic framing of the next explicit loop. Another output of the system is ELTM, where information encoded into LTM is dependent on the type of processing performed by WM. Explicit and implicit processes run in parallel, the implicit being rapid, the explicit is a relatively slow feedback loop.

As Rönnberg et al.’s ELU model focuses on language processing, Edwards (2016) proposed a hybrid Auditory Scene Analysis (ASA) and ELU model that could be applied to the processing of environmental sounds and listening to music as well (see Fig 1.6). ASA refers to the organization of auditory signal components into perceptually meaningful objects and plays an important role in the perception of complex sound environments (Bregman, 1990). It involves the ability to integrate sound inputs that belong together and segregate those that originate from different sound sources. To do so, binaural (e.g., interaural time and intensity difference), temporal (onset, offset, duration), and pitch cues (fundamental frequency and harmonic structure) are processed. Components that have similar features are then grouped together. Once auditory objects are formed, the listener may then focus their attention on a selected one and ignore others. These auditory objects can be the voice of a specific talker in a cocktail-party situation, a relevant environmental sound in a

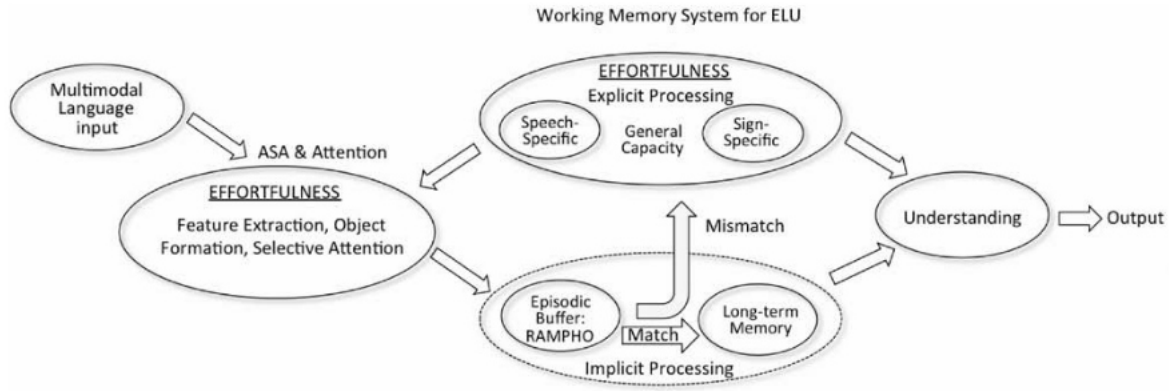


FIGURE 1.6: Hybrid Auditory Scene Analysis (ASA) and Ease of Language Understanding (ELU) model, based on Rönnerberg et al. (2008) ELU model. From Edwards (2016).

complex mixture, or an individual music instrument in an ensemble. In Edward's hybrid model, cognitive effort is exerted within the *ASA & Attention* module and the *Explicit Processing* module of the ELU model (see Fig 1.6). The *ASA & Attention* module is added to the ELU model to include critical auditory processing before the implicit cognitive processing of speech and then, better represent the effect of the auditory peripheral and central processing on the need for cognitive effort. Indeed, if the signal representation is degraded at the auditory periphery (due to hearing-loss for instance), ASA is weakened, producing an auditory scene with poorer representations of auditory objects, resulting in poorer match to the stored representation and so, more cognitive resources have to be allocated to interpret the auditory input, inducing more effort. In this way, the hybrid ASA and ELU model could be a fair representation of resources needed to interpret all sounds, and not just speech. However, further research using nonspeech signals need to be conducted to fully validate and generalize this hybrid model (Edwards, 2016).

In addition to acknowledging that cognition is important during listening, we need to dig deeper to fully understand effortful listening. What remains unclear is the modulation of the allocation of cognitive capacity during listening within and across individuals, even when the listening task does not require the participant's maximum capacity. Also, as self-reported listening effort and behavioral measures are not always in agreement (McGarrigle et al., 2014), influences behind self-reported measures still need to be investigated. In a more drastic way, the reason

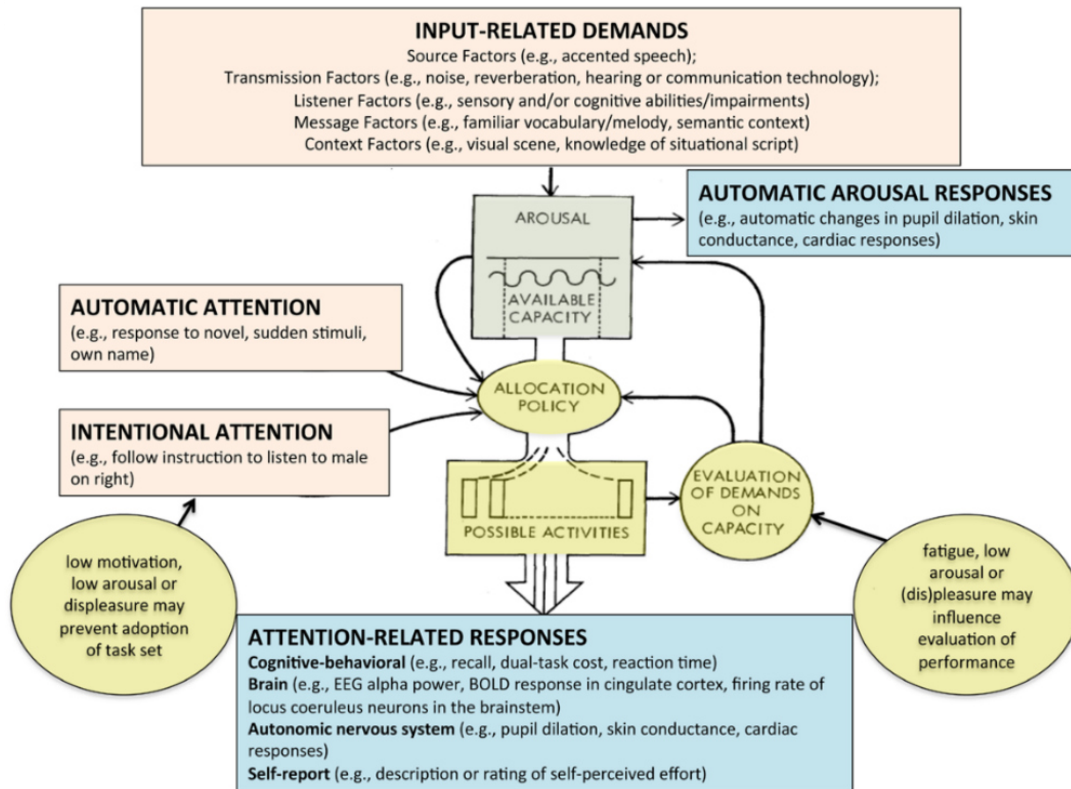


FIGURE 1.7: The Framework for Understanding Effortful Listening (FUEL).
From Pichora-Fuller et al. (2016).

why participants sometimes quit or disengage instead of persisting in the listening task is still to be identified. Pichora-Fuller et al. (2016) then proposed a Framework for Understanding Effortful Listening (FUEL), in which the relationship between cognitive demands and the supply of cognitive capacity meets a motivational dimension, fatigue, and pleasure.

The Framework for Understanding Effortful Listening (FUEL)

The willingness to deliberately *spend* resources to accurately achieve rewarding or meaningful goals seems to be a key component to explain why people decide to engage (or not) in effortful listening. The FUEL elaboration was based on the notion that listeners evaluate a benefice from the effort to expend relative to the costs of allocation of cognitive resources (Richter, 2016). Following this idea, listening has a certain importance and a cost-benefit analysis is conducted by listeners during effortful listening. Furthermore, if goals are externally imposed, the control and management

of resources that are needed to complete the task, can rapidly induce fatigue, contrary to demanding self-initiated and meaningful operations, that can be accompanied with little or no complaints of fatigue (for instance, an enthusiastic video game player that can exert extreme mental effort towards successful completion of the game, for several hours) (Hornsby, Naylor, and Bess, 2016). Following this idea, fatigue seems to hinge on motivation (Hockey, 2013; Hornsby, Naylor, and Bess, 2016). Another important parameter to take into account to understand effortful listening is arousal. Arousal has been described as “a fundamental property of behavior that has proven difficult to define or to explain precisely with neurobiological mechanisms” (Aston-Jones and Cohen, 2005). According to Aston-Jones and Cohen (2005), “The importance of arousal is undeniable: it is closely related to other phenomena such as sleep, attention, anxiety, stress, and motivation. Dampened arousal leads to drowsiness and, in the limit, sleep. Heightened arousal (brought on by the sudden appearance of an environmentally salient event or a strongly motivating memory) can facilitate behavior but in the limit can also lead to distractibility and anxiety.”. Kahneman, in his seminal Capacity Model of Attention (1973), stated that “the key observation that variations of physiological arousal accompany variations of effort shows that the limited capacity of the cognitive system and the arousal system must be closely related.” In light of these findings and observations, the widespread hypothesis saying that effort increases with difficulty or demand for cognitive capacity seems insufficient to understand the role of motivation and arousal in listeners strategy regarding their engagement (or not) in effortful listening.

Pichora-Fuller et al. (2016) proposed a FUEL based on Kahneman’s capacity model of attention (1973) (see Fig 1.7). His capacity model relies on the fluctuation of the “available capacity” with the “arousal” and the “allocation policy,” managing how much of the available capacity will be allocated to which activities. Kahneman states that the allocation policy “is controlled by four factors: 1) Enduring dispositions which reflect the rules of involuntary attention (e.g., allocate capacity to any novel signal; to any object in sudden motion; to any conversation in which one’s name is mentioned); 2) Momentary intentions (e.g., listen to the voice on the right ear- phone; look for a redheaded man with a scar); 3) The evaluation of demands; 4) Effects of arousal.” According to Kahneman, “the level of arousal is controlled by

two sets of factors: 1) the demands imposed by the activities in which the organism engages, or prepares to engage; and 2) miscellaneous determinants, including the intensity of stimulation and the physiological effects of drugs or drive states". In Pichora-Fuller et al.'s FUEL, the original core component from Kahneman's model was kept and is represented in green in Figure 1.7 as the available cognitive capacity varying with arousal. The core evaluation components were also preserved and are represented in yellow: the evaluation of demands on capacity, the allocation policy, and the possible activities to which capacity is allocated. The two bubbles colored in yellow are adapted from Kahneman's model showing the effects of high and low arousal on attention and performance, to which have been added fatigue and (dis)pleasure that can influence the evaluation of performance without being the results of performance. The subjective (unpleasant) experience of fatigue is thought to actually trigger the individual evaluation of the benefits of successful performance relative to the effort required to achieve, or maintain, it (Hockey, 2013). In the same way, effort can be predisposed by (dis)pleasure, as pleasure in anticipation of and while performing a task can be motivating (Matthen, 2016). Importantly, the effects of arousal or motivation level on performance could explain why some participants are quitting even when the demand for capacity did not reach maximum available capacity supply. Salmon-colored boxes represent direct inputs to the allocation policy or indirect inputs via the cognitive capacity component. Direct inputs to the allocation policy are "automatic attention" and "intentional attention" related to bottom-up and top-down attention mechanisms respectively. Examples given in "input-related demands", as well as those in the previous boxes, are adapted to stimulus, individual, and environmental factors linked to effortful listening. These input-related demands include factors affecting the quality of the source signal, signal transmission, and listener abilities, known to decrease intelligibility and make listening situations more challenging (Mattys et al., 2012). Blue boxes represent responses or outputs. Following Kahneman's model, manifestations of arousal would include automatic responses such as pupillary responses, increase in skin conductance or changes in cardiac responses. Finally, "attention-related responses" are eligible measures obtained to quantify listening effort, as they carry information about the allocation of capacity or effort increase.

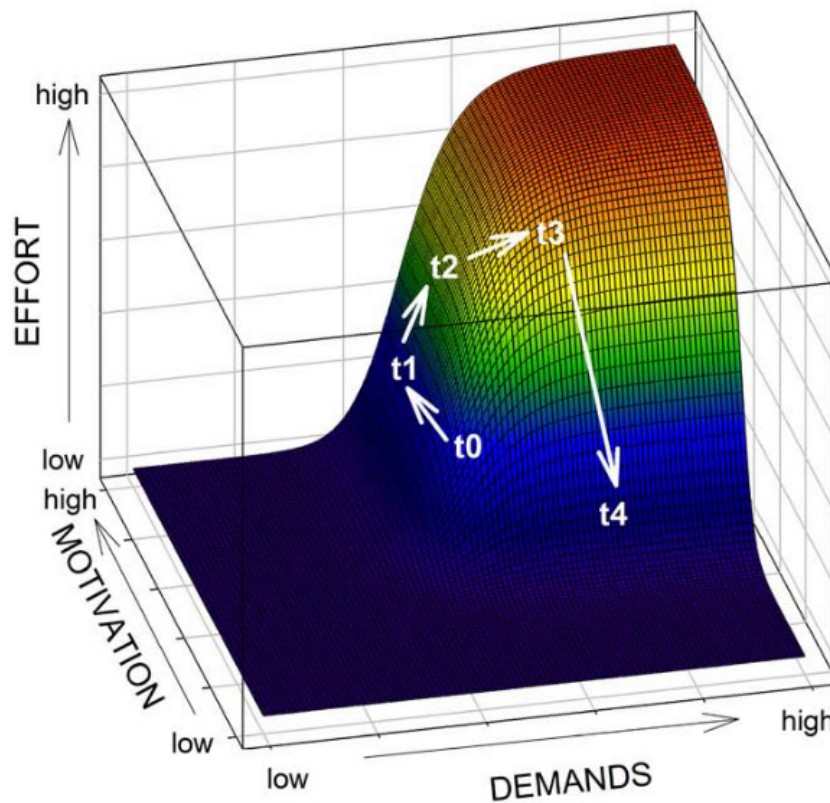


FIGURE 1.8: Three-dimensional representation of effort variation as a function of the demands for capacity needed to perform an activity and the motivational arousal of the person. White arrows represent how the expending effort might change over time. From Pichora-Fuller et al. (2016).

As it seems crucial to understand effort in terms of cognition and motivational arousal, Pichora-Fuller et al., inspired by Kahneman's work, modeled the relationship between effort, demands and motivation using a three-dimensional (3D) figure (see Fig 1.8). This representation is based on Yerkes and Dodson's theory (1908) stating that the quality of performance varies non-linearly with arousal level. Following this idea, depending on the complexity of the task, performance can be reduced for either very low or very high arousal levels. With a third axis representing motivation, the variation of expended effort, according to the allocation policy, with both the demands and the motivation dimensions can be illustrated. The demand dimension is directly linked to input-related demands (e.g., listeners factors, signal properties) and task demands based on automatic and intentional attention factors (e.g., monitoring of the auditory environment and given instructions respectively). The motivation value on the third axis would depend on how arousal or fatigue may influence the individual's appraisal of the importance of success and the amount of

expending resources to meet demands on capacity. White arrows on the 3D plot represent how the expending effort might change over time. Segment t0 to t1 shows little change in effort while demands stay low, although there is increasing motivation as the person is engaging in the task (in a cocktail party situation for instance, the conversation a person took part in becomes interesting and the background noise is easy to ignore). Segments t1 to t2 to t3 show an expansion in effort while motivation is kept relatively high but demands increase gradually (the conversation is still very interesting but it becomes difficult to ignore the background noise as more people arrive at the party). Segment t3 to t4 shows a drop in effort while demands remain relatively high but with a sharp decrease in motivation (the conversation took another turn and becomes uninteresting as the level of background noise remains steady). This last segment possibly illustrates a person "quitting" on one task with the development of fatigue and an effort-reward ratio becoming discouraging.

As there is no agreement on what would be an appropriate scale for any of the three dimensions yet, the units are unspecified on the axes for effort, demands, and motivation but only range from low to high. The main asset of this three dimensions representation, is that some methods for assessing effort may be more sensitive to task demands or factors related to the nature of the sensory input, while other measures may be more sensitive to factors related to motivation. Yet, others may be influenced by an interaction of demands and motivation, including individual differences in auditory abilities and motivation (Alhanbali et al., 2019). Therefore, this model can be used to represent inter and intra-individual differences across conditions, as well as fluctuations in effort related to variations in demands and motivation whilst engaging in a complex task.

In Pichora-Fuller et al.'s FUEL, contrary to Rönnberg et al.'s ELU model, working-memory processes are not mentioned, as the FUEL is inspired by Kahneman's Capacity Model of Attention (1973). However, rather than absent, these working-memory processes seem to be implicit since Kahneman emphasized the importance of object or event formation and the binding of stimulus attributes when attention is allocated (Kahneman, 1973, pp. 105) (represented by the RAMBPHO in the ELU model, see Fig 1.5). Moreover, recall and reaction time, given as cognitive-behavioral

attention-related responses examples, are related to memory processes. Indeed, recall is linked to (short-term or long-term) storage, and reaction time is modulated, in part, by working memory operations to reconstruct degraded information (represented by the explicit processing loop in the ELU model, see Fig 1.5). Although the two models did not focus on the same cognitive processes involved in effortful listening, the key component in these models are that there is a limited-capacity of mental resources that can be allocated to doing tasks, that there are individual differences in maximum capacity, and that the amount of capacity allocated to tasks increases as the tasks become more difficult or demanding, inducing cognitive effort.

Listening in acoustically challenging conditions is then a complex task that requires listeners to engage cognitive resources to successfully understand an auditory message, resulting in cognitive effort. Processes executed during effortful listening include auditory selective attention mechanisms with top-down (or intentional) facilitatory and inhibitory processes necessary to select accurately relevant information among complex stimulation. Working-memory mechanisms are also activated during effortful listening in order to fill in, or infer, missing information and match it to the stored representation of the auditory object. Moreover, a motivational aspect seems to be crucial in the concept of listening effort, as the willingness to deliberately "make an effort" and spend resources during listening can influence intentional cognitive processes and performance.

1.2.3 Hearing-impairment and listening effort

To understand a degraded auditory signal, the allocation of cognitive resources related to working memory and attention are necessary, therefore increasing listening effort. This allocation comes at a cost as cognitive resources are considered to be limited and shared across tasks (Baddeley and Hitch, 1974; Kahneman, 1973). As a result, sustained listening effort may lead to fatigue, a common complaint by hearing-impaired individuals (McGarrigle et al., 2014). Hearing-impairment is caused by multiple dysfunctions through the auditory pathway. These dysfunctions can be located at the peripheral level, or can happen at higher levels of processing. The processing of the auditory information is then altered, implying the engagement

of extra cognitive resources and effort to understand an auditory message, all the more in noisy environments. The following section will then deal with the impact of hearing impairment on listening effort, first in children then in adults.

Children

Sensorineural hearing loss is a peripheral deficiency coming with the damage of auditory nerve or sensory organs (including the cochlea) in the inner ear. This hearing loss can be congenital, due to (non-)genetic factors or syndromes (such as Down or Alport syndrome), or it can be acquired later by the child, due to infections, injuries or exposure to loud noises (Smith, Bale, and White, 2005). A common noisy, acoustically adverse environment to which children are exposed everyday is the classroom, where they develop key cognitive, linguistic, and academic skills. However, as demonstrated earlier, speech understanding in noise relies on cognitive skills such as working-memory and attention, which are not completely matured in school-age children (Gomes et al., 2000; Luna et al., 2004). As hearing-impaired children experience more difficulties to understand speech in noise than normal-hearing children (Leibold et al., 2013; Ruscetta, Arjmand, and Pratt, 2005), it seems fair to imply that learning in such adverse conditions will come with increased cognitive demands and listening effort. Studies investigating listening effort in school-age children without learning disabilities (5 to 13 years old) revealed an increased listening effort in hearing-impaired children compared to normal hearing children using behavioural measures (e.g., reaction times and performances in dual-task paradigms) (Hicks and Tharpe, 2002; McGarrigle et al., 2019). However this result has not been systematically demonstrated (Lewis et al., 2016; Stelmachowicz et al., 2007). Since children included in Hicks and Tharpe's (2002) study had more severe hearing loss, Lewis et al. (2016) suggested that the effects of listening effort in children may be related to hearing loss severity, but this hypothesis could not yet be completely verified (McGarrigle et al., 2019). The use of dual-task paradigms seemed a good way to represent the multitasking aspect of classroom environments, however, given the unpredictable nature of attention allocation in children and the reliance of this method on assumptions regarding cognitive resource allocation, the dual-task approach might not have been an ideal technique for objectively measuring listening

effort in children. The inherent variability of the child population makes it even more difficult to fully understand effortful listening among children and further research is needed to find more reliable and sensitive measures of listening effort in children with sensorineural hearing loss.

In the same way as, children with diagnosed sensory hearing loss experience difficulties in complex auditory environments, children displaying normal or near-normal hearing acuity can encounter these listening difficulties as well. These difficulties, characterized by poor perception of speech and non-speech sounds according to the British Society of Audiology (2018), are experienced by children with auditory processing disorders (APD). APD has its origins in impaired neural function, which may include both the afferent and efferent pathways of the central auditory nervous system, as well as other neural processing systems that provide 'top-down' modulation of the central auditory nervous system (British Society of Audiology, 2018), making auditory processing difficult and effortful. As a result, difficulties understanding speech in noisy environments, problems in locating the source of a signal, fail to response correctly to verbal information, frequently asking for repetition of information, reduced attention to auditory information and easy distraction are frequently reported symptoms of APD (American Academy of Audiology, 2010). Indeed, children (6 to 16 years old) with APD were rated by parent or teacher-based questionnaires as having more listening difficulties and poorer listening skills compared with their typically developing peers (Barry et al., 2015; Ferguson et al., 2011; Kreisman et al., 2012; Moore et al., 2010). They also show poorer performances in speech-in-noise tests, as well as in other cognitive, language, and reading behavioral measurements, than typically developing children (Barry et al., 2015; De Wit et al., 2016; Lagacé et al., 2011; Moore et al., 2010). In light of these findings, one may question the distinction between APD and other developmental disorders, such as a specific language impairment, dyslexia, learning disorder, attention-deficit hyperactivity disorder, and autism spectrum disorders, having in common developmental delays. De Wit's (2018) review on this specific question came to the conclusion that there is evident overlap between these developmental disorders, however the current measurement instruments used in clinical practice do not provide a clear distinction between the various disorders, especially for APD, as there is no standard

reference for its assessment yet.

Adults

The most common age-related disability in the human population is sensorineural hearing loss, often coming with the degeneration of outer hair cells in the cochlea. Due to hearing impairment, the internal representation of the acoustic stimuli is degraded and hearing-impaired listeners suffer more from adverse listening conditions in terms of speech perception performance as compared with normal-hearing listeners (Hagerman, 1984; Hopkins, Moore, and Stone, 2008; Plomp, 1986; Shinn-Cunningham and Best, 2008). Attempts have been made to also explore listening effort in hearing impairment, using a range of methods including self-report as well as behavioral and psycho-physiological measures (see Ohlenforst et al., 2017a, for review). Studies using subjective measures to quantify listening effort during speech recognition mostly came to the conclusion that hearing-impaired listeners experienced increased listening effort compared to normal-hearing participants (Ahlstrom, Horwitz, and Dubno, 2014; Desjardins and Doherty, 2013; Dwyer, Firszt, and Reeder, 2014; Feuerstein, 1992). However, some did not reach such conclusions, finding no difference in perceived effort between the two populations (Desjardins and Doherty, 2013; Zekveld, Kramer, and Festen, 2011). Disparities in outcomes were also observed when other aforementioned methods were used. Increased listening effort expressed through behavioral measures (e.g., reaction times or performances in dual-task paradigms) was found increased for hearing-impaired individuals in several studies (Rakerd, Seitz, and Whearty, 1996; Tun, McCoy, and Wingfield, 2009; Wu et al., 2014). Studies using phonemic restoration (recalling of degraded sentences filled with noise bursts), showed that the degree of restoration was affected by hearing-loss; suggesting that top-down restoration capacities decreased with the severity of hearing-loss (Başkent, 2010; Başkent, Eiler, and Edwards, 2010). Other studies, on the other hand, could not conclude on the effect of hearing-loss on listening effort (Neher, Grimm, and Hohmann, 2014; Wu et al., 2014). Physiological measures (such as pupil dilation, EEG or fMRI recordings) however, seems to offer more homogeneous results with increased responses linked to listening effort among hearing-impaired participants compared to normal-hearing ones (Korczak,

Kurtzberg, and Stapells, 2005; Kramer et al., 1997; Petersen et al., 2015; Zekveld, Kramer, and Festen, 2011).

In keeping with the idea that hearing-impaired people might experience increased listening effort in everyday life, the potential benefits of hearing device features (such as noise reduction) on this cognitive effort were also investigated (see Ohlenforst et al., 2017a, for review as well). As hearing-aid noise reduction does not always provide an improvement in intelligibility (Nordrum et al., 2006), some studies found a significant reduced listening effort in hearing-impaired patients whilst wearing their devices using subjective measures (Ahlstrom, Horwitz, and Dubno, 2014; Bentler et al., 2008; Hällgren et al., 2005; Noble and Gatehouse, 2006); behavioural measures (Downs, 1982; Gatehouse and Gordon, 1990; Picou, Ricketts, and Hornsby, 2013) and physiological measures (Bernarding et al., 2017; Jensen et al., 2018; Korczak, Kurtzberg, and Stapells, 2005). Again, the evidence of hearing-aid benefits could not always be demonstrated (Bentler and Duve, 2000; Humes et al., 1997; Picou, Aspell, and Ricketts, 2014) and sometimes, listeners reported more listening effort with hearing-aid noise reduction processing (Brons, Houben, and Dreschler, 2014; Neher et al., 2014).

The lack of systematic evidence that listening effort was increased with hearing impairment, and that hearing-impaired people benefit from their devices in terms of listening effort, might be explained by the fact that cognitive compensation abilities seem to be highly variable across individuals (Baskent et al., 2016). This variability might be a direct consequence from the many etiologies hearing impairment has and other physiological limitations it could cause. The individual differences in cognitive resources (e. g., linguistic knowledge, vocabulary, cognitive capacity) and the effect of age (being an important factor as many hearing-impaired individuals are in advanced age) also surely increase the variability amongst the results of different studies. Another important point might be the great diversity of measurement methods, experimental setups applied and stimuli used, as the different collected measures may not assess the same cognitive processes (Ohlenforst et al., 2017a).

1.3 How to measure listening effort ?

In the past decades, listening effort has been assessed using a wide range of measurements, each probably tapping into specific aspect of listening effort and modulating our understanding of effortful listening a different way. The following section will describe the several techniques used to investigate listening effort and their contributions to the understanding of the different processes involved.

1.3.1 Subjective measures

Self-reported measures Self-report measures of listening effort are often collected via questionnaires or rating scales. One of the most used questionnaire is the multi-dimensional speech, spatial, and qualities (SSQ) hearing scale (Gatehouse and Noble, 2004) which measures the extent of listening difficulties experienced in various real-world settings. The original questionnaire is composed of 49-item related to the effort required in everyday listening situations (examples: "Do you have to concentrate very much when listening to someone or something?"; "Can you easily ignore other sounds when trying to listen to something?"; "Do you have to put in a lot of effort to hear what is being said in conversation with others?" (Gatehouse and Noble, 2004)). Participants give a response on a scale of 0 (examples: "Concentrate Hard"; "Not easily ignore"; "Lot of effort") to 10 (examples: "Not need to concentrate"; "Easily ignore"; "No effort"), with lower numbers indicating more difficulty or effort. This questionnaire has been adapted for specific purpose in studies. For example, to evaluate the acclimatization to hearing aids, Dawes et al. (2014) used the SSQ-Difference version modified by Gatehouse to report any change in a specific ability over a particular period of time. They also added a "listening effort" subscale from the effort-related questions in the SSQ hearing scale in order to examine changes in listening effort related to the adaptation of hearing aids. New hearing-aid users reported significantly less listening effort after wearing their hearing aids for three months compared to a control group of experienced hearing-aid users. Recently, a shorter version of the SSQ has been developed, composed of 15 items maintaining the three-factor structure of the full SSQ (Moulin et al., 2019). This new 15-item SSQ affords a substantial reduction in the number of items and, thus, in test time and its

Speech subscores and Spatial subscores appeared to be more sensitive to differences in self-evaluated hearing abilities between normal hearing and hearing-impaired subjects than the full SSQ (Moulin et al., 2019). Another questionnaire assessing listening effort in hearing-impaired individuals daily life can be found in literature: the Effort Assessment Scale (EAS), self-assembled by Alhanbali et al. (2017). The EAS is a 6-item questionnaire derived from the SSQ and Alkhamra's PhD work (2010), in which responses are provided on a visual analog scale from 0 to 10 with 0 indicating "no effort" and 10 "lots of effort". Alhanbali et al. used their questionnaire to assess listening effort among different groups of hearing-impaired people and found similarities in listening-related effort between the different groups, suggesting that the aspects of listening experience evaluated by the EAS were not predicted by the severity of hearing impairment.

Self-report judgments of effort are also used during experimental listening tasks: participants can be asked to indicate on a scale how effortful they found each particular trial (Van Esch et al., 2013). As questionnaire-based ratings provide an individual retrospective judgement about the effort involved in everyday listening, during experimental task, real-time perceived judgements are given immediately after completing each trial. These self-report scales are often used complementary to other measures, such as physiological ones (Koelewijn et al., 2012b; Mackersie and Cones, 2011; Zekveld, Kramer, and Festen, 2011). Self-report measures of listening effort give the advantage of quick and easy data to collect and interpret, providing insight into how effortful speech processing is experienced by the individual. However, their subjective nature gives them limitations inherent in participant's judgment. For example, individuals' conception or "thresholds" of effort might be different. Indeed, older adults tend to underestimate their perceived listening effort. A study showed that despite comparably poor behavioural performance in a listening task, self-reported listening effort in elderly subjects were less extreme compared to younger adults (Larsby et al., 2005). Furthermore, interpretations of "effort" may vary, as some individuals may use objective task difficulty (or their performance) rather than mental exertion engaged during the task to report their effort rating. Therefore, using self-report measures alone seems insufficient to fully evaluate changes in the mental exertion required to understand an auditory message.

1.3.2 Behavioral measures

Behavioral responses to assess listening effort have been used in two types of protocols: during single tasking and multi-tasking via dual-task paradigms.

Single task paradigms In single-task paradigms, participants are usually asked to listen and repeat the identified stimuli (words, sentences, digits etc) (Gatehouse and Gordon, 1990; Meister et al., 2018) or to use the setup equipment (keyboard/mouse) to answer (Houben, Doorn-bierman, and Dreschler, 2013; Koch and Janse, 2016; Van Den Tillaart-Haverkate et al., 2017). Speech perception in noise performance is assessed by accuracy, that is the proportion of correct responses given by the participant, in each listening condition. As participant's performance brings direct information on participant's perception ability during the task, response times may provide additional information regarding the listening effort associated with speech perception (Gatehouse and Gordon, 1990; Houben, Doorn-bierman, and Dreschler, 2013; Meister et al., 2018; Van Den Tillaart-Haverkate et al., 2017). Indeed, studies showed slower response times in challenging conditions with low signal to noise ratios (SNRs), even at optimal intelligibility, reflecting a required increased listening effort to understand speech in difficult conditions (Houben, Doorn-bierman, and Dreschler, 2013; Van Den Tillaart-Haverkate et al., 2017). In everyday spoken situations, understanding might be compromised by slowed speech processing. As response times are believed to correlate with speech processing rate, they represent an important factor to consider when assessing listening effort. Indeed, speech comprehension difficulties have been shown to be modulated by speech rate, in hearing-impaired individuals (Piquado et al., 2012) as well as in normal-hearing adults (Koch and Janse, 2016), response times increasing with speech rate during experiments. Following ELU model's theories, a slowed phonological processing and/or lexical access might be the reason to this behavioral effect, the impact of which is thought to be modulated by the individual's working-memory capacity (Rönnberg, Holmer, and Rudner, 2019; Rönnberg et al., 2008, 2013).

Dual-task paradigms Multi-tasking methods such as the dual-task paradigm, was originally developed as a measure of attention allocation, going along with Kahneman's capacity model (1973) stating that there is only a finite amount of cognitive resources that must be distributed efficiently between various mental operations. When performing two tasks simultaneously, if the primary one becomes more taxing, drops in performance on the other task should be observed. Secondary task performance may therefore be interpreted as reflecting the amount of effort allocated to the primary task. For the assessment of listening effort, a speech recognition task with varying SNRs, is usually used as the primary task (Anderson Gosselin and Gagné, 2011; Hicks and Tharpe, 2002; Howard, Munro, and Plack, 2010; Picou, Gordon, and Ricketts, 2016). Secondary tasks may include, among others, memory tasks (Hornsby, 2013; Ng et al., 2015), visual tracking tasks (Desjardins and Doherty, 2013; Desjardins and Doherty, 2014) or driving a car simulator (Wu et al., 2014). The multi-tasking method appears to have good ecological validity regarding speech processing. Indeed, multiple simultaneous mental operations have to be performed in our daily life, their efficient execution being necessary in working or learning environments. However, behavioral measures collected during dual-task paradigms, as well as single task paradigms, do not provide temporal information about effort, while effortful listening requires cognitive processes distributed over time (Pichora-Fuller et al., 2016; Rönnberg, Holmer, and Rudner, 2019).

1.3.3 Objective measures

Pupillometry

Pupillometry is a technique measuring pupil size fluctuations, reflecting autonomic nervous system's activity. Pupil size modulations are an adaptive response to changes in the environment such as light (the *pupil light reflex*) (Reeves, 1920), or appear with "arousing" or emotionally relevant stimuli (Hamel, 1974; Hess and Polt, 1960, 1966). These fluctuations have also been used to express cognitive processes such as working memory load or executive load (Chatham, Frank, and Munakata, 2009; Hess and Polt, 1964; Kahneman and Beatty, 1966; Karatekin, Couperus, and Marcus, 2004; Laeng et al., 2011; Van Gerven et al., 2004). The changing size of

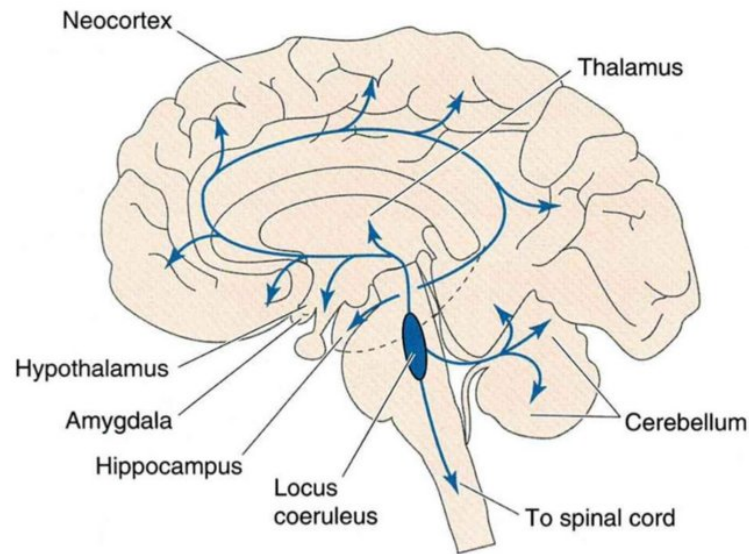


FIGURE 1.9: Projections of the Locus Coeruleus-Norepinephrine (LC-NE) system.
From Breedlove et al. (2010).

the eye's pupil is controlled by muscle activity in the iris and is determined by the tone of the *dilator* and the *constrictor*, pupillary dilation resulting from a stimulation of the dilator or an inhibition of the constrictor. Pupillary responses occur spontaneously and is the result of a neural inhibitory mechanism on the parasympathetic oculomotor complex by the noradrenergic system's locus coeruleus (LC) (Wilhelm, Wilhelm, and Lüdtke, 1999). The LC is a subcortical brain structure that constitutes the noradrenergic system's hub to the whole brain (Aston-Jones and Cohen, 2005; Sara, 2009). The LC is found in the brainstem and gives rise to the sole source of the neuro-transmitter norepinephrine (NE) to the cortex, cerebellum, and hippocampus (see Fig 1.9). As, the LC sends its densest innervations to the brain areas known to be involved in selective attention, the noradrenergic system, originating in the LC, is thought to mediate the functional integration of the whole attentional brain system (Corbetta, Patel, and Shulman, 2008; Coull et al., 1999; Sara, 2009). An alerting, orienting, and executive networks can be distinguished in the brain, with the alerting network being innervated by the NE system and including the LC, right frontal cortex, and regions of the parietal cortex (Posner and Fan, 2008). Within this representation, NE plays a crucial role in energizing the cortical system and promoting adequate levels of activation for cognitive performance. A very tight link between the online pupillary response and the activation of the LC and NE system have been

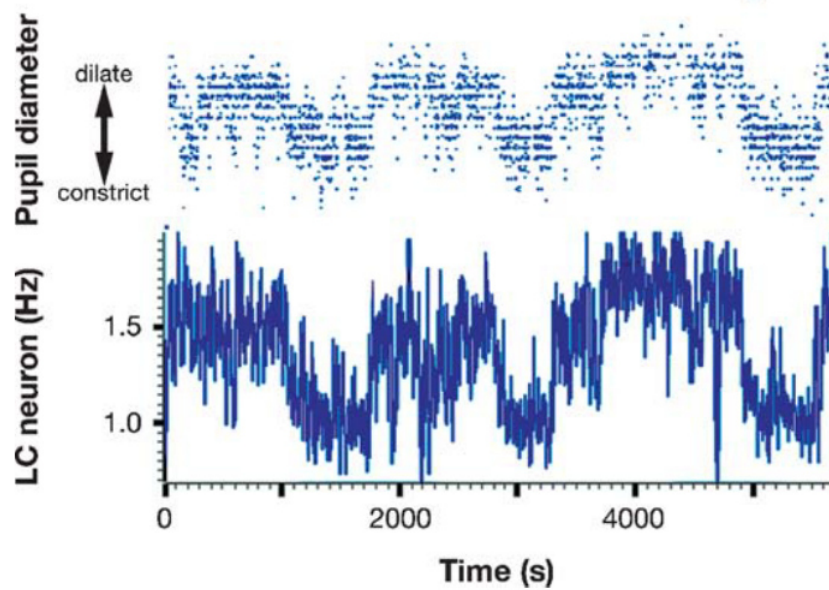


FIGURE 1.10: Tonic pupil diameter and baseline firing rate of an LC neuron in monkey. From Aston-Jones and Cohen (Aston-Jones and Cohen, 2005).

established over the years, as LC might be a key node within the neural circuits that control the muscles of the iris and the NE system (Koss, 1986; Samuels and Szabadi, 2008) (see Fig 1.10). According to Aston-Jones and Cohen (2005), two different modes of LC activity correspond to different patterns of behavior. In the phasic mode, LC cells exhibit activation when processing task-relevant stimuli, triggering time-locked “rapid” (phasic) and large pupillary dilations (Beatty, 1982; Kahneman and Peavler, 1969; Poock, 1973; Simpson, 1969). In the tonic mode, LC cells do not respond phasically to task events, however this mode seems to express mental state of arousal or vigilance. This arousal state can be expressed through baseline level of the pupil, and is thought to have a non-linear relationship with performance (Yerkes and Dodson, 1908) (see Fig 1.11). Indeed, sustained processing or effort yields an increase in the pupil tonic response, as difficulty and/or arousal increases, performance gradually degrades and large increases in pupil baseline are jointly observed (Beatty, 1982; Granholm et al., 1996; Howells, Stein, and Russell, 2010; Lavie, 1979; Peavler, 1974; Verney, Granholm, and Marshall, 2004). Conversely, when a person is fatigued after sustained attention or is sleepy, the tonic state is low and the pupil begins to fluctuate (this pattern of fluctuations being called *hippus*) while its average diameter gradually decreases (Beatty, 1982; Karatekin, Marcus, and Couperus, 2007). This dissociation in functional modes represents two fundamental cognitive

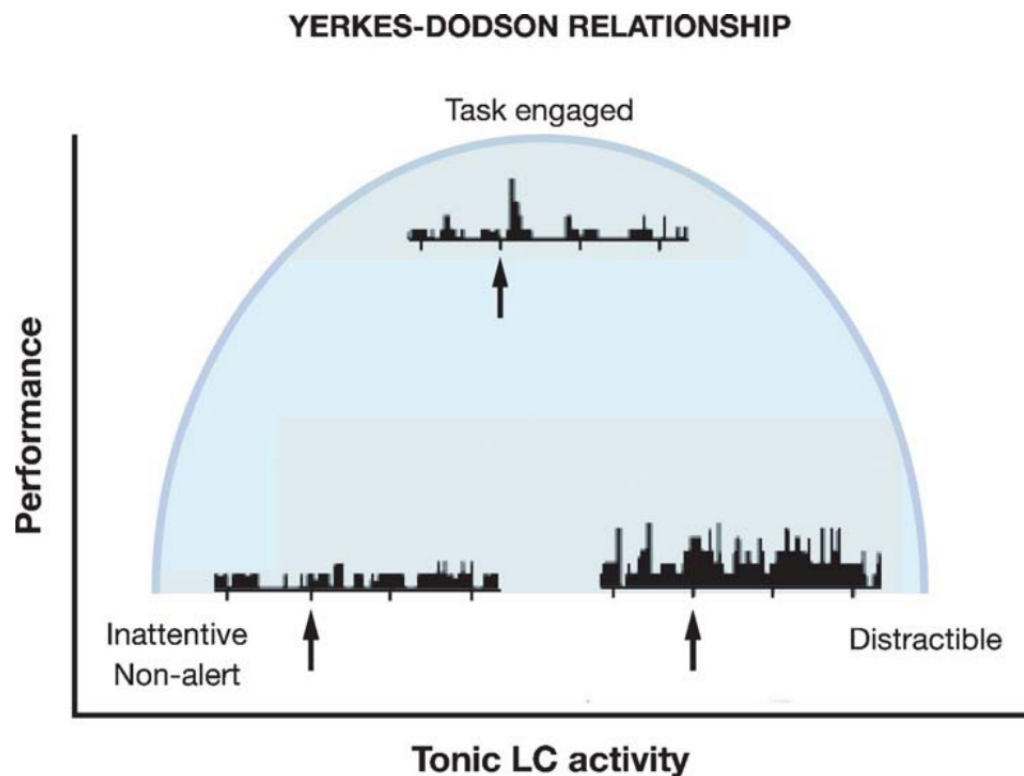


FIGURE 1.11: Inverted-U relationship between LC activity and performance on tasks that require focused attention. The spiking activity of the locus coeruleus (from intracerebral animal recordings) is represented before and after target presentation (indicated by the arrow). At low levels of LC activity (inattentive state), poor performances are observed. Optimal performances are obtained where the tonic LC activity is at a moderate level (a phasic activation is also observed after target presentation). Poor performances are also observed with high levels of tonic LC activity (distractible state). From Aston-Jones and Cohen (Aston-Jones and Cohen, 2005).

mechanisms: an *exploitation* mode adjusting attentional filtering to optimize performance during a specific task (the phasic mode), and an *exploration* mode adjusting the scope of attention to optimize shifts of performance between tasks (the tonic mode) (Aston-Jones and Cohen, 2005). In this way, a decrease in tonic LC activity observed whenever subjects engage in a demanding task, would reflect a top-down filtering narrowing the attentional focus to task-relevant events or information. A high tonic LC activity on the other hand, would correspond to an exploratory state, with a broaden sensitivity to either external or internal (mental) events (Laeng, Sirois, and Gredebäck, 2012). Pupil dilation is therefore not a straightforward index of effort but rather a complex mixture that reflects the combined contributions of the autonomic nervous system (Laeng, Sirois, and Gredebäck, 2012; Zekveld, Koelewijn, and

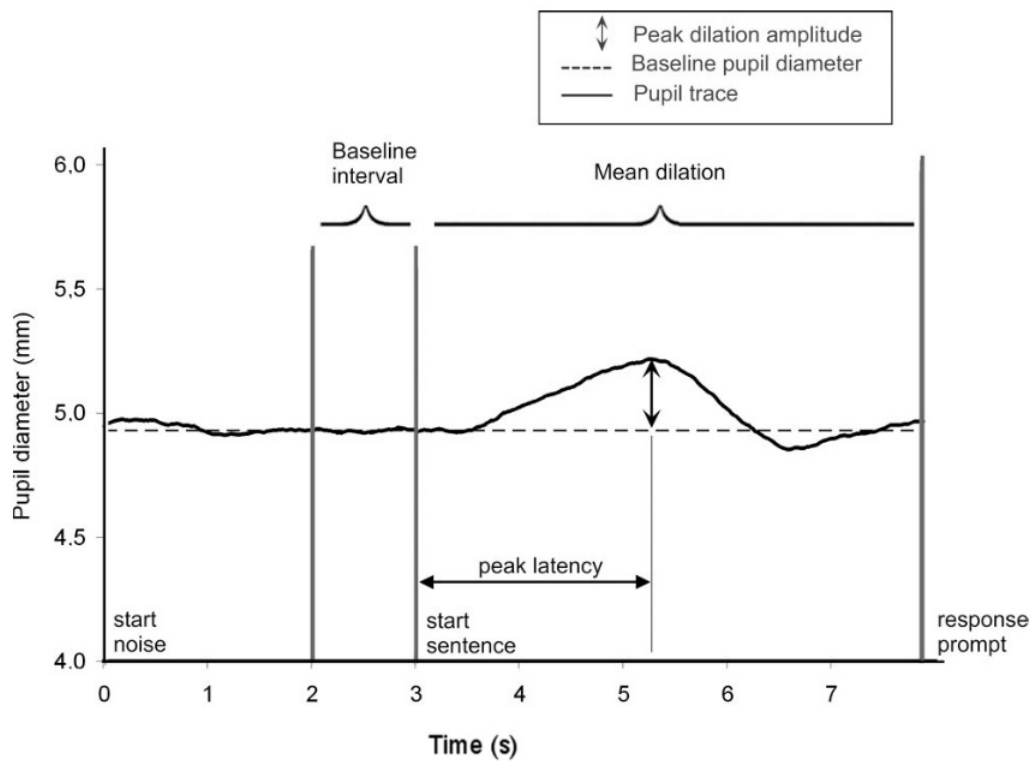


FIGURE 1.12: Pupil diameter time course during sentence recognition in noise. Participants hear a sentence in noise and have to repeat it after the response prompt. The baseline value is the mean pupil diameter during the second preceding stimuli presentation (baseline interval). The peak pupil dilation (PPD) is the maximum value between stimuli onset and response prompt relative to baseline (dashed black line).

The peak latency is time interval between stimulus onset and PPD. The mean dilation is the average pupil diameter between stimulus onset and response prompt relative to baseline. Tonic activity during the task can be expressed through the baseline value. PPD, peak latency and mean dilation reflect phasic activity. From Zekveld et al. (2010).

Kramer, 2018).

Pupillometry is a time-series measurement and therefore allows to record pupil size modulations at different time landmarks and has been widely used in the auditory domain (see Zekveld, Koelewijn, and Kramer, 2018, for review). Dilations induced by cognitive processes are clearly small (compared to those due to luminance changes), ranging from 0.1 to 0.5 mm (Laeng, Sirois, and Gredebäck, 2012), and are relatively slow to emerge, estimates ranging from 0.5 to 1.5 s (Hoeks and Levelt, 1993) (see Fig 1.12). While measuring pupil size, participant-related factors have to be taken into account (Winn et al., 2018). Older listeners pupil dilation responses are weaken, with narrow ranges of dilation due to increased rigidity in the pupil

with age (*senile miosis*) (Winn et al., 1994), and taking longer to reach maximum dilation or constriction (Bitsios, Prettyman, and Szabadi, 1996). Smaller pupil dilations are also observed in older listeners with hearing loss compared with young control groups with normal hearing (Koelewijn et al., 2014a). However, it does not necessarily mean that older or hearing-impaired listeners experienced less effort during the tasks. Several reasons could explain this result, including *senile miosis*, but also the fatigue reported by hearing-impaired individuals (Wang et al., 2018a). Pupil dilation is also affected by drugs intake (Steinhauer et al., 2004) (that is frequent in older populations), as well as by caffeine intake (Abokyi, Owusu-Mensah, and Osei, 2017; Wilhelm et al., 2014). Therefore, an equivalent amount of pupil dilation across two participants does not necessarily mean that they engaged in the task in the same way. In light of these existing inter-individual differences in pupil dynamic range, some prior control tasks measuring dynamic range could be performed (Piquado, Isaacowitz, and Wingfield, 2010) (recommended when comparing younger and older adults), and some further normalization methods during analysis might be applied (Winn et al., 2018).

The influence of input-related demands has been expressed using pupil dilation relative to baseline. There is a robust effect of intelligibility level whilst listening in noise on the pupil response. Indeed, various studies presenting stimuli at different SNRs (usually leading to 50%, 70% and 80% recognition rates) during speech recognition tasks, showed enlarged pupil dilations for lower intelligibility levels in normal hearing people (Koelewijn et al., 2012a,b, 2014b, 2015; McGarrigle et al., 2017a; Wendt, Dau, and Hjortkjær, 2016; Zekveld, Festen, and Kramer, 2013; Zekveld and Kramer, 2014; Zekveld, Kramer, and Festen, 2010; Zekveld et al., 2014b). The same outcome was observed for incorrectly recognized sentences compared to correctly perceived ones when SNRs are fixed (Zekveld, Kramer, and Festen, 2010). Similar effects of intelligibility have been observed among hearing-impaired listeners (Koelewijn et al., 2014a; Kramer et al., 1997; Zekveld, Kramer, and Festen, 2011). Hearing-aids processing, affecting intelligibility, have also been shown to influence pupil dilation, pupil size increasing with decreased intelligibility (Wendt, Hietkamp, and Lunner, 2017). Intelligibility can also be reduced by applying a masker signal (e.g., interfering-speech signals or noise maskers) or by degrading the quality of the

auditory stimuli. Speech masked with a single-talker masker evokes larger pupil dilations relative to baseline, than speech masked with fluctuating noise in normal hearing individuals and in listeners with hearing loss (Koelewijn et al., 2012a,b, 2014a; Zekveld et al., 2014b). Consistently, several studies have examined the effect of spectral degradation applied on sentences and showed larger pupil size changes with the more severely degraded sentences (McMahon et al., 2016; Miles et al., 2017; Wagner, Toffanin, and Başkent, 2016; Winn, 2016; Winn, Edwards, and Litovsky, 2015; Zekveld et al., 2014b). Linguistic processing, on presented stimuli, also has an impact on evoked pupil responses. Indeed, increased word frequency, absence of lexical competitors, facilitated semantic processing, or lessen neighborhood density tend to reduce or fasten the pupil dilation response (Koch and Janse, 2016; Kuchinsky et al., 2013; Kuipers and Thierry, 2011; Wagner, Toffanin, and Başkent, 2016). Conversely, pupil dilation is enhanced when sentence complexity is increased by semantic complexity or stimulus length (Ahern and Beatty, 1981; Kramer et al., 2013; Piquado, Isaacowitz, and Wingfield, 2010; Wendt, Dau, and Hjortkjær, 2016), conflicting prosody (Engelhardt, Ferreira, and Patsenko, 2010; Zellin et al., 2011), and ambiguous pronoun processing (Vogelzang, Hendriks, and Rijn, 2016).

As mentioned earlier, cognitive task-evoked pupil dilations are objectively small, they might be so for easy tasks but also for very hard tasks, possibly leading to discouragement due to repetitive failure. If a task is considerably demanding and the participant gets overly fatigued, it is highly probable that the effort will be reduced because of less engagement, leading to reduced pupil responses relative to baseline (McGarrigle et al., 2017b; Wang et al., 2018a). Notably, Gilzenrat et al. (2010) reported a larger baseline pupil level and small phasic dilations when it was impossible to differentiate two tones in a tone-discrimination task. Habituation effects have also been reported through pupillometry, showing a decrease of overall pupil size when a stimulus is repeatedly presented (McGarrigle et al., 2017a; Schlemmer et al., 2005), and smaller pupil responses to sentences through test session (McGarrigle et al., 2017b; Stanners and Headley, 1972). Besides time-on-task fatigue, motivation have also been shown to have an effect on phasic pupil responses, high monetary reward triggering higher dilations than low monetary reward during a digit span task (Bijleveld, Custers, and Aarts, 2009). Therefore, the participant's motivation

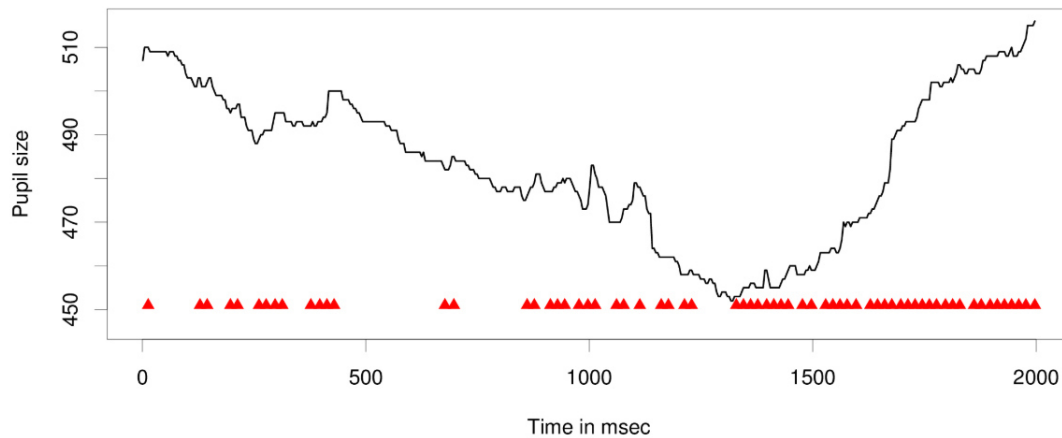


FIGURE 1.13: Recording of pupil size during linguistic processing. Red triangles indicate rapid pupil dilations. From Demberg and Sayeed (2016).

and arousal state during the task modulates the amount of evoked pupil dilation. Pupillary responses then appear to also be an index of an individual *willingness* to exert worthwhile effort to achieve a goal or accurately perform a task. This willingness, or intentional engagement, has a critical role in the study of effort, as specified in the FUEL framework (Pichora-Fuller et al., 2016).

Pupillary responses can be observed as time-based task-evoked pupil response (TEPR), as in the studies aforementioned, but they can also be analyzed in the frequency domain. Indeed, the high-frequency components in the pupil signal have been used to quantify cognitive activity, through the Index of Cognitive Activity (ICA) (Marshall, 2000; Marshall, 2002; Marshall, 2007). This index comes from the wavelet decomposition of the pupillary signal and represents the number of rapid tiny increases in pupil size per second (Marshall, 2000; Marshall, 2002) (see Fig 1.13). Low values are associated with little cognitive effort and high values indicates strong cognitive effort. Several studies have used this index to assess listening effort, showing increased cognitive activity with linguistic complexity during sentence comprehension (Demberg and Sayeed, 2016), and during dual-task settings combining language comprehension and driving (Demberg, 2013; Dlugosch, Conti, and Bengler, 2013; Vogels, Demberg, and Kray, 2018).

EEG

Electroencephalography (EEG) is a neuroimaging technique based on recording the spontaneous electrical currents produced by brain activity, through electrodes placed on the scalp. EEG offers a millisecond-range temporal resolution and allows the observation of transitory phenomena, making it a particularly powerful technique to investigate sensory processing and auditory mechanisms. Applications of EEG usually center around two main cortical responses: event-related responses (fluctuations of brain activity time-locked to the presentation of a stimulus), and neural oscillations (repetitive patterns of neural activity).

Event-related responses Event-related potentials (ERPs) are variations in electrical voltage, elicited by a stimulus and time-locked to the presentation of this stimulus. Components of the ERP waveform are thought to be the manifestation of a specific cerebral process and are differentiated based on their latency, sign (positive or negative) and scalp topography. ERPs have been widely used in attention research, as they allow the observation of the rapid sequence of events leading to the full attention processing of sensory information (Luck and Kappenman, 2011; Luck, Woodman, and Vogel, 2000). The activity of cortical networks involved in sensory and cognitive processing of auditory stimuli is reflected by ERPs elicited from 50 ms to 500 ms (and more) following the onset of the stimulus (Näätänen, 1990) (see Fig 1.14).

A sequence of obligatory responses necessarily emerge from auditory stimulation: a first positive deflection, the P50 (or P1) around 50 ms, followed by a large N1-P2 complex. They reflect the classic sensory processing of incoming sounds and arise even if the attention is not oriented towards the stimulus. The P50 is associated with activation of areas in and beyond the primary auditory cortex, including adjacent auditory association areas and the frontal lobe (Korzyukov et al., 2007; Weisser et al., 2001). The N1 is the most studied obligatory auditory evoked potential. This component peaks negatively around 100 ms and presents a fronto-central scalp topography, associated with a positivity around the mastoids and is mainly generated in auditory areas (Näätänen and Picton, 1987) (see Fig 1.15). The N1 emerges only after an abrupt acoustic event, such as the attack or the end of a sound, or a change

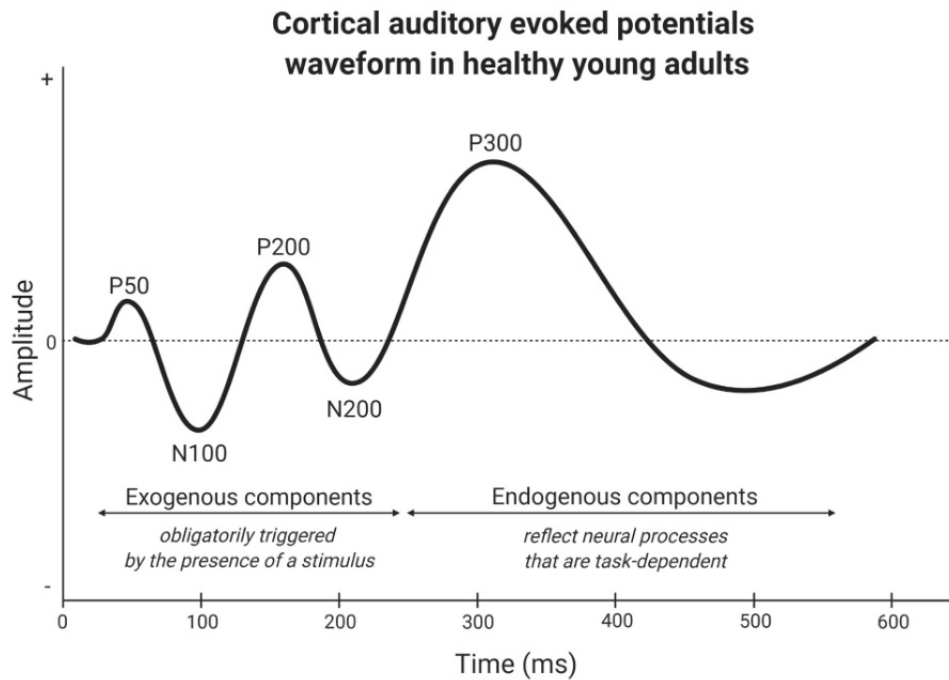


FIGURE 1.14: Event-related potentials locked to auditory stimulus onset in healthy young adults. The baseline is represented by the black dashed line. Adapted from Cardon et al. (2020).

in pitch reflecting a detection of change in acoustic features (Näätänen and Picton, 1987). The P2 response peaks around 180 ms after sound onset and displays a fronto-central scalp topography (Crowley and Colrain, 2004). The N1 and the P2 have often been proposed as a complex, being indistinct parts of a same component, the vertex potential (Davis and Zerlin, 1966). However, functional, developmental, and experimental dissociations of the auditory N1 and P2 responses suggest that the two components represent at least partially independent processes (Crowley and Colrain, 2004). The P2 appears to reflect further stimulus evaluation, including stimulus classification or the early process of attentional allocation (Arnott et al., 2011; García-Larrea, Lukaszewicz, and Mauguière, 1992). Obligatory auditory evoked potentials are modulated by habituation, their amplitude being reduced when a sequence of stimulation is repeated. In paired-click paradigms during which two clicks are presented within 500 ms of each other, the amplitude of the P50 elicited by the second click is found decreased (Knott, Millar, and Fisher, 2009; Smith, Boutors, and Schwarzkopf, 1994). This effect has been associated to an automatic neural process of filtering redundant, irrelevant information, called *sensory gating* (Jones et al., 2016).

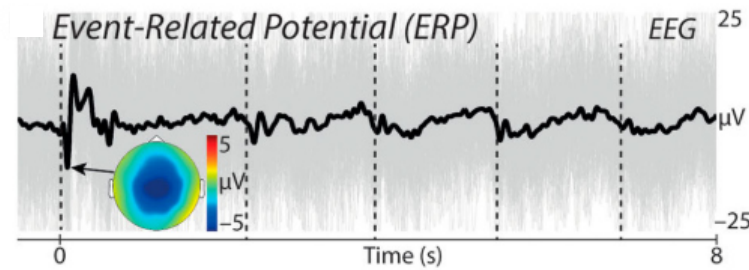


FIGURE 1.15: N1 component and its topographic map locked to speech onset. Adapted from Wöstmann et al. (2017).

A distinction can be made between short-term habituation, an exponential reduction of the amplitude which reaches asymptote by the third or fourth repetition of a sound (Fruhstorfer, Soveri, and Järvilehto, 1970; Ritter, Vaughan, and Costa, 1968a; Woods and Elmasian, 1986), and long-term habituation, which can be observed over the course of a block or an experiment. Long-term habituation relates to the classical definition of habituation, i.e. an adaptation to loss of novelty (Sokolov, 1963), while short-term habituation would stand as a reflection of the refractory period effect (Budd et al., 1998; Ritter, Vaughan, and Costa, 1968a).

Top-down attention processes can be expressed on ERPs in different ways: (1) top-down anticipatory mechanisms that are reflected in ERPs during the period preceding an expected upcoming target, (2) top-down selective attention can facilitate the processing of attended stimuli and lead to enhanced obligatory ERPs, (3) top-down projections can influence the high-level processing of incoming stimuli and are reflected by late ERPs. Anticipatory behavior, includes motor preparation, top-down attention and arousal processes, as participants are not only preparing to respond, but also waiting for a critical stimulus to happen. This is reflected at the cortical level by a specific ERP, the contingent negative variation (CNV). The CNV is a negative slow wave that follows the sequence of obligatory ERPs elicited by a warning cue and whose amplitude increases with time (Brunia and Boxtel, 2001) (see Fig 1.16a and c). A large amplitude of the CNV, especially before the onset of the target stimulus, is associated with faster responses, across participants or across trials of a same participant (Brunia and Vingerhoets, 1980; Hillyard, 1969), suggesting a causal relationship between the CNV and behavioral performance. Top-down selective attention is also reflected in the obligatory ERPs amplitude. In selective dichotic

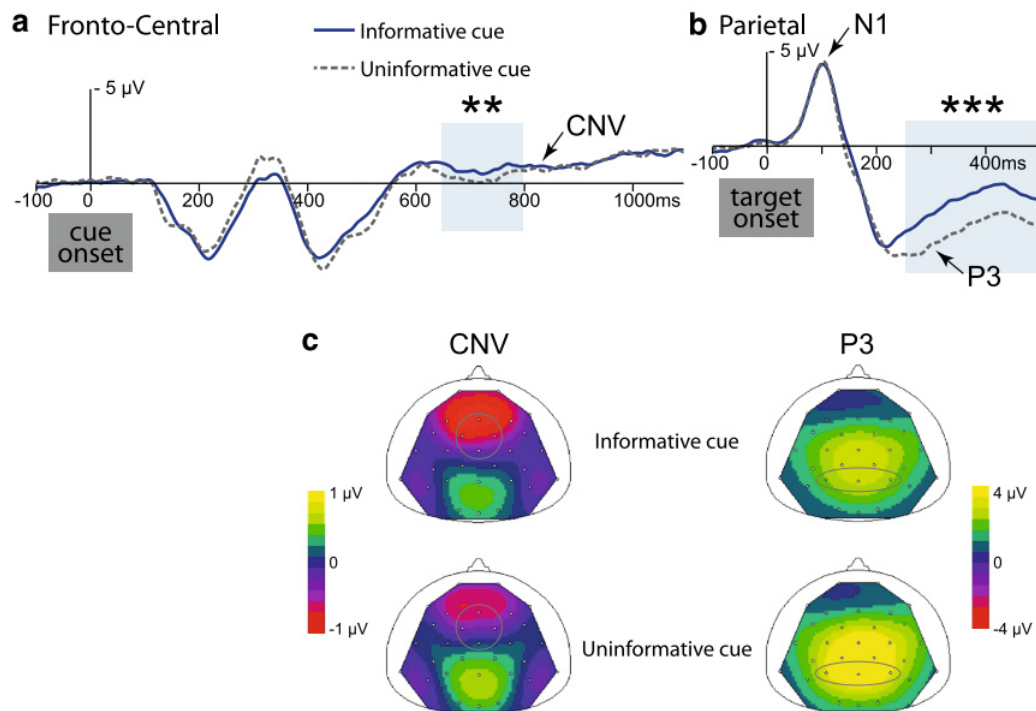


FIGURE 1.16: Evoked potentials elicited during a cueing paradigm with visual cues indicating (or not) in which ear a monoaural auditory target will be presented. a. Contingent negative variation (CNV) at fronto-central electrodes elicited by a cue before target stimulus presentation. The CNV is modulated by the informative aspect of the cue, informative cues leading to increased CNV. b. Parietal N1 and P3 components locked to target stimulus onset. The P3 amplitude is modulated as well by the informative aspect of the cue, uninformative cues leading to greater P3 amplitudes. c. Topographic maps associated with the fronto-central CNV in the 650-800 ms window after cue onset (left) and parietal P3 component in the 250-500 ms window after target stimuli onset (right). Fronto-central and parietal group of electrodes are circled in black. Adapted from Bidet-Caulet et al. (2015).

paradigms, it has been noted that the amplitude of the N1 elicited by attended tones is larger than for the ignored tones (Alcaini et al., 1995; Giard et al., 2000; Hillyard et al., 1973; Näätänen, 1982, 1990). Modulations in N1 component have also been observed during the processing of spectrally-degraded speech stimuli. An increase in N1 amplitude was observed with spectral degradation, suggesting an increase in 'neural effort' to decode degraded speech (Obleser and Kotz, 2011). In a similar way, increase in mental load results in enhanced N1 and P2 amplitudes (Pinal et al., 2014). As previously mentioned, top-down processes implications can be observed in late ERPs. Indeed, auditory infrequent or remarkable stimuli trigger later ERPs which reflect further cognitive evaluation of the stimulus, most notably a negativity evoked between 180 and 350 ms post-stimulus called the N200 (or N2), and a

late positive wave around 300 ms post-stimulus, the P300 response. These components have been mainly explored using active oddball paradigms, an experimental design in which infrequent deviant sounds are interleaved in a regular sequence of repetitive sounds (standard sounds) (Näätänen and Picton, 1986; Patel and Azzam, 2005). Active oddball paradigms include target sounds which require a behavioral response or novel sounds, rare task-irrelevant unexpected sounds. Target and novel sounds elicit a N200 and a P300, which have been considered to reflect the involvement of attention in the processing of the stimulus (Patel and Azzam, 2005). P300 responses are usually conceptualized within the framework of the *orienting response* as described by Sokolov (1963; 1990), defined as the organism's immediate response to a change in its environment, including the automatic attention orienting towards significant, meaningful events (see Fig 1.16b and c right). The N200 and P300 can be decomposed in three distinct components that can be separated based on their latency, scalp topography and conditions of elicitation (Barry, Steiner, and De Blasio, 2016; Patel and Azzam, 2005), however I will further focus on the P3b (also referred as "target-P3") and N2b in this manuscript, these component being relevant to the processes involved in listening effort and an empirical study presented later. Notably, the N2b and P3b are elicited by target stimuli for which the participant is required to respond mentally or physically (Patel and Azzam, 2005; Polich, 2007; Polich and Criado, 2006) and are modulated by task difficulty and mental load (Isreal et al., 1980a,b; Miller et al., 2011; Pinal et al., 2014). The N2b is thought to correspond to voluntary processing, and is elicited when subjects selectively attend to auditory deviations (Näätänen and Picton, 1986; Patel and Azzam, 2005). The P3b appears to reflect the orientation of attention towards a stimulus, and its cognitive evaluation (Patel and Azzam, 2005; Polich, 2007). The P3b is maximal over parietal electrodes and has a peak latency around 300 ms, the N2b peaks negatively around 200 ms and has a fronto-central topography (Näätänen and Picton, 1986; Patel and Azzam, 2005).

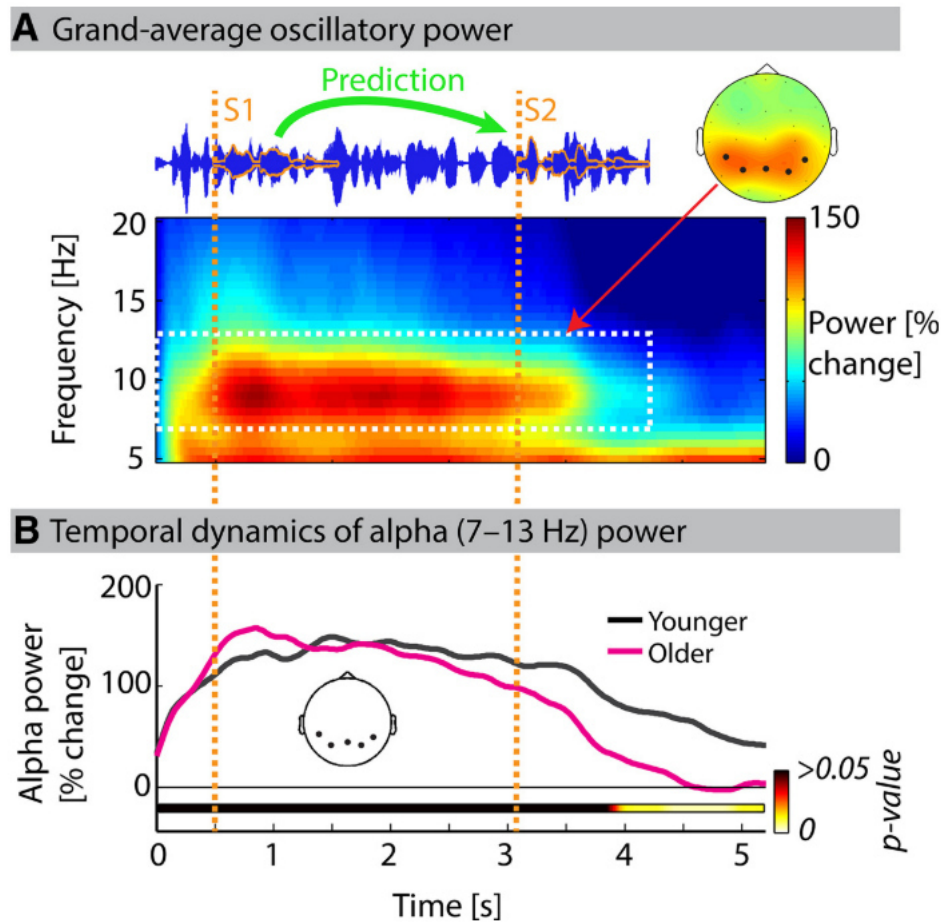


FIGURE 1.17: Alpha oscillatory power during auditory number, embedded in speech masker, comparison task in young and older listeners. A. Alpha power (7-13 Hz) elicited during auditory stimulation averaged across groups. Strongest alpha power is found in parietal electrodes (highlighted in topographic map). B. Time course of mean alpha power change averaged across parietal electrodes for each group. From Wöstmann et al. (2015).

Neural oscillations Neural oscillations consist in periodic signals generated by the brain and can be observed using EEG. Neural oscillations result from rhythmic patterns of action potentials produced by a given population of neurons, leading to synchronized activity in a large neuronal ensemble (Fries, 2005). They are characterized by their main properties: frequency, power, and phase. Oscillations can be classified into frequency bands, including delta (1–4 Hz), theta (4–7 Hz), alpha (7–15 Hz), beta (15–30 Hz) and gamma (>30 Hz) bands. Power is the amount of energy in a frequency band and is associated with the amplitude of the sine wave. Phase is the position along the sine wave at any given time point. Each frequency band is thought to correspond to specific cognitive processes. In particular, alpha activity is believed to play a key role in perceptual, attentional and memory processes (Sauseng and

Klimesch, 2008). Alpha oscillations are usually observed among awake, eyes-shut and inactive participants and are maximal over occipito-parietal electrodes. Therefore, alpha oscillations were usually considered to reflect *cortical idling*, namely an electrophysiological correlate of the deactivated state of cortical areas (Pfurtscheller, Stancák, and Neuper, 1996). However, studies later gathered evidence against the idling hypothesis, suggesting that alpha activity's functional role has been underestimated. Indeed, during working memory experiments, strong increase in alpha power with memory load were found during the retention interval (Jensen et al., 2002; Tuladhar et al., 2007), suggesting that alpha increase either reflect active processing related to cognitive operations (Palva and Palva, 2007), or inhibition of regions not required for the task (Klimesch, Sauseng, and Hanslmayr, 2007). The latter was confirmed by studies of visuospatial attention that showed alpha desynchronization in the occipital area contralateral to the irrelevant item (Kelly et al., 2006; Rihs, Michel, and Thut, 2007; Thut et al., 2006a), and cross-modal studies showing higher parieto-occipital alpha activity when attention was directed towards the auditory modality (Fu et al., 2001; Niu et al., 2020). Then, according to this *gating by inhibition* hypothesis, alpha oscillations are thought to participate in shaping functional architecture of the different brain networks. This theory states that, neural pathways could be either task-relevant or irrelevant according to the task to perform, and that alpha power would increase in task-irrelevant brain areas (see Fig 1.17), blocking information processing along task-irrelevant pathways, and subsequently gating the information flow to the task-relevant pathway (Jensen and Mazaheri, 2010). Moreover, alpha power appears to be a good predictor of behavioral performance, increased alpha power (or alpha *synchronization*) in irrelevant regions and/or decreased alpha power in relevant regions during the anticipation being correlated with reaction time (Bonnetfond and Jensen, 2012; Händel, Haarmeier, and Jensen, 2011; Mazaheri et al., 2014; Payne, Guillory, and Sekuler, 2013; Thut et al., 2006b). In light of these findings, alpha synchronization and desynchronization in sensory cortices have been proposed to express top-down attentional inhibitory and facilitatory mechanisms, respectively. In the past decade, alpha activity has received attention from researchers interested in listening processes in adverse conditions. Obleser et al. (Obleser et al., 2012) manipulated both memory load and auditory

stimulus degradation in an auditory working-memory task. Increased alpha power was found during the memorization period for both the increased memory load condition and the condition with more degraded auditory stimuli. Other studies found similar outcomes, showing enhanced parietal alpha activity with increased acoustic challenge during masked auditory number comparison task (Wöstmann et al., 2015) and word comprehension (Becker et al., 2013; Obleser and Weisz, 2012). Therefore, alpha oscillatory power is believed to reflect the functional inhibition associated with stimuli processing in complex acoustic configurations, and may be a relevant indicator of listening effort.

Other objective measures

Other objective techniques have been used to assess effortful listening, among those, skin conductance, fMRI and fNIRS. Skin conductance (or electrodermal activity) reflects the amount of moisture on the surface of the skin and is assessed by measuring the skin's capacity to conduct an electrical current (Boucsein, 2012). As with the pupil response, changes in skin conductance are influenced by parasympathetic and sympathetic activity and associated with changes in arousal. Increases in skin conductance have been linked to cognitive demands through dichotic-digits task in which task difficulty was manipulated by varying the number of digits for recall and whether digits were presented to one ear or both ears simultaneously (Mackersie and Cones, 2011). Similar results were found during sentence recall in noise (Mackersie and Calderon-Moultrie, 2016; Mackersie and Kearney, 2017) and trends suggesting increase in electrodermal activity with sentence degradation (Holube et al., 2016).

Neuroimaging techniques such as fMRI or fNIRS have also been used to assess listening effort. Several studies used changes in hemodynamic activity to assess cognitive demands due to speech degradation (via noise-vocoding) or masking (by fluctuating noise). Increased activity in the fronto-temporal network (associated to the processing of complex auditory stimuli such as speech, and cognitive functions such as working memory (Binder et al., 1994; Friederici, Meyer, and Von Cramon, 2000; Specht, Shah, and Jäncke, 2000)) was found when participants were required to attend to degraded speech, suggesting a compensatory effort required to perform

challenging listening tasks (Erb and Obleser, 2013; Lawrence et al., 2018; Obleser and Kotz, 2010; Wijayasiri, Hartley, and Wiggins, 2017; Wild et al., 2012; Zekveld et al., 2006).

The effort exerted by an individual to complete a task being a combination of the demands of the task, the cognitive resources, and the motivation to use the cognitive resources (Pichora-Fuller et al., 2016), listening effort seems to be a multidimensional process involving multiple cognitive systems with influence of multiple factors (Peelle, 2018). As various measures of listening effort have been used in research settings (self-reported, behavioral, physiological and electroencephalographic measures), they do not always correlate with each other (McGarrigle et al., 2014).

Inconsistent relationship between self-report, behavioral, and physiological measures of listening effort have been reported. Some studies reported no association between self-report, behavioral, and physiological measures of listening effort (Anderson Gosselin and Gagné, 2011; Larsby et al., 2005; Wendt, Dau, and Hjortkjær, 2016; Zekveld, Kramer, and Festen, 2010, 2011). For instance, increased phasic pupil response was found to be associated with decreased self-reported effort and improved task performance, suggesting that larger pupil dilation could be an indicator of higher levels of attentional focus and vigilance that does not necessarily relate to perceived effort (Wendt, Dau, and Hjortkjær, 2016). Therefore, non-significant correlations between self-report and behavioral/physiological measures of listening effort might be due to the fact that these measures assess different aspects of listening effort (Mackersie, MacPhee, and Heldt, 2015). There is a lack of meaningful correlations between different physiological measures of listening effort as well. Indeed, no correlation between alpha power and pupil size was found during degraded speech recognition (McMahon et al., 2016; Miles et al., 2017), suggesting that the physiological processes indexed by these measures were modulated by different neurophysiological or attentional networks.

Although all measures have been interpreted in terms of “listening effort”, they do not always agree well with each other, but also across participant groups (Ohlenforst et al., 2017b; Petersen et al., 2015), or between studies (McMahon et al., 2016; Obleser and Weisz, 2012). Variability in experimental methods and the aspects of

cognitive demands they may assess might be an explanation to these inconsistent findings, but it could also be due to the unreliability of these measures (Alhanbali et al., 2019; Koo and Li, 2016). Alhanbali et al. (2019) then investigated the reliability of the previous measures (self-report, behavior, pupillometry and EEG) by testing a subgroup of participants during a speech-in-noise task (digits presented in noise had to be recalled) on two separate occasions, as well as the correlation between these measures. Despite good reliability of the measures, they were only weakly correlated with each other, suggesting that they tap into different underlying dimensions. It then remains unclear if listening effort is a single concept, or a conglomerate of multiple phenomena. However, it seems unlikely to fully explain effortful listening using a single dimension, supporting the multidimensional nature of listening effort (Alhanbali et al., 2019; Matthen, 2016).

Objectives

In our everyday lives, we are confronted to complex auditory situations that need to be processed in order to apprehend, understand and adapt to our auditory environment. As it is not possible (nor necessary) to process all of the auditory information, crucial cognitive operations are set up to filter and process relevant information. These operations include auditory selective attention mechanisms and working-memory processes, engaging the deployment of cognitive resources therefore leading to cognitive effort, especially in noisy environments. The extent to which these cognitive resources are engaged depends definitely on the complexity of the auditory environment to process, but is also modulated by motivational aspects. Effortful listening implies then a complex mixture of internal processes, that researchers tried to understand and disentangle in the last two decades. Listening effort has been studied through a large panel of methods. Different types of measures have been used such as, subjective, behavioral and objective ones. Inconsistent relationships were found between these measure outcomes, suggesting that they tap into different underlying mechanisms of listening effort. Listening effort seems then to be a multidimensional process, rather than a single concept, that is not yet fully understood.

This PhD work thus aims at bringing new insights on the investigation of listening effort, first through methodological consideration (especially concerning the analysis of pupillometric recordings), then with empirical studies using complementary measures (subjective, behavioral and objective). More precisely, this work aimed at specifying the most appropriate way of assessing listening effort and the relationship between different measures of listening effort. The second chapter of this thesis will focus on the methodological study of the pupillometric signal obtained during the assessment of listening effort in hearing-impaired patients during a word-in-noise recognition test. First, several methods of normalization were

compared to assess their influence on the outcomes of task-evoked pupil responses. Then, a complementary analysis was performed on the pupillometric signal in the frequency domain using wavelet decomposition to explore the cognitive-related high frequency components of the signal. The third chapter will then focus on results of empirical studies in which subjective, behavioral and objective measures have been concurrently used. The results obtained in hearing-impaired patients will be first presented. Then, results obtained among a healthy young population during a tone discrimination task, using simultaneous pupillometry and EEG recordings, will be presented.

Chapter 2

Methodological study

The present chapter will focus on the methodological investigation of the pupillometric signal during the assessment of listening effort among hearing-impaired patients. A first study will be presented, dealing with the comparison of signal processing methods broadly used to study task-evoked pupil responses. A complementary study will be then presented, focusing on the frequency-based analysis of the pupillary responses to assess cognitive effort. Data analyzed in these studies were acquired before the beginning of the PhD.

2.1 Comparing methods of analysis in puillometry: application to the assessment of listening effort in hearing-impaired patients

Comparing methods of analysis in pupillometry: application to the assessment of listening effort in hearing-impaired patients.

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Keywords: Pupil dilation response, baseline, normalization, anticipation, attention, hearing aid

Abstract

Numerous studies showed that task-evoked pupil dilation is an objective marker of cognitive activity and listening effort. However, these studies differ in their experimental and analysis methods. Whereas most studies focus on a single method, the present study sought to compare different pupil-dilation data analysis methods, including different normalization techniques, baseline periods, and baseline durations, in order to assess their influence on the outcomes of pupillometry results obtained in an auditory task. To that purpose, we used pupillometry data recorded in response to words in noise in hearing-impaired individuals. The start-time of the baseline relative to stimulus timing turned out to have a significant influence on conclusions. In particular, a significant interaction in the effects of signal-to-noise ratio and hearing-aid use on pupil dilation was observed when the baseline period used started early relative to the word—an effect likely related to anticipatory, pre-stimulus cognitive processes, such as attention mobilization. This was the case even with only correct-response trials included in analyses, so that any confounding effect of performance in the word-repetition task was eliminated. Different normalization methods and baseline durations showed similar results, however the use of z-score transformation homogenized variability across conditions without affecting the qualitative aspect of the results. The consistency of results regardless of normalization methods, and the fact that differences in pupil dilation and subjective measures of listening effort could be observed despite perfect performance in the task, underlines the relevance of pupillometry as an objective measure of listening effort.

Highlights:

- Different normalization techniques of the pupil dilation response result in similar outcomes.
- The choice of the baseline period is crucial to assess attention mobilization, in particular anticipation during listening effort, using the pupil dilation response.
- Pupil dilation response can reveal subtle changes in cognitive demands even in the case of perfect performances.

Introduction

Studies investigating cognitive effort have used different methods, such as questionnaires and behavioral indices, or objective measures, such as pupillometry. Pupillometry is a well-known neurophysiological investigation technique, based on measuring the size of the pupil. From silver photography to high sampling rate eye-tracking systems, pupillometry has drastically evolved over the years, and it has been used in a wide range of research fields. Changes in pupil size are now known to be linked to the activation of the locus-coeruleus-norepinephrine (LC-NE) system (Aston-jones & Cohen, 2005) and have been associated with several neurophysiological and cognitive phenomena, such as adaptation to brightness (Barlow, 1972; Reeves, 1920), arousal and emotion processing (Bradley, Miccoli, Escrig, & Lang, 2008; Partala & Surakka, 2003), or increases in cognitive demands (Beatty, 1982; Hess & Polt, 1964; Payne, Parry, & Harasymiw, 1968).

Over the past twenty years or so, numerous studies have used pupillometry to investigate cognitive effort, using different methods of analysis (see Table 1). While some earlier studies used changes in raw pupil size as measures of cognitive activity (Hyönä, Tammola, & Alaja, 1995; Just & Carpenter, 1993; Kahneman & Beatty, 1966), in more recent years, it has become customary to measure pupil-size changes relative to a baseline period using subtractive baseline correction (see Table 1). However, the dynamic range of pupil size, i.e., the difference between baseline and peak pupil size, can vary widely across individuals. Therefore, in two different individuals performing the same task, the same amount of pupil dilation may in fact correspond to different amounts of cognitive effort. Given such inter-individual variability, some authors, e.g., Winn, Wendt, Koelewijn, & Kuchinsky (2018), have advised that normalization methods be applied, in addition to baseline correction (some examples are described in Table 1). Analyses of pupil-dilation data may also vary with respect to the selected baseline period (see Table 1). Although it is customary in pupillometry studies, to use as baseline a period preceding stimulus onset, the duration of that period, and how close in time it is, from stimulus onset, can vary widely across studies. While most studies have used a 1000-ms baseline, baseline durations can actually vary from as short as 100 ms to as long as 2000 ms (see Table 1). Given substantial differences in pupil-data analysis methods across studies, it seems important to ask whether

different analysis methods can lead to different conclusions. This issue has recently been investigated by Attard-Johnson, Ciardha, & Bindemann (2019) regarding pupillary responses recorded to measure arousal elicited by viewing pictures of men and women. The use of different analysis methods resulted in similar outcomes on their specific data set, but this methodological matter needs to be addressed for the study of other cognitive processes, such as listening effort.

In recent years, pupillometry has been applied to measuring listening effort. The latter has been defined by McGarrigle et al. (2014) as “*the mental exertion required to attend to, and understand, an auditory message*”. In those applications, pupil diameter is recorded during various speech-in-noise recognition tasks (Koelewijn, Zekveld, Festen, & Kramer, 2014; Kuchinsky et al., 2013; Ohlenforst et al., 2018; Zekveld, Kramer, & Festen, 2010, 2011). In most of those tasks, participants are asked to repeat as correctly as possible sentences heard in adverse conditions, while the diameter of their pupils is being recorded. In those studies, a common working hypothesis is that changes in cognitive load are associated to changes in pupil size: the more challenging the listening condition, the larger the pupil dilation. However, in some cases, the listening situation can be so challenging that some participants may stop trying to perform the task correctly; consequently, no modification, or even a decrease in pupil dilation, may be observed in these test conditions. Another complication in the interpretation of the results of these studies, stems from the multiplicity of the cognitive processes involved in task performance. Being able to correctly repeat a sentence involves attention, short-term memory, and a host of auditory and linguistic processes. Thus, pupil dilation may reflect more complex cognitive processes than purely auditory processing of the stimulus (Zekveld, Kramer, Rönnerberg, & Rudner, 2019). Lastly, it is conceivable that in tasks with a predictable (e.g., repeating) temporal structure, participants start mobilizing cognitive resources, such as attention, *in advance* of the stimulus; such anticipatory effects underline the importance of selecting an adequate baseline in analyses.

Following a review of analysis methods used in pupillometry studies involving listening tasks (Table 1), the present study systematically compares several normalization methods, and several ways of taking into account baselines. The different analysis methods were applied to data from a listening study in hearing-impaired patients. An additional question, which this study sought to address, is

whether pupil-dilation data collected during a word-in-noise recognition test – a task widely used in clinical audiology and hearing research to evaluate speech-perception performance – in hearing-impaired individuals, could be used to assess listening effort at the single-item (i.e., single-word) level. To investigate this hypothesis, test conditions varying in the amount of effort were included into the experimental design, and differences in pupil dilation between these conditions were tested. Importantly, variations in listening effort across conditions can exist, despite similar performance scores across the same conditions. Here, the words were presented at high signal-to-noise ratios, so that recognition performance was generally high. Another hypothesis, which was tested in this study, is that listening effort, reflected in pupil-dilation changes, is a combination anticipatory and stimulus-processing efforts. To test this hypothesis, we systematically analyzed the pupillometry data using four different baselines (with different timings relative to stimulus onset), and five normalization techniques (subtractive baseline correction, proportional change from baseline, within-trial mean scaling, grand mean scaling and z-score transformation).

Table 1

Studies investigating auditory cognitive demands and their respective method and parameters used in analysis

Study	Method	Computation	Baseline period	Baseline duration	Task	Cue
Zekveld et al. (2018)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Beginning of stimulus presentation	1000ms	Active	A, V
Zekveld et al. (2014a)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Beginning of trial	1000ms	Active	A
Winn et al. (2015)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Beginning of trial	2000ms	Active	No
Kramer et al. (1997)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Prior to noise onset	1000ms	Active	A
Lewis & Bidelman (2020)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Prior to stimulus onset	100ms	Active	No
Zellin et al. (2011)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Prior to stimulus onset	200ms	Active	V
Wetzel et al. (2016)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Prior to stimulus onset	200ms	Passive	No

Widmann et al. (2018)						
Zekveld et al. (2010)						
Zekveld et al. (2011)						
Koelewijn et al. (2012)						
Koelewijn et al. (2014a)						
Koelewijn et al. (2014b)						
Zekveld & Kramer (2014)						
Zekveld et al. (2014b)						
Koelewijn et al. (2015)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Prior to stimulus onset	1000ms	Active	A
Koelewijn et al. (2017)						
Ohlenforst et al. (2017)						
Wendt et al. (2017)						
Francis et al. (2018)						
Jensen et al. (2018)						
Ohlenforst et al. (2018)						
Wang et al. (2018a)						
Wang et al. (2018b)						
Wendt et al. (2018)						
Kramer et al. (2013)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Prior to stimulus onset	1500ms	Active	A
McMahon et al. (2016)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Prior to stimulus onset	2000ms	Active	A
Borghini & Hazan (2018)	Baseline correction	The average pupil size in the baseline period is subtracted from data points.	Prior to stimulus onset	2000ms	Active	A, V
McCloy et al. (2017)	Deconvolution	Pupil data are first baseline corrected on each trial then data points are dividing by the standard deviation of pupil sizes across all trials. Pupil data are then deconvolved with pupil impulse response kernel.	Prior to trial onset	500ms	Active	A
McCloy et al. (2018)						
Engelhardt et al. (2010)	Grand-mean scaling	Pupil data are normalized by calculating the grand mean of the complete trace and then			Active	No

		dividing each data point by the grand mean.					
Winn & Moore (2018)	Individual dynamic range scaling	Pupil dilation is expressed as a proportion of each participant's dynamic range.			Active	A	
Ayasse et al. (2017)	Individual dynamic range scaling	Pupil dilation is expressed as a proportion of each participant's dynamic range.			Active	V	
Wagner et al. (2016b)	Proportional change from baseline	Pupil data are normalized by first applying a baseline correction then dividing all data point by the baseline (it can be expressed in percentage by multiplying by 100).	Prior to stimulus onset	200ms	Active	No	
Wagner et al. (2016a)	Proportional change from baseline	Pupil data are normalized by first applying a baseline correction then dividing all data point by the baseline (it can be expressed in percentage by multiplying by 100).	Prior to stimulus onset	200ms	Active	V	
Wagner et al. (2019)	Proportional change from baseline	Pupil data are normalized by first applying a baseline correction then dividing all data point by the baseline (it can be expressed in percentage by multiplying by 100).	Prior to stimulus onset	500ms	Active	V	
Miles et al. (2017) Winn & Moore (2018)	Proportional change from baseline	Pupil data are normalized by first applying a baseline correction then dividing all data point by the baseline (it can be expressed in percentage by multiplying by 100).	Prior to stimulus onset	1000ms	Active	A	
Hyönä et al. (1995)	Raw pupil size	Differences in raw pupil sizes are observed.			Active	No	
Wendt et al. (2016)	Within-trial mean scaling	The minimum value of the entire trial is subtracted from data points. Then, pupil data are normalized by calculating the mean of all data points in each trial and then dividing each data point by the mean. Baseline correction is then applied.	Prior to stimulus onset	1000ms	Active	A, V	
Mcgarrrigle et al. (2016)	Within-trial mean scaling	Pupil data are normalized by calculating the mean of all data points in each trial and then dividing each data point by the mean. Baseline correction is then applied.	Prior to stimulus onset	1000ms	Active	A	
Kuchinsky et al. (2013) Kuchinsky et al. (2014) Kuchinsky et al. (2016)	Within-trial mean scaling	Pupil data are normalized by calculating the mean of all data points in each trial and then dividing each data point by the mean. Baseline correction is then applied.	Prior to stimulus onset	1000ms	Active	A, V	
Ayasse et al. (2017)	Within-trial mean scaling	Pupil data are normalized by calculating the mean of all data points in each trial and then dividing each data point by the mean.	Prior to stimulus onset	2000ms	Active	V	

Korn & Bach (2016)	Z-score transformation	Pupil diameters are expressed as z-scores then baseline corrected.	Beginning of trial	First data point	Passive	No
McCloy et al. (2016)	Z-score transformation	Pupil diameters are baseline corrected then expressed as z-scores.	Prior to stimulus onset	500ms	Active	A

Table 1. The cue column indicates whether participants are given indices regarding stimulus presentation or not. Cues might be explicit (a visual (V) or auditory (A) indication before the presentation of the stimulus) or implicit (the beginning of the noise before the presentation of a sentence in adverse conditions for instance).

Material and methods

Participants

Thirty participants (15 male, 15 female) aged between 29 and 91 years old (mean: 70 years old) were recruited among hearing-impaired patients of a hearing-aid dispenser. All participants provided written informed consent in accordance with the Declaration of Helsinki (General Assembly of the World Medical Association, 2014) and all data were processed anonymously. Participants were screened for major cognitive alterations and dementia using the MoCA test (7.2) (<http://www.mocatest.org/>) (Nasreddine & Patel, 2016). They also completed a listening effort questionnaire adapted from the Effort Assessment Scale (EAS) (Alhanbali, Dawes, Lloyd, & Munro, 2017). Participants had a mean hearing loss (Pure Tone Average at 500, 1000, 2000 and 4000 Hz) of 44 dB HL in the better ear (SD = 13.5 dB HL) and 54.6 dB HL in the worse ear (SD = 14.9 dB HL). Based on participants' answers to a hearing-aid use questionnaire, they had been wearing hearing-aids for 3.6 years on average, for an average of approximately 10-hour per day.

Pupillometry session

Prior to the main tests, the sound level of the dissyllabic words was adjusted individually to yield at least 90% word-correct scores unaided, i.e., without hearing-aids, in “quiet”. In the context of this study, “quiet” test conditions refer to conditions in which words were presented in a background of speech-shaped noise (i.e., noise having the same long-term average power spectrum as the words), with a high (30 dB) signal-to-noise ratio (SNR). The reason background noise was included even in “quiet” conditions is that the room in which participants were tested was not entirely sound-proof, and the computer used to control the test procedure could not be moved outside of the room. The individually adjusted sound level was then kept constant for the entire duration of the tests. For the “noisy” conditions, the SNR was adjusted individually prior to the start of the main test, in such a way that scores measured without hearing-aids in the presence of background noise would also equal around 75%. Following these preliminary, individual adjustments of signal level and SNR, four different conditions were tested:

- two “quiet” conditions, one with hearing-aids (Quiet Aided) and one without hearing-aids (Quiet Unaided);
- two “noisy” conditions, one with hearing-aids (Noise Aided) and the other without the hearing-aids (Noise Unaided);

For the tests with hearing-aids, each participant used his/her own hearing-aids, with their habitual gain settings. The hearing-aids included different brands (Phonak, Starkey) as well as different models. To facilitate analyses and interpretations of the results, except for the feedback-canceller, the signal-processing algorithms on these hearing-aids, such as noise-reduction and directional processing, were turned off for the duration of the tests. A subset of participants also performed a fifth condition, in which they were tested with their hearing-aids on, but with the hearing-aid noise-reduction algorithm turned on. However, because this condition could only be tested in a subset of participants, while a complete dataset was needed for the current study, results of this fifth condition were not included into this study.

For each condition, two lists of 12 dissyllabic words were presented to the participant (leading to a total of 8 different 12-word lists). Participants were asked to repeat the word or what they had heard, even if it was a single syllable or a single phoneme, after an auditory cue (see Stimuli section). There was a short training block of five words (not included in the 12-word lists), for participants to familiarize themselves with the task; in particular, participants had to learn to wait for the cue before repeating the word – an important methodological feature of the present study.

Word order within a list, 12-word lists and test conditions were randomized across participants. At the end of each 12-word list, participants rated the perceived difficulty of the task using a 10-point visual analogue scale (1: very easy task, 10: very difficult task). Each 12-word sequence lasted approximately 2 min 30 s and this pupillometry session lasted approximately 1 hour, including breaks and calibration procedure.

Apparatus

The walls in the room were covered with acoustic panels and the room was illuminated by a lamp placed above and behind the participant. The participant was comfortably seated in front of three

loudspeakers (Yamaha, HS 50M) (see Figure 1). The first one, directly in front of the participant, was used to play the target words – consistent with the most common conversation-listening situation, with an interlocutor in front. The two other loudspeakers were used to play the noise, and were positioned at -60° and $+60^\circ$ angles relative to the midline. Each loudspeaker was placed at a distance of 1.20 m from the participant. A microphone installed next to the participant was used to record answers during the task. The eye-tracking system (SensoMotoric Instrument, RED250mobile (Berlin, Germany)) was placed at a maximum of 70 cm in front of the participant. Data were sampled at 250 Hz with a 0.4° spatial resolution. Eye positions and pupil data were recorded for both eyes. A five-point calibration was performed with fixation points displayed on the panel in front of the participant. During the task, participants were asked to fixate a white cue on the loudspeaker in front of them.

Figure 1

Experimental setup

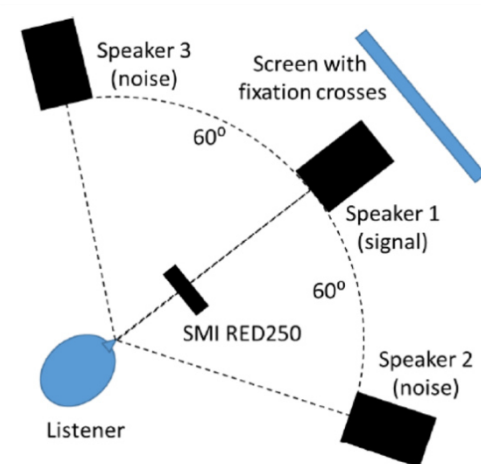


Figure 1. Schematic depiction of the experimental setup. The participant was seated in front of three loudspeakers. The first one directly placed in front of them and was used to play the target signals (words). The two other loudspeakers were at a 60° angle from the front one and were used to play the noise. The eye-tracking system was placed in front of the participant. During the tests, participants had to fixate a visual cue on the loudspeaker in front of them.

Stimuli

Words used as stimuli were disyllabic words, with high frequency occurrence in the French language and pronounced by a female voice. Each word lasted 500 ms on average. Word lists were balanced with respect to their linguistic, acoustic, and psychometric properties (Moulin et al., 2017).

Each trial was designed as follows (see Figure 2):

- first second: stationary noise;
- auditory cue (“Beep”: 500 Hz pure-tone lasting 400 ms), announcing the occurrence of the next word;
- 1.5 s of stationary noise preceding the word;
- 4 s (including the word) to process the word;
- auditory cue (“Blop”: two 400-Hz pure tones followed by a 450-Hz pure-tone, each 100 ms in duration, separated by a 50-ms inter-stimulus interval), announcing the start of the temporal window for repeating the word;
- 5 s temporal window, to allow the participant to repeat the word that he/she just heard.

Each trial lasted 12.25 s.

Figure 2

Design of one trial with baseline periods used in analyses

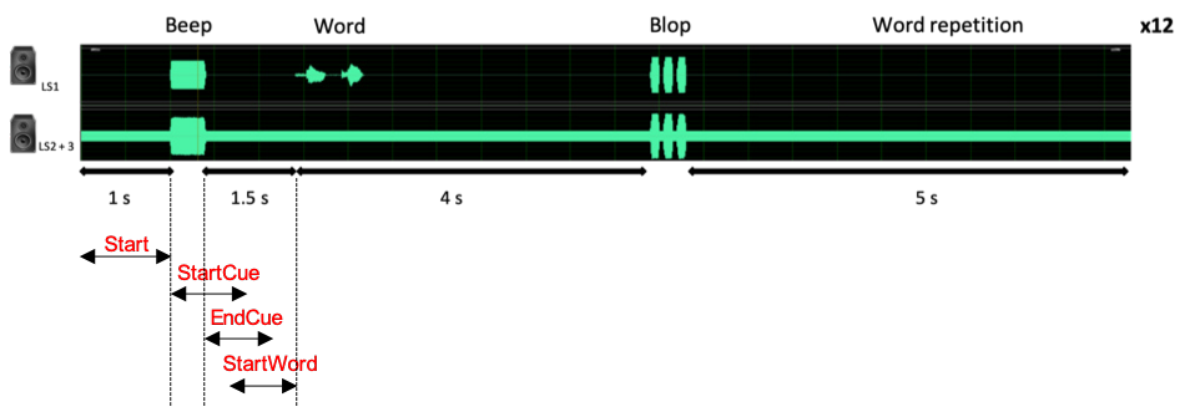


Figure 2. Noise is first played, followed by a first auditory cue announcing the beginning of the word (“Beep”). After the word has been processed, a second auditory cue allows participant to repeat the word heard (“Blop”). Time is fixed for all trials. Each block contains 12 trials.

Analyses

Subjective data

Speech perception scores

A correct answer was recorded when participants repeated the whole word correctly after the auditory cue. Scores are averaged across conditions for each participant and expressed as percentages. Percentages were then converted to *rau* scores using Studebaker's (1985) method.

Subjective rating

Subjective ratings given at the end of each sequence in the pupillometry session are also averaged across conditions for each participant. Similarly, subjective ratings were expressed as percentages (100% = maximum effort) and converted to *rau* scores.

Pupillometric data

To allow for adaptation of the participant and of the hearing-aids to changes in the signal and/or noise levels, only data corresponding to the 10 last words of each 12-word block were included in the analyses. Trials for which participants repeated the word before the auditory cue were also excluded from analysis.

Pre-processing of pupil data

Pupil diameters were recorded binocularly and continuously using an SMI° RED eye-tracking system. Data were sampled at 250 Hz. All data processing and analysis were performed using Python (Python Software Foundation. Python Language Reference, version 3.7. Available at <http://www.python.org/>), the “cili” library (Acland & Braver, 2014) was adapted for data pre-processing. Zero values and pupil diameters below two standard errors of the mean were coded respectively as blinks and “half-blinks”. Blink events were linearly interpolated from 8 ms before the starting point until 16 ms after the ending point of the blink. “Half-blink” events were interpolated from 40 ms before the starting point until 40 ms after the ending point of the “half-blink”. The data were then corrected for artefacts due to eye movements using linear interpolation. Each step of this pre-processing

was performed for both eyes. Pupil data were then smoothed using a low-pass 7th order Butterworth filter (cut-off frequency: 25 Hz) to remove high frequency artefacts. Trials containing more than 60% of interpolated data were rejected. Finally, traces were visually inspected to manually include or exclude trials. Following these criteria, 3 participants were excluded from analysis due to insufficient recording of pupil data and too much interpolated data. Around 10% of trials were excluded from the remaining data of 27 participants, leading to 474, 501, 471, 473 trials in the Quiet Aided, Quiet Unaided, Noise Aided, Noise Unaided conditions respectively. For each participant, we chose to analyze pupil traces from the eye in which we found least interpolations and missing data across all conditions.

Task-Evoked Pupil Response (TEPR): baseline-related analysis

Overall, task performance was high, with a mean *rau* score of 95.3 (SEM=3.8) in the Quiet Aided condition, 93.8 (SEM=4) in the Quiet Unaided condition, 73.4 (SEM=3.7) in the Noise Aided condition and 77.6 (SEM=2.1) in the Noise Unaided condition. To identify changes in pupil dilation related to listening effort unbiased by response correctness, main analyses focused on pupil responses measured during correct-response trials (“hits”) only. However, analyses including data from all trials (correct and incorrect) were also performed, and their results were compared with those of the main analyses using only correct-response trials (Supplementary Figures 3S to 6S). Therefore, participants who repeated correctly at least 8 entire words out of 20 (2 x 10 words per condition) for each condition were included in the analyses (N = 20 participants).

Baseline correction

All included trials were baseline-corrected. Baseline correction is a common operation in pupillometry, whereby the average pupil size measured over some time period (epoch) prior to stimulus onset is computed, then subtracted from pupil-dilation measurements collected over a subsequent epoch –typically, post stimulus onset. To investigate the influence of the choice of baseline epoch, analyses were performed using four different baseline epochs (see Figure 2), with durations of 500 ms (Supplementary Figures 1S to 4S) or 1 s: *Baseline Start*: The first baseline period used in these analyses coincided with the trial onset, defined as the onset of the background noise. This baseline period is the most anterior, relative to the onset of the word. *Baseline StartCue*: This baseline period started with the

onset of the cue announcing the word. *Baseline EndCue*: This baseline period started with the offset of the cue announcing the word. *Baseline StartWord*: This baseline period *ended* with the onset of the word.

Normalization

To take inter-individual differences in pupil-dilation dynamic range into account, several normalization methods (Winn et al., 2018) were applied on the data. This was done separately, for each baseline correction described above. Results obtained using these normalization methods were then compared with results obtained using baseline-corrected data (Koelewijn, Shinn-Cunningham, et al., 2014; Kramer, Zekveld, Koelewijn, & Beek, 2010; Zekveld, Rudner, et al., 2011) to observe potential differences.

Proportional change from baseline: One way to express local deviation from baseline is to present the percentage of pupillary dilation (Hess & Polt, 1964; Payne et al., 1968) or to express data as a proportional change from baseline (Johnson et al., 2014; Wierda, Rijn, Taatgen, & Martens, 2012). In our analysis, task-evoked pupil dilation was expressed in this way for each data point x : $x_{norm} = (x_{data} - baseline)/baseline$ (Wierda et al. 2012).

Within-trial mean scaling: This method has been used in previous studies to ensure a consistent scaling of pupil across trials and participants (Kuchinsky et al., 2014, 2013, 2016). Each trial data point was divided by the mean of the relevant period of the trial (from the start of the trial to the cue before the repetition of the word), then, a baseline correction was performed.

Grand mean scaling: Grand mean scaling has also been used to assess change in pupil size (Engelhardt et al., 2010). The grand mean of the whole time series (periods from the start of each trial to the cue before the repetition of the word of the entire block (10 words)) was computed and each data point was divided by the grand mean. Then, we applied baseline correction on the normalized data.

Z-score transformation: Finally, a z-score transformation was applied (McCloy et al., 2016; Nassar et al., 2012). To do so, the mean of the relevant period of the trial (from the start of the trial to the cue before the repetition of the word) was subtracted from each trial data point, then each data point

was divided by the standard deviation of the relevant period of the trial. The z-score transformation was followed by a baseline correction.

Statistical analyses

Behavioral data

Participants' subjective ratings expressed as *rau* scores were analyzed separately using a Linear Mixed-effects Model (LMM) to test within-subject effects of hearing-aid (Aided vs Unaided) and background noise (Quiet vs Noise). The model contained fixed-effects for the hearing-aid factor (Aided vs Unaided), the noise factor (Quiet vs Noise) and interaction between these two factors. A random-effect was also added to the model, to account for individual variance in intercept and slope for the noise factor ($R^2_m=0.3140$, $R^2_c=0.8123$). A type-II ANOVA (using type-II Wald X^2 test) was then applied to the model.

Pupillometric data

Since we are interested in anticipation processes and how different conditions could affect them, statistical analyses were conducted on two time-windows: anticipation and stimulus processing. The anticipation window is defined between the cue announcing the word and the beginning of the word (i.e., 1900 ms long). The stimulus processing window is defined between the beginning of the word and the cue before the repetition of the word (i.e., 4000 ms).

Between-subject variability between conditions over time was inspected for each normalization method. To do so, a ratio was computed for each time point. This ratio was computed per normalization method as follows: $h(t)/H$, with $h(t)$ the width of the confidence interval of the group mean computed for each time point per condition and H the width of the confidence interval of the group mean computed on the entire time window per condition. H is then constant for each time window and condition.

Further statistics were conducted in order to find within-subject effects of the different factors on the amplitude dilation of the pupil during the task. Listening effort is usually assessed using the maximum dilation value (peak pupil dilation) in a defined window (Koelewijn, Zekveld, et al., 2014;

Ohlenforst et al., 2018; Wang, Kramer, et al., 2018; Zekveld, Heslenfeld, et al., 2014; Zekveld & Kramer, 2014; Zekveld, Rudner, et al., 2014). In our study a peak value would hardly be definable in the anticipation window, we will then use the mean dilation of the pupil in the two time-windows to assess cognitive demands during the task (Koelewijn et al., 2012; Kramer et al., 2013; Zekveld et al., 2010; Zekveld, Kramer, et al., 2011). Therefore, dependent variables were defined as the mean dilation in the anticipation window and the mean dilation around the peak pupil dilation (maximum dilation) in the stimulus processing window. Since the stimulus processing window is larger than the anticipation window, the mean dilation in the stimulus processing window was computed on the same length as in the anticipation window (i.e., 1900 ms) centered around peak pupil dilation. Mean dilations of the pupil were analyzed using a Linear Mixed-effects Model (LMM). For each window separately (Anticipation and Stimulus processing), the model contained fixed-effects for the hearing-aid factor (Aided vs Unaided), the noise factor (Quiet vs Noise) and interaction between these two factors. A random-effect was also added to the model to account for individual variance in intercept for any within-subject factor ($R^2m=0.0726$, $R^2c=0.4678$). We then performed a type-II ANOVA (using type-II Wald X^2 test) on the model. Post-hoc pairwise comparisons were conducted using least-squares means testing. Analysis were conducted with R (R Development Core Team, 2020), the “lme4” package (Bates, Mächler, Bolker, & Walker, 2015) was used to compute the model, the “car” package (Fox & Weisberg, 2019) was used to compute the type-II ANOVA and the “emmeans” package was used to compute least-squares means testing (Searle, Speed, & Milliken, 1980).

Results

Behavioral data

As mentioned earlier, the task was very well completed with high speech perception scores (see Material and Methods section). The subjective difficulty of the task was rated as follows: 17.2 (SEM=5.3) in the Quiet Aided condition, 14.1 (SEM=4.6) in the Quiet Unaided condition, 53.2 (SEM=5.9) in the Noise Aided condition and 40 (SEM=5.2) in the Noise Unaided condition. The type-II ANOVA indicated significant effect of noise on subjective ratings ($X^2(1, N=20)=28.30, p=1*10e-7$) showing that the task was perceived as easier when words were presented with a high SNR. A significant effect of aid was also found on subjective ratings ($X^2(1, N=20)=8.46, p=0.0036$) indicating that participants rated the task as easier when they were not wearing their hearing aids.

Pupillometric data

Different patterns were observed in participants pupil traces. In more challenging conditions, some participants showed a dilation peak when the word is presented and when the word is repeated (see Figure 3: left), but other showed a continuous increase in dilation from the beginning of the trial to the presentation of the word reflecting preparation to process the word (see Figure 3: right). In this particular case, the choice of the baseline period can have a critical outcome regarding the measure of the listening effort: if the chosen baseline period was too close to the word, this anticipation would not be taken into account. Following this idea, several baseline periods were tested (see Figure 4.a to 4.d). As well as different patterns of dilation, differences in terms of variability and pupil size were observed in collected data. In light of such inter-individual variability, several normalization methods were computed as well (see Figure 4.1 to 4.5).

Figure 3
Different individual dilation patterns

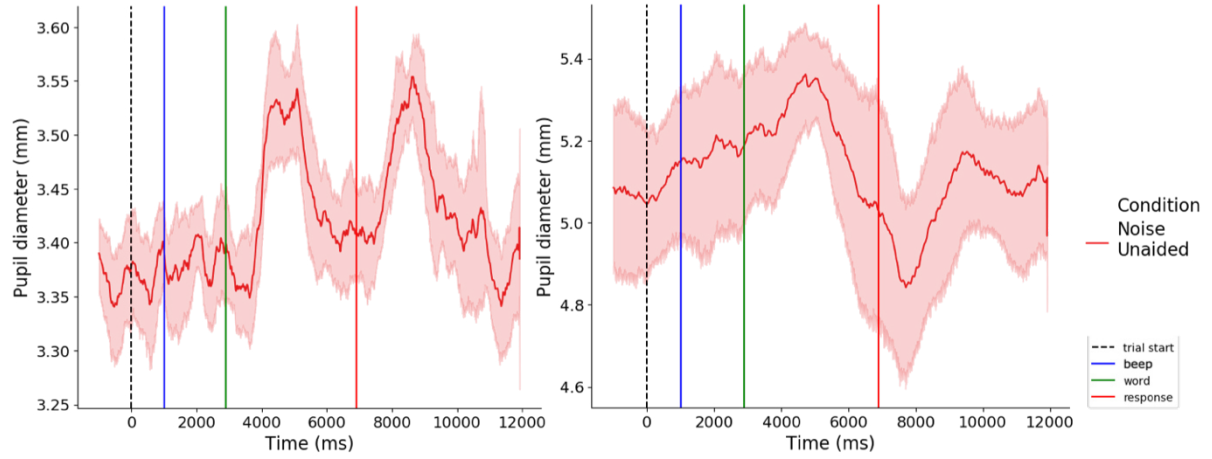


Figure 3. Left: Pupil trace from a participant showing no dilation increase before the word presentation (green line) in a more challenging condition (words presented in noise) ($N=1$). Right: Pupil trace from a participant showing a continuous increase in dilation before the word presentation (green line) in a more challenging condition (words presented in noise) ($N=1$). Traces were obtained by averaging the correctly answered trials of the 10 last trials of each block (the 2 first trials are excluded) in the Noise Unaided condition. Traces represent raw pupil diameter during the task. Shaded areas represent 95% confidence intervals.

Figure 4
Individual pupil-dilation patterns computed using different normalization methods and baseline periods

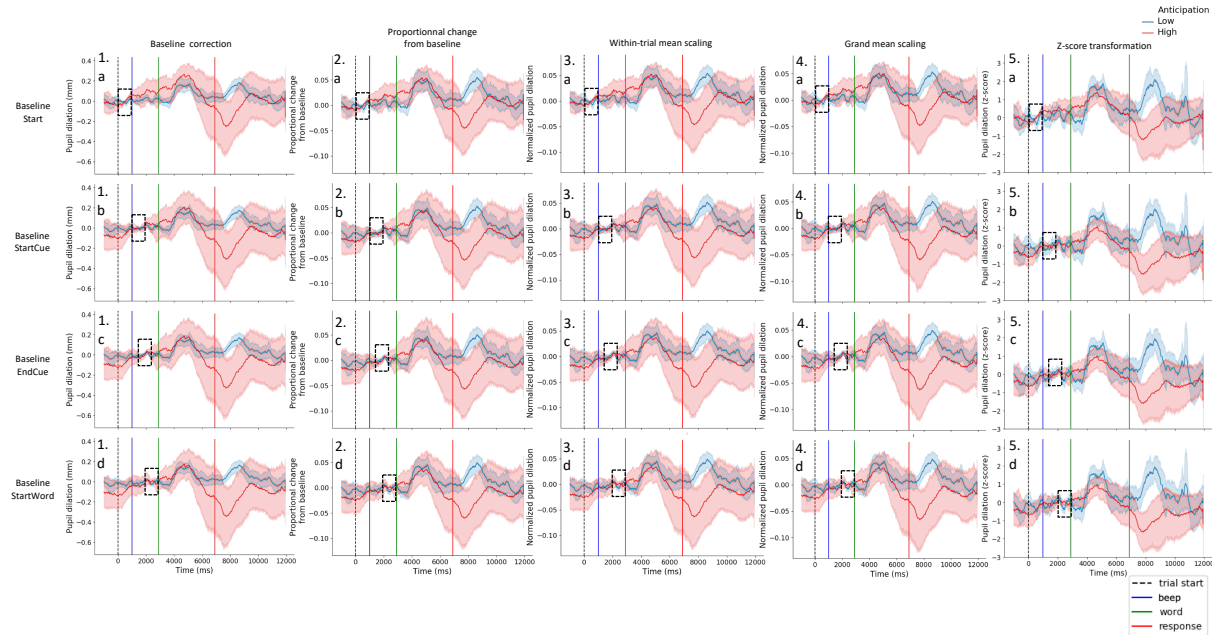


Figure 4. Pupil traces obtained by averaging the correctly answered trials in the Noise Unaided condition. Blue traces were obtained from a participant presenting no increase in pupil dilation before the word presentation (green line). Red traces were obtained from a participant showing a continuous increase in pupil dilation before the word presentation (green line). Traces were computed using several normalization methods (1: baseline correction only, 2: proportional change from baseline, 3: within-trial mean scaling, 4: grand mean scaling, 5: z-score transformation) and several baseline periods (dashed rectangles) (a: Start: from start (dashed black line) to the auditory cue before word presentation (blue line), b: StartCue: starting at the beginning of

the auditory cue before word presentation (blue line), *c*: *EndCue*: starting at the end of the auditory cue before word presentation, *d*: *StartWord*: ending at the beginning of the word (green line)). Baseline lengths were set at 1000ms. Shaded areas represent 95% confidence intervals.

When considering all participants (N=20), the choice of the baseline period influenced dilation values obtained in the stimulus processing windows, after words were presented to participants (i.e. 2900 ms to 6900 ms from trial start) (see Figure 5 & 6). When the baseline *Start period* (the most anterior to the word) was used, anticipation processes could be observed, especially when words were presented in noise (see Figure 6.a to 6.d). Therefore, further analyses were conducted on traces obtained with baseline correction using the baseline *Start*.

Applied to all participants (N=20), the different normalization techniques showed similar patterns (see Figure 5 & 6). However, the z-score transformation seemed to better homogenize the variability between conditions (see Figures 5.5 and 6.5), we looked at the variability between conditions over time in the anticipation and processing window for each normalization method (using the baseline period *Start*). As observed in Figure 7, only the z-score transformation provided homogenous variability between conditions. This normalization method was then used in further analysis.

Figure 5

Group pupil dilation in the Quiet condition according to different normalization methods and baseline periods

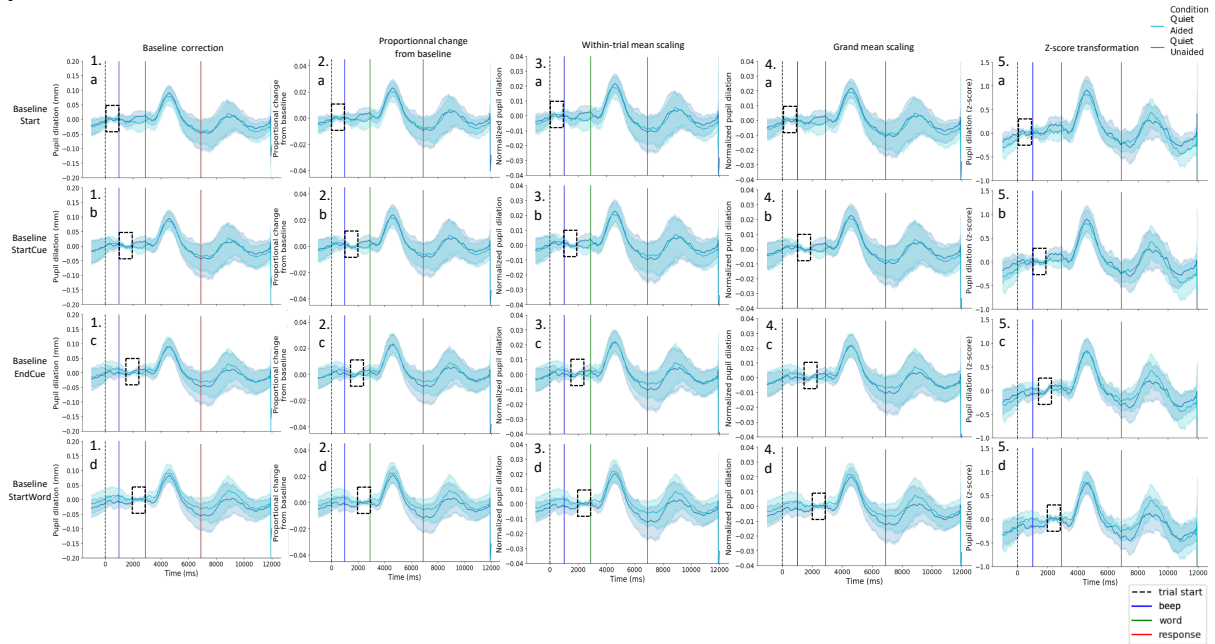


Figure 5. Pupil traces obtained by averaging the correctly answered trials in the Quiet conditions ($N=20$). Light blue traces were obtained in the Quiet Aided condition, dark blue traces were obtained in the Quiet Unaided condition. Traces were computed using several normalization methods (1: baseline correction only, 2: proportional change from baseline, 3: within-trial mean scaling, 4: grand mean scaling, 5: z-score transformation) and several baseline periods (dashed rectangles) (a: Start: from start (dashed black line) to the auditory cue before word presentation (blue line), b: StartCue: starting at the beginning of the auditory cue before word presentation (blue line), c: EndCue: starting at the end of the auditory cue before word presentation, d: StartWord: ending at the beginning of the word (green line)). Baseline lengths were set at 1000ms. Shaded areas represent 95% confidence intervals.

Figure 6

Group pupil dilation in the Noise condition according to different normalization methods and baseline periods

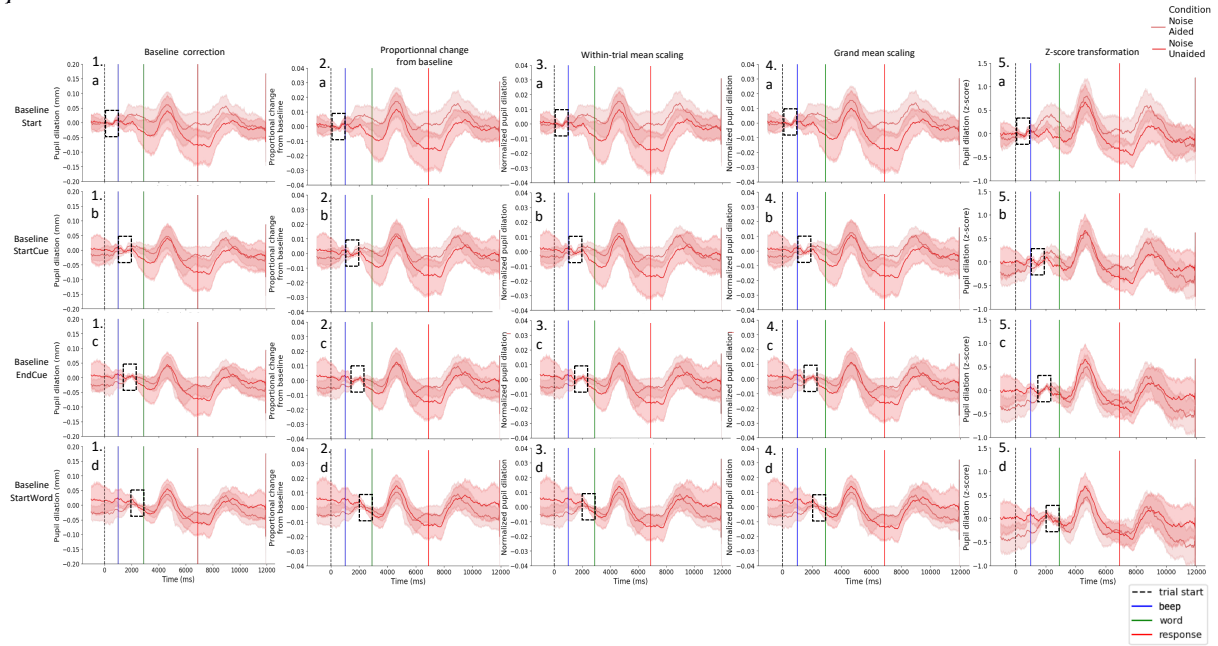


Figure 6. Pupil traces obtained by averaging the correctly answered trials in the Noise conditions ($N=20$). Light red traces were obtained in the Noise Aided condition, dark red traces were obtained in the Noise Unaided condition. Traces were computed using several normalization methods (1: baseline correction only, 2: proportional change from baseline, 3: within-trial mean scaling, 4: grand mean scaling, 5: z-score transformation) and several baseline periods (dashed rectangles) (a: Start: from start (dashed black line) to the auditory cue before word presentation (blue line), b: StartCue: starting at the beginning of the auditory cue before word presentation (blue line), c: EndCue: starting at the end of the auditory cue before word representation, d: StartWord: ending at the beginning of the word (green line)). Baseline lengths were set at 1000ms. Shaded area represent 95% confidence intervals.

Figure 7

Inter-subject variability according to different normalization methods

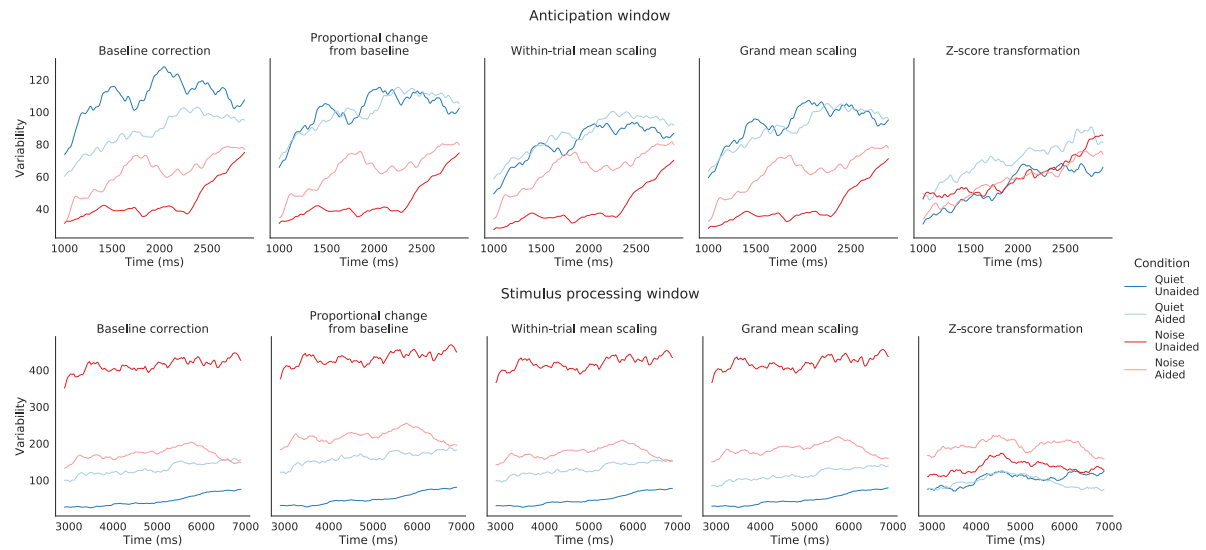


Figure 7. Variability over time for each condition per normalization method in the anticipation window (Top) and in the processing window (Bottom). The 1000ms baseline period Start was used and only correctly answered trials were included.

As well as different baseline periods and normalization methods, different baseline lengths were tested (500 ms and 1000 ms). Similar results were obtained with both baseline lengths (see supplementary figures 1S to 4S).

Results obtained with all traces included (words repeated correctly or not) and those obtained with only hit trials (word repeated correctly only) showed similar results (see supplementary figures 3S to 6S).

In the following, we applied z-score transformation and 1000 ms baseline period from start to our pupil responses, in order to compare pupil dilation between the different conditions, and between the different time windows, using hit trials only.

Hearing in noise

In addition to the methodological investigation, our work aimed at highlighting pupillometric measures contribution to listening effort measures. Therefore, statistics were conducted in order to find within-subject effects of noise and hearing-aid on objective pupillometric responses elicited by participants. The type-II ANOVA was performed on z-score transformed pupil dilation amplitude using a 1000 ms baseline *Start* for baseline correction only when participants repeated the word correctly (hits

only) (see Figure 8: left). Statistical analyses in the anticipation window showed a main interaction between the aid and noise factor ($X^2(1, N=20)=6.87, p=0.0088$). Post-hoc pairwise comparisons showed an effect of the aid in the Noise condition only: mean pupil dilation in the anticipation window was significantly larger when participants wore their hearing-aids rather than not ($p=0.0039$). They also showed an effect of the noise in the Aided condition only: the mean pupil dilation in the anticipation window was significantly larger when words were presented in a low SNR condition rather than in a high SNR condition ($p=0.0106$) (see Figure 8: middle). No significant effects of factors on mean pupil dilation were found in the stimulus processing window (see Figure 8: right).

Figure 8

Pupillary measures using z-score transformation and Start baseline period

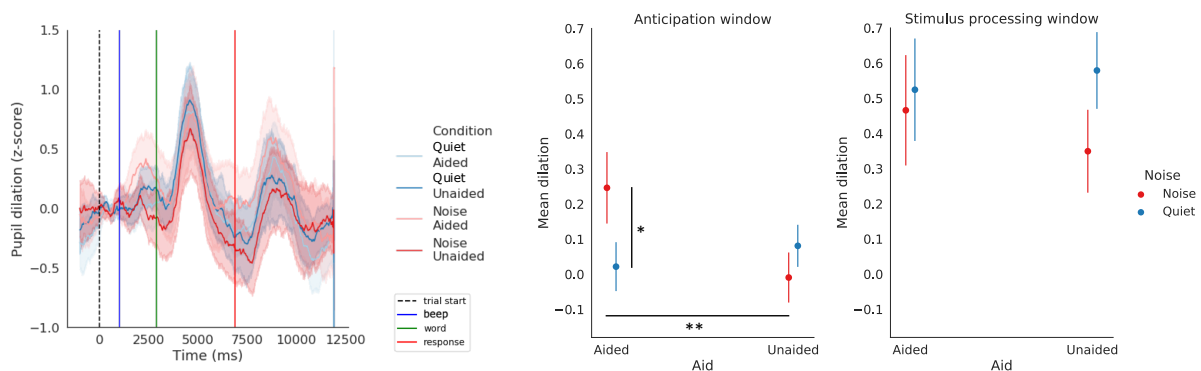


Figure 8. Left: Pupil traces obtained by averaging the correctly answered trials of the 10 last trials of each block in the different conditions ($N=20$). Traces were computed using z-score transformation and 1000ms baseline Start period (from start (dashed black line) to the auditory cue before word presentation (blue line)). Shaded areas represent 95% confidence intervals. Middle: Mean dilation in the anticipation window (from the auditory cue before word presentation (blue line) to the word presentation (green line)). Right: Mean dilation in the stimulus processing window (centered around maximum dilation between the word presentation (green line) and the cue before the repetition of the word (red line), with the same length as the anticipation window). Error bars represent standard errors of the mean.

** $p < 0.01$

Discussion

Pupillary responses have been widely used to assess cognitive effort and various ways of analyzing them are described in the literature (see Table 1). In audiology, pupil responses are mostly processed using subtractive baseline correction with a 1-s pre-stimulus baseline (see Table 1). Other analysis methods have been used as well, but the aforementioned processing seems to prevail in this research area. While Attard-Johnson et al. (2019) compared different pupillometric analysis methods to measure arousal in response to images, to our knowledge, such systematic comparisons had not been undertaken in the context of listening-effort studies. In the present study, we compared several methods of analysis using different normalization techniques, baseline periods and baseline durations, using data collected during a speech-in-noise task to assess listening effort in hearing-impaired listeners. Five normalization techniques were compared: subtractive baseline correction, proportional change from baseline, within-trial mean scaling, grand mean scaling and z-score transformation; as well as four baseline periods: anterior to just before stimulus onset; and two baseline durations: 500 ms and 1 s.

The different normalization methods yielded similar results. Attard-Johnson et al. (2019) reached similar conclusions when comparing raw pupil sizes, z-scored pupillary data, percentage changes in pupil size and subtractive baseline corrected data recorded to measure arousal elicited by viewing images. Three of the normalization methods included in the current study were also considered in this previous study, but the two studies used different stimuli (images vs uttered words), different populations (healthy vs hearing-impaired), different recording systems (SR EyeLink 1000 recording left eye at 1000Hz vs SMI REDmobile250 recording both eyes at 250Hz), and they investigated very different cognitive processes (sexual arousal vs listening effort). This makes more detailed comparisons between these studies difficult. However, the consistent conclusions of these two studies regarding the lack of impact of the normalization method on the pupil dilation pattern suggests that this conclusion may hold across different applications of pupillometry, including different types of stimuli, populations, and cognitive processes. Although pupillary traces observed with the different normalization methods were highly similar, the z-score transformation elicited an uniformed inter-subject variability between conditions, while greater differences in terms of variance were observed between easy and most adverse

conditions with other methods (see Figure 7). The standardization of the data therefore homogenized variability across conditions without affecting the qualitative aspect of the results.

Importantly, the results reveal that the choice of baseline period can have a major impact on the conclusions of studies involving pupillometry to evaluate listening effort. This conclusion may apply, in particular, to studies in which participants may anticipate the occurrence of perceptual or motor demands, which require effort for correct task performance. In the current study, an attempt was made to control for such anticipatory processes, by including into the stimulus sequence explicit cues to announce the occurrence of target stimuli and response periods. However, even with such precautions, some participants only showed a dilation peak during stimulus presentation, while for others, pupil dilation increased continuously, starting as soon as cue presentation. The latter pattern was observed for words in high-level noise, but not for words in low-level noise, suggesting greater cognitive preparation when listening conditions are challenging than when they are less so. The comparison of several baseline periods showed that the early increase in pupil dilation observed in some participants was taken into account in the results, when the chosen period was the most anterior to stimulus presentation. Therefore, it appears that using a baseline period well before cue onset allowed us to measure both anticipatory processes and stimulus processing. While a few pupil-dilation studies have explicitly limited or controlled for the influence of anticipatory processes on pupil dilation (Lewis & Bidelman, 2020; Winn et al., 2015), most studies of listening effort using implicit or explicit cues have focused exclusively on pupil dilation during stimulus processing. Anticipation has also been observed with pupillometry, when participants were engaged in a difficult attention task (McCloy et al., 2016, 2017) or preparing to answer questions in a task involving linguistic challenge (Vogelzang, Hendriks, & van Rijn, 2016). In particular, McCloy observed that participants' pupil started to show greater dilation as soon as they were informed that they would have to switch their attention from one talker to another, instead of just maintaining their attention on one talker. Likewise, Vogelzang et al. (2016) showed that pupil dilation remained larger during the presentation of a story with a complex structure until participants had to answer a question about the story, while pupil dilation slowly decreased before a question about a simpler story. Previous fMRI studies (Kurniawan, Guitart-Masip, Dayan, & Dolan,

2013; Vassena et al., 2014) showed that preparation to cognitively demanding tasks seemed to rely on the same brain system than the one implied in attentional control (Krebs, Boehler, Roberts, Song, & Woldorff, 2012; Voisin, Bidet-Caulet, Bertrand, & Fonlupt, 2006) and working memory (Engström, Landtblom, & Karlsson, 2013). These findings suggest that anticipatory effects in speech-in-noise listening tasks should be considered for inclusion into the overall measure of listening effort. In this context, it may be important to use baseline periods that precede explicit or implicit cues to stimulus and/or response periods.

Finally, results obtained using two different baseline durations (500 and 1000 ms) were similar. These findings are in accordance with Winn et al. (2018), who compared baseline-corrected pupil data using different baseline lengths (ranging from 100 ms to 3 s) and found negligible differences between the resulting curves. Although, the baseline durations being compared in the present study only differed by a factor of two, in the literature, baseline-period durations typically range from 100 ms (Lewis & Bidelman, 2020) to 2 s (Ayasse et al., 2017; Winn et al., 2015) (see Table 1). This variability may be related, in part, to differences in recording devices and techniques. For instance, if the recording sampling rate is relatively low, longer baseline durations (>1000ms) may be needed to prevent the occurrence of blink (during the baseline period) to lead to the necessary elimination of the trial (Winn et al., 2018); with a higher sampling rate, longer baseline periods are more affected by pupil fluctuations (Mathôt, Fabius, Heusden, & Stigchel, 2018). Using short baseline periods may reduce the risk that baseline estimates be contaminated by after-effects from the previous trial (Winn et al., 2018), but it increases the risk that precise baseline estimation be precluded due to a blink or some other source of physiological “noise” in the recording (Mathôt et al., 2018).

Similarly to studies investigating listening effort with speech-in-noise task requiring participants to repeat sentences (Koelewijn, Zekveld, et al., 2014; Koelewijn, Zekveld, Lunner, & Kramer, 2018; Ohlenforst et al., 2018; Wang, Kramer, et al., 2018; Zekveld & Kramer, 2014; Zekveld et al., 2010; Zekveld, Kramer, et al., 2011), we managed to obtain clear pupillary responses to shorter stimuli such as disyllabic words. Contrary to previous studies assessing listening effort at different intelligibility levels (Koelewijn et al., 2012; Koelewijn, Zekveld, et al., 2014; Zekveld, Heslenfeld, et al., 2014;

Zekveld & Kramer, 2014; Zekveld et al., 2010; Zekveld, Kramer, et al., 2011), our aim was to investigate whether pupillary responses can provide information about listening effort even when speech intelligibility is perfect, i.e., when only correct-response trials are included in the analysis. Sounds levels were adjusted individually to yield scores above 90% in quiet without hearing-aids, in order to have a sufficient number of hit responses per condition per patient. One limitation of this methodological choice is that the resulting sound levels were relatively high (above the typical conversational level for speech), so that when participants wore their hearing-aids, the level of these sounds may have been unusually high (compared to conversational speech). This may partly explain the surprising outcome, whereby participants rated the listening task as more effortful with hearing-aid than without. However, since higher listening-effort ratings in aided than unaided conditions were observed, mainly, in low SNR conditions, a more likely explanation is that this effect was caused by the background noise being amplified by the hearing-aids compared to the high SNR conditions. Although only correct-response trials were used in the main data analyses, the greater listening effort in the Noise Aided than in the Noise Unaided condition is consistent with the results of these analyses: an interaction between the factors, “noise” and “hearing-aid” was observed for pupil dilation measured during the anticipation window, and post-hoc comparisons revealed that participants pupil dilation was greater in the Noise Aided than in the Noise Unaided condition. However, no effect of hearing-aid or noise on pupil dilation was found in the stimulus processing window. Even though hearing-aid or noise effects are usually observed during the processing period, Zekveld, Kramer, et al. (2018) did not observe any effect of signal-to-noise ratio on pupil responses during this specific time window in a concurrent memory and auditory perception task. This result indicates that differences in listening effort are not systematically observed during the processing of the target stimulus, especially when maximum intelligibility is reached, but could be observed at a different period during the trial. Indeed, in the present study, differences in provided effort during the task were observed before stimulus processing, during the anticipation window. Therefore, this time window played a key role to highlight differences in listening effort during this task. As Kuchinsky et al. (2014, 2013) did in an orthographic Visual Word Paradigm, we managed to show subtle changes in cognitive load during a speech in noise recognition task via pupil dilation with short uttered words in older adults and exclusively in correct trials. Such

differences could not be observed with subjective measures, hence proving the convenience of the use of an objective measure, such as pupillary responses, to effectively assess listening effort.

To conclude, this study compared several methods of analyzing pupillary responses during a speech-in-noise task in hearing-impaired patients. In agreement with previous findings, different normalization methods and baseline durations result in similar pupil dilation patterns. Importantly, the present results highlight the strong influence of the choice of baseline period, with regards to anticipatory processes during effortful listening. A significant impact of baseline period on conclusions was observed, even though only correct-response trials were included in the analyses, so that task performance and intelligibility were near perfect. The findings confirm the feasibility, and potential usefulness, of pupil-dilation as an objective measure to investigate listening effort in older hearing-impaired individuals, with or without hearing-aids.

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Conflict of interest statement

The authors have no conflicts of interest to declare that are relevant to the content of this article

Open Practices Statement

Pupillometric data, stimuli material and data processing script (Python language) are available at <https://hal.archives-ouvertes.fr/hal-03185825>. However we cannot make available indirectly identifying data. Indeed, according to the French MR003 regulation, indirectly identifying data of persons participating in research and directly or indirectly identifying data of professionals involved in research may be transferred outside the European Union when the transfer is strictly necessary for implementation of the research or the exploitation of its results and under the conditions provided for in Chapter V of the General Data Protection Regulation (GDPR), which is the new legislation that governs the processing of personal data in Europe.

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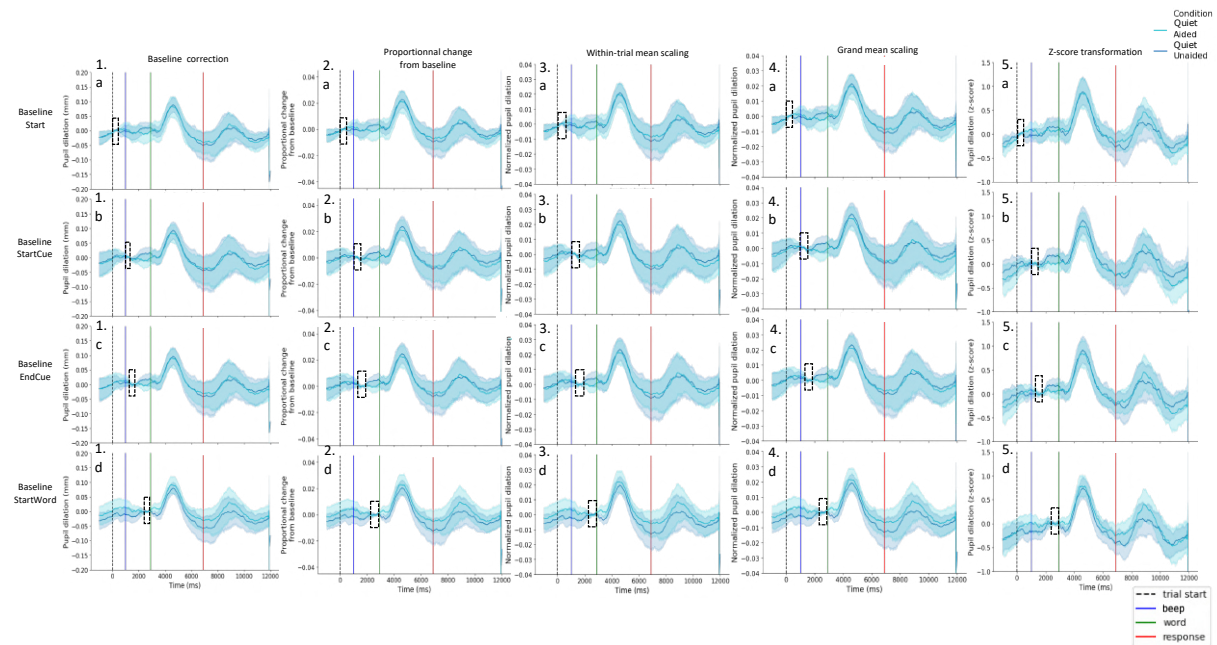
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SUPPLEMENTARY DATA

Figure 1S

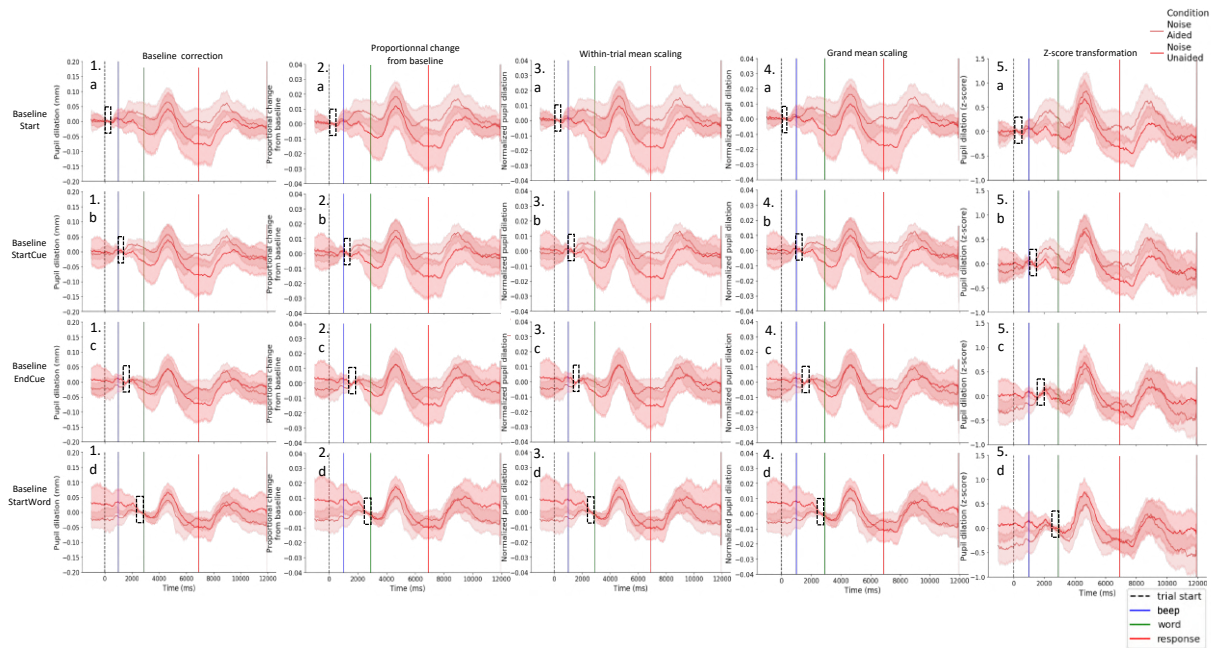
Group pupil dilation in the Quiet condition according to different normalization methods and baseline periods: correct trials only and 500ms baseline periods



Pupil traces obtained by averaging the correctly answered trials of the 10 last trials of each block (the 2 first trials are excluded) in the Quiet conditions (N=20). Light blue traces were obtained in the Quiet Aided condition, dark blue traces were obtained in the Quiet Unaided condition. Traces were computed using several normalization methods (1: baseline correction only, 2: proportional change from baseline, 3: within-trial mean scaling, 4: grand mean scaling, 5: z-score transformation) and several baseline periods (dashed rectangles) (a: *Start*: from start (dashed black line) to the auditory cue before word presentation (blue line), b: *StartCue*: starting at the beginning of the auditory cue before word presentation (blue line), c: *EndCue*: starting at the end of the auditory cue before word presentation, d: *StartWord*: ending at the beginning of the word (green line)) with a 500ms baseline duration. Shaded areas represent 95% confidence intervals.

Figure 2S

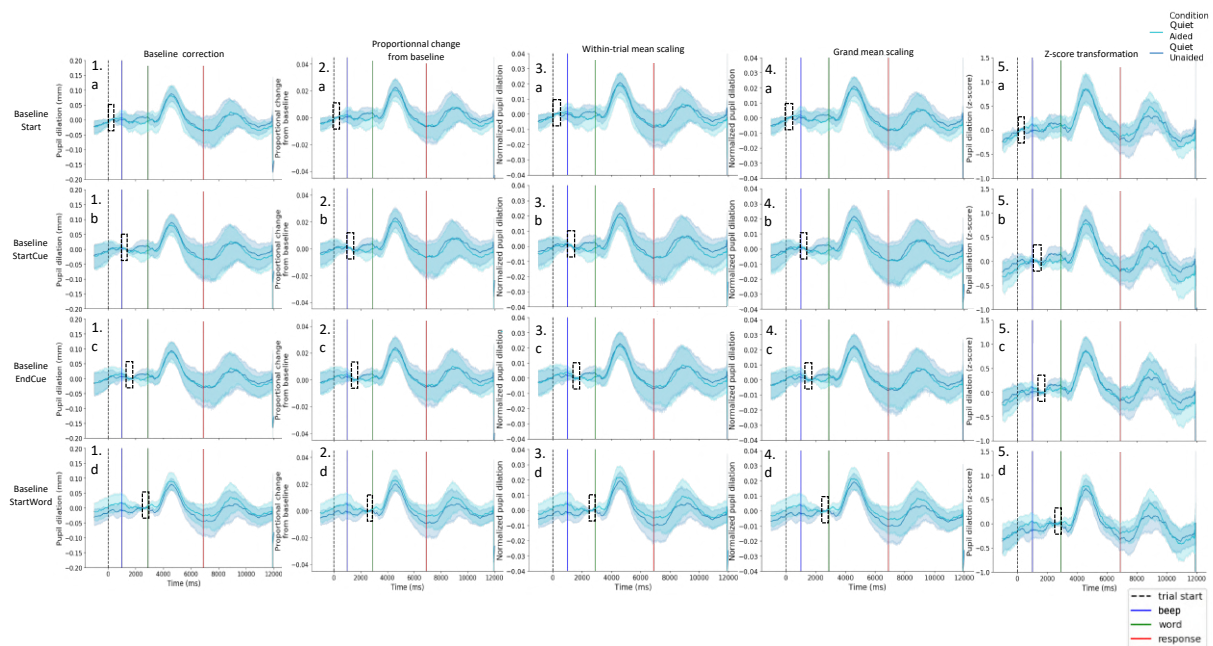
Group pupil dilation in the Noise condition according to different normalization methods and baseline periods: correct trials only and 500ms baseline periods



Pupil traces obtained by averaging the correctly answered trials of the 10 last trials of each block (the 2 first trials are excluded) in the Noise conditions (N=20). Light red traces were obtained in the Noise Aided condition, dark red traces were obtained in the Noise Unaided condition. Traces were computed using several normalization methods (1: baseline correction only, 2: proportional change from baseline, 3: within-trial mean scaling, 4: grand mean scaling, 5: z-score transformation) and several baseline periods (dashed rectangles) (a: *Start*: from start (dashed black line) to the auditory cue before word presentation (blue line), b: *StartCue*: starting at the beginning of the auditory cue before word presentation (blue line), c: *EndCue*: starting at the end of the auditory cue before word presentation, d: *StartWord*: ending at the beginning of the word (green line)) with a 500ms baseline duration. Shaded areas represent 95% confidence intervals.

Figure 3S

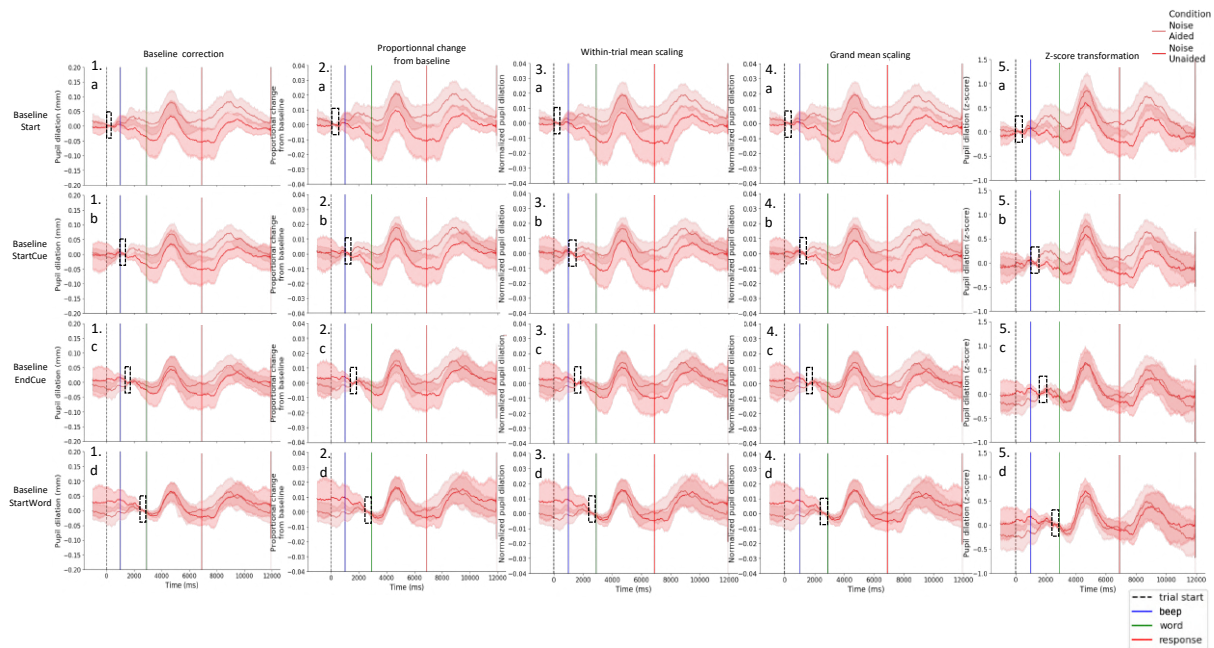
Group pupil dilation in the Quiet condition according to different normalization methods and baseline periods: all trials and 500ms baseline periods



Pupil traces obtained by averaging the last 10 trials of each block (the 2 first trials are excluded) in the Quiet conditions (N=20). Light blue traces were obtained in the Quiet Aided condition, dark blue traces were obtained in the Quiet Unaided condition. Traces were computed using several normalization methods (1: baseline correction only, 2: proportional change from baseline, 3: within-trial mean scaling, 4: grand mean scaling, 5: z-score transformation) and several baseline periods (dashed rectangles) (a: *Start*: from start (dashed black line) to the auditory cue before word presentation (blue line), b: *StartCue*: starting at the beginning of the auditory cue before word presentation (blue line), c: *EndCue*: starting at the end of the auditory cue before word presentation, d: *StartWord*: ending at the beginning of the word (green line)) with a 500ms baseline duration. Shaded areas represent 95% confidence intervals.

Figure 4S

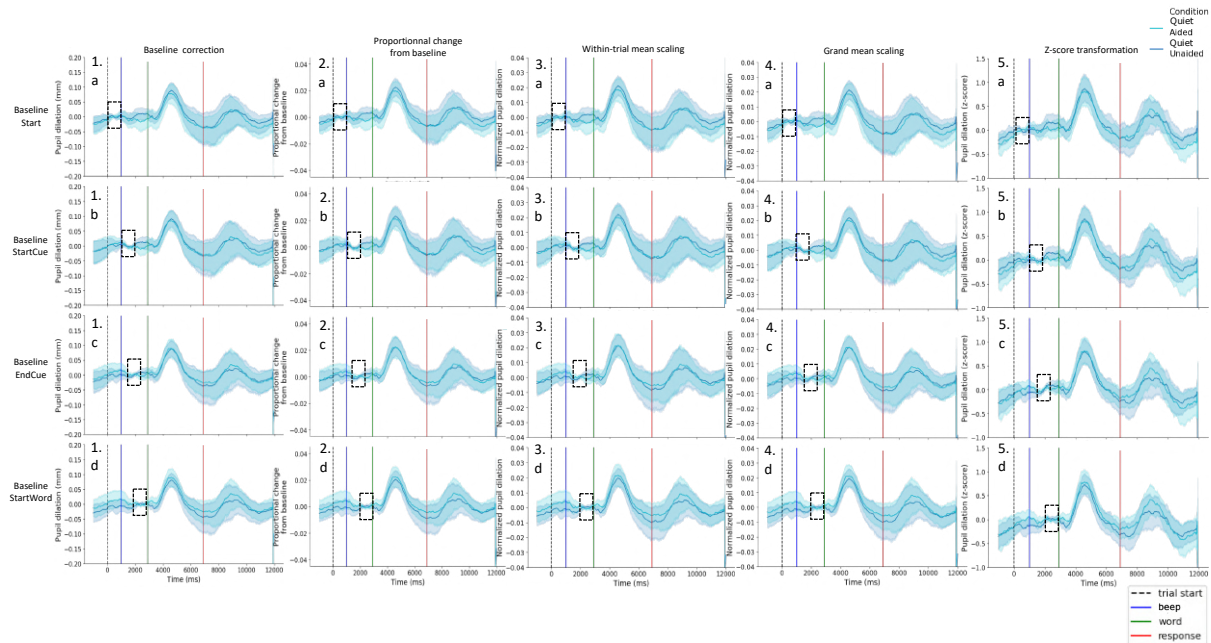
Group pupil dilation in the Noise condition according to different normalization methods and baseline periods: all trials and 500ms baseline periods



Pupil traces obtained by averaging the last 10 trials of each block (the 2 first trials are excluded) in the Noise conditions (N=20). Light red traces were obtained in the Noise Aided condition, dark red traces were obtained in the Noise Unaided condition. Traces were computed using several normalization methods (1: baseline correction only, 2: proportional change from baseline, 3: within-trial mean scaling, 4: grand mean scaling, 5: z-score transformation) and several baseline periods (dashed rectangles) (a: *Start*: from start (dashed black line) to the auditory cue before word presentation (blue line), b: *StartCue*: starting at the beginning of the auditory cue before word presentation (blue line), c: *EndCue*: starting at the end of the auditory cue before word presentation, d: *StartWord*: ending at the beginning of the word (green line)) with a 500ms baseline duration. Shaded areas represent 95% confidence intervals.

Figure 5S

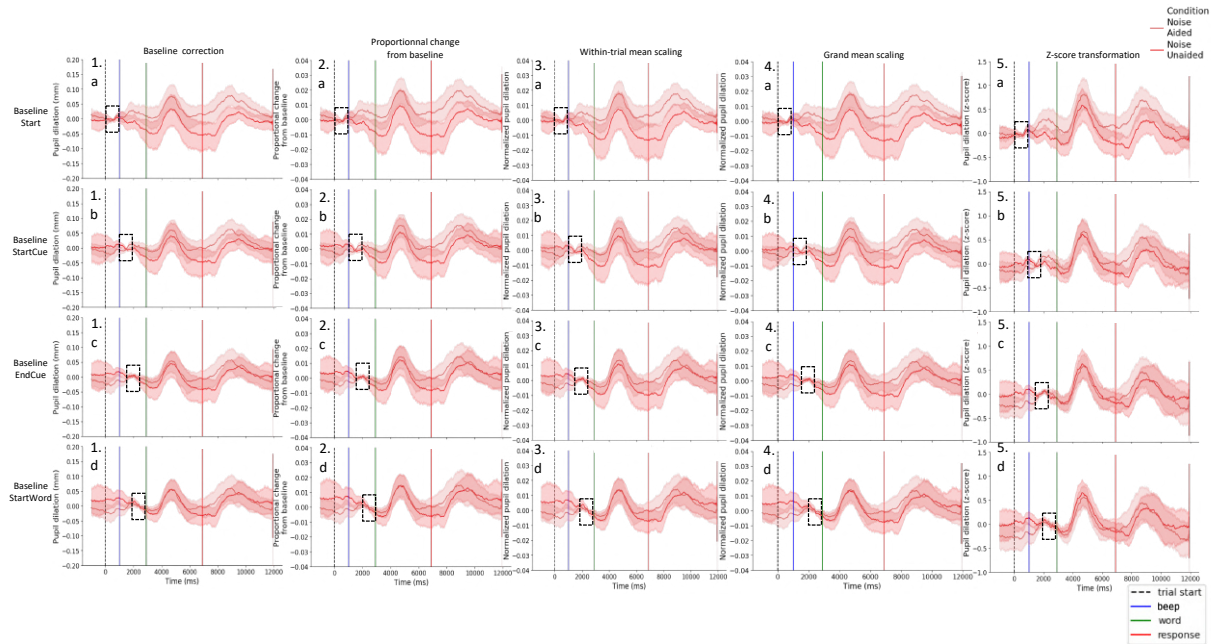
Group pupil dilation in the Quiet condition according to different normalization methods and baseline periods: all trials and 1000ms baseline periods



Pupil traces obtained by averaging the last 10 trials of each block (the 2 first trials are excluded) in the Quiet conditions (N=20). Light blue traces were obtained in the Quiet Aided condition, dark blue traces were obtained in the Quiet Unaided condition. Traces were computed using several normalization methods (1: baseline correction only, 2: proportional change from baseline, 3: within-trial mean scaling, 4: grand mean scaling, 5: z-score transformation) and several baseline periods (dashed rectangles) (a: *Start*: from start (dashed black line) to the auditory cue before word presentation (blue line), b: *StartCue*: starting at the beginning of the auditory cue before word presentation (blue line), c: *EndCue*: starting at the end of the auditory cue before word presentation, d: *StartWord*: ending at the beginning of the word (green line)) with a 1000ms baseline duration. Shaded areas represent 95% confidence intervals.

Figure 6S

Group pupil dilation in the Noise condition according to different normalization methods and baseline periods: all trials and 1000ms baseline periods



Pupil traces obtained by averaging the last 10 trials of each block (the 2 first trials are excluded) in the Noise conditions (N=20). Light red traces were obtained in the Noise Aided condition, dark red traces were obtained in the Noise Unaided condition. Traces were computed using several normalization methods (1: baseline correction only, 2: proportional change from baseline, 3: within-trial mean scaling, 4: grand mean scaling, 5: z-score transformation) and several baseline periods (dashed rectangles) (a: *Start*: from start (dashed black line) to the auditory cue before word presentation (blue line), b: *StartCue*: starting at the beginning of the auditory cue before word presentation (blue line), c: *EndCue*: starting at the end of the auditory cue before word presentation, d: *StartWord*: ending at the beginning of the word (green line)) with a 1000ms baseline duration. Shaded areas represent 95% confidence intervals.

2.2 Complementary analysis: Index of Pupillary Activity

To fully investigate pupil responses associated with listening effort, a complementary analysis was conducted. The present section will focus on the frequency-based analysis of the pupillometric signal, recorded among hearing-impaired listeners during the word-in-noise recognition task presented in the previous part.

2.2.1 Introduction

An individual's pupil responses can show continual oscillations (pupillary *hippus*), even in the presence of steady light. This phenomenon is known as the pupil *light reflex*. When the individual is engaged in a task requiring significant cognitive processing and is exposed to psychosensory stimuli, the pupil responds differently. The cognitive processing required to complete the task results in brief dilations and this phenomenon is called the *dilation reflex* (Loewenfeld, 1993). Both reflexes are transitory events with pulsing of the pupil diameter, however during the dilation reflex the pulses are irregular and sharp. As most cognitive tasks are carried out in lighted situations, the light reflex will be present and both dilation and light reflexes may occur at the same time. Then, when studying cognitive activity through pupillary responses, one may wonder how to separate the dilation reflex from the light reflex. Two decades ago, Marshall (2000) addressed this specific question and developed a technique that can identify and remove the light reflex to reveal the dilation reflex that accompanies cognitive activity. Her method relies on the wavelet decomposition of the pupil signal into several independent components, to extract high-frequency components that are associated with cognitive activity. From this wavelet analysis, the number of brief and sharp dilations that happen per second is computed and represents an Index of Cognitive Activity (ICA), higher values being associated with higher cognitive activity. To test the effect of light and cognitive effort on the ICA, Marshall tested four conditions: light plus cognitive effort, dark plus cognitive effort, light plus no cognitive effort, dark plus no cognitive effort (Marshall, 2002). The cognitive task was mental computation of arithmetic items that were presented orally. High levels of ICA were recorded during the cognitive tasks, in both light and dark conditions, whereas low levels were recorded when

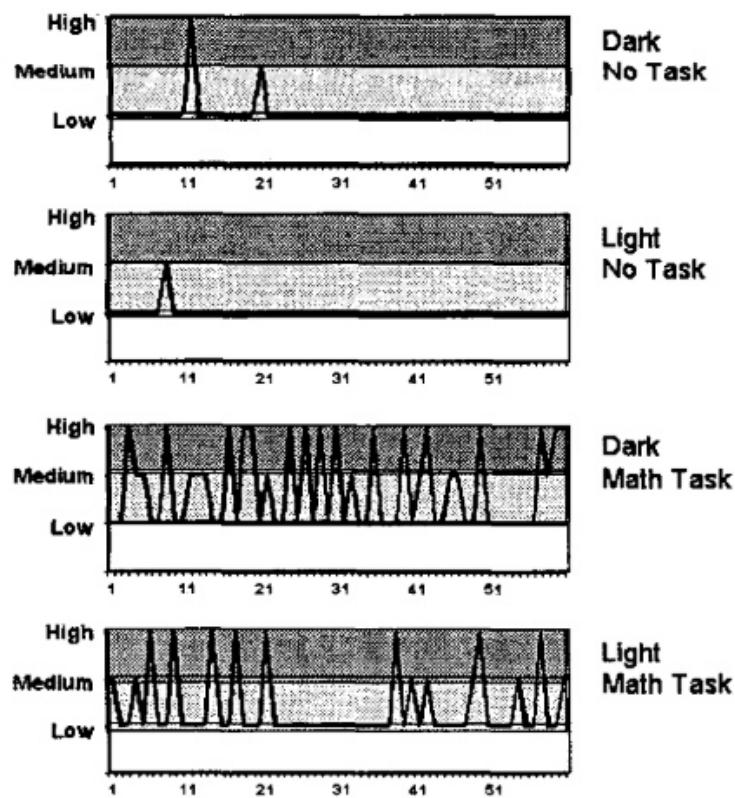


FIGURE 2.1: Cognitive effort estimated by the Index of Cognitive Activity (ICA) during for conditions: Dark/No task, Light/No task, Dark/Math Task, Light/Math task. The ICA is presented as three levels of intensity (High, Medium, Low) over one minute. From Marshall (2002).

no task was given, in both light and dark conditions as well. The light and dark conditions were similar irrespective of the task (see Fig 2.1). The ICA then seems to effectively capture cognitive activity independently from light conditions. More recently, the ICA has been showed to be a useful measure to evaluate differences in cognitive effort during sentence comprehension (Demberg and Sayeed, 2016), and dual-task settings (Vogels, Demberg, and Kray, 2018).

Marshall's ICA is a proprietary closed-source measure. However, researchers have been able to use it in their studies, using the ICA module included by eye-tracking vendors in their own software (as specified by Demberg and Sayeed (2016), Vogels et al. (2018) or Ankener et al. (2018) for instance). The commercialization of the ICA then allowed researchers to use it to study cognitive workload, however, its detailed implementation is not available due to its proprietary nature (only principal steps are available in Marshall, 2000). Duchowski et al. (2018) then decided to

implement their own index inspired by Marshall's one, called the Index of Pupillary Activity (IPA). The implementation of Duchowski et al.'s IPA has been made completely accessible. Therefore, we used Duchowski et al.'s IPA (2018) to measure cognitive effort in this study.

Baseline-related pupil size analyses give an overall representation of pupillary activity during the task, including changes due to the light reflex even when light conditions are controlled. To extract the specific components related to cognitive activity during our word-in-noise task, the pupillary signal recorded was thus analysed in the frequency domain. For all analyses described below, we used non-smoothed pupil traces from the eye in which we found least interpolations and missing data across all conditions (see Material and Methods in Chapter 2 Section 1 for detailed preprocessing of the pupillometric data).

2.2.2 Method

IPA computation To assess the cognitive activity engaged during the task, we extracted the Index of Pupillary Activity (IPA) from our data. To do so, we followed Duchowski et al. (2018) instructions to compute their Marshall's Index of Cognitive Activity (ICA) (Marshall, 2000) adaptation. The ICA was designed to separate pupil's reactions due to light and cognitive processes, and is computed as the number of times per second an abrupt discontinuity of frequency is detected in the pupil signal (Marshall, 2002; Marshall, 2007). Computation of both ICA and IPA relies on the wavelet decomposition of the pupil signal. Peaks of the wavelet coefficients obtained after decomposition represent frequency changes in the signal. Then, wavelet coefficients must be "de-noised", using thresholding technique, to find significant peaks. As Marshall's and Duchowski et al.'s implementation are similar, they differ however in certain aspects, such as the choice of wavelet, and the thresholding technique to use. In this study, we followed Duchowski's implementation to compute the IPA (see Listings 1 and 2 in Duchowski et al., 2018). We first decomposed our signal using Daubechies-16 wavelet (as recommend for 250 Hz sampled data (Marshall, 2000)) at the second level of resolution. We then looked for abrupt variations in the signal by detecting the local maxima of wavelet coefficients modulus. Finally, we selected significant peaks using the *universal threshold* technique (Donoho and

Johnstone, 1994). The IPA is then defined as the number of coefficients left per second. The higher is the IPA, the stronger is the provided cognitive effort. Wavelet analyses were computed using the Python “pywt” library (Lee et al., 2019).

On one hand, following Duchowski et al. (2018), one IPA was computed per trial (from trial start, to the auditory cue indicating participants to repeat the word: the temporal window in which participants had to repeat the word was excluded during the IPA computation). On the other hand, following Demberg and Sayeed (2016), the number of abrupt discontinuities detected in the pupil signal was computed every 500 ms to obtain a time-based evolution of this index during trials. Following the previous study (see Chapter 2 Section 1), for both computations, only the last 10 trials of each block were included in the analysis (the 2 first trials are excluded) and Hit trials only were included.

Statistical analyses Statistics were conducted in order to find within-subject effects of noise and hearing-aid on single IPAs per trial. Trial-based IPAs were analyzed using a Linear Mixed-effects Model (LMM) to test within-subject effects of hearing-aid (Aided vs Unaided) and background noise (Quiet vs Noise). The models contained fixed-effects for the hearing-aid factor (Aided vs Unaided), the noise factor (Quiet vs Noise) and interaction between these two factors. A random-effect was also added to the models, to account for individual variance in intercept (performance: $R^2_m=0.01$, $R^2_c=0.15$).

2.2.3 Preliminary results

Greater mean IPAs were found in the Unaided conditions (Quiet: 3.38 (SEM=0.12), Noise: 3.52 (SEM=0.13)) than in the Aided conditions (Quiet: 3.32 (SEM=0.10), Noise: 3.28 (SEM=0.12)) (see Fig 2.2). However, no statistical significant effect of noise nor hearing-aids was found on IPA values. The number of rapid dilations per 500 ms time window over the whole trial is presented on Figure 2.3. The Aided and Unaided curves are practically overlapping in both Quiet and Noise conditions, and seem overall noisy. Then, no further statistical analyses were conducted on the number of rapid dilations per 500 ms time window over the trial.

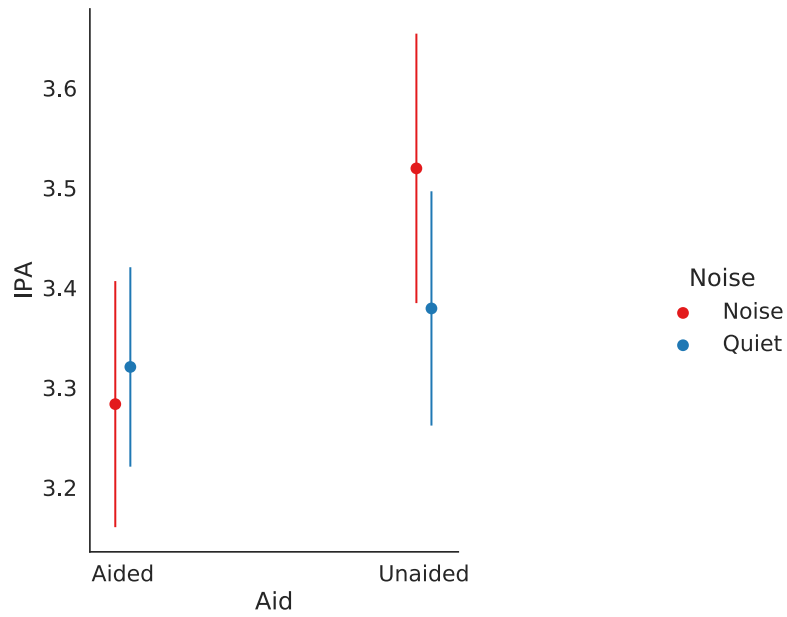


FIGURE 2.2: Mean Index of Pupillary Activity (IPA) for each condition during Hit trials only (N=20). Only the last 10 trials of each block were included (the 2 first trials are excluded). Error bars represent standard errors of the mean.

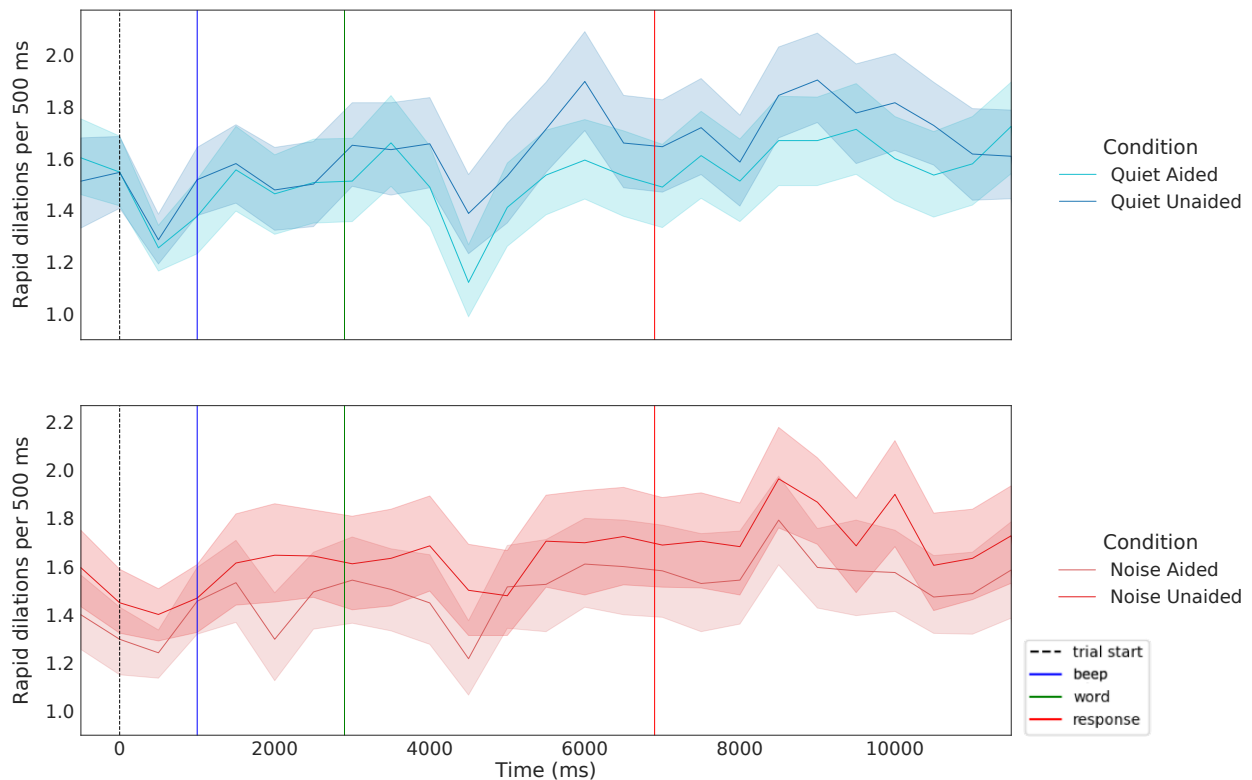


FIGURE 2.3: Number of rapid dilations per 500 ms time window during the whole trial in the Quiet (upper panel) and Noise conditions (lower panel). Traces were obtained by averaging the last 10 trials of each block (the 2 first trials are excluded) (N=20). Hit trials only are included. Shaded areas represent 95% confidence intervals.

2.3 General Discussion

In this chapter, a methodological investigation was lead on the pupillometric signal during the assessment of listening effort. To do so, pupil responses during a word-in-noise task were recorded among hearing-impaired patients. Pupil responses were analyzed in two different manners. First, task-evoked pupil responses were examined using baseline-related analysis techniques. Then, high-frequency components of the pupillary activity were extracted to assess cognitive activity during the task through the Index of Pupillary activity.

In the first study, several task-evoked pupil responses processing techniques were reviewed and compared. Different baseline periods (with different timings relative to stimulus onset) and durations (short: 500 ms and long: 1000 ms) were tested, as well as different normalization methods (subtractive baseline correction, proportional change from baseline, within-trial mean scaling, grand mean scaling and z-score transformation). The different use of normalization techniques and baseline durations resulted in similar outcomes (the z-score transformation gave a more uniformed variability across conditions however), suggesting the robustness of pupillometry regarding the assessment of listening effort among this specific population. Importantly, the choice of baseline period had a major impact on conclusions regarding the evaluation on listening effort. Indeed, anticipation processes during the task could have been observed when the baseline period was the most anterior to stimulus presentation, showing that participants elicited greater cognitive preparation when the listening conditions were more challenging.

Less conclusive results were found using the frequency analysis of the pupillometric signal. No effect of noise nor hearing-aid were observed on trial-based IPA. One explanation could be that the computation of the index on the whole trial might have not been precise enough to capture modulation in cognitive activity during our task. Indeed, the differences in cognitive effort previously observed were not located at the large phasic response to the processing of the word, but were rather subtle and during the anticipation period. Therefore, a more fine-grained analyse with the evolution of this index during the trial seemed more appropriate to effectively capture the effort exerted during the task. Unfortunately, at first glance, this

second analysis did not seem to be conclusive either. One explanation could be that the reduced pupil dynamic in older individuals (Bitsios, Prettyman, and Szabadi, 1996) did not allow to observe clear changes in rapid dilations during the task. Indeed, in most studies that have used the ICA/IPA to assess cognitive activity, participants were young and healthy (Ankenier, Sekicki, and Staudte, 2018; Demberg and Sayeed, 2016; Dlugosch, Conti, and Bengler, 2013; Duchowski et al., 2018; Kahya et al., 2018; Vogels, Demberg, and Kray, 2018). One recent study, investigating the relationship between postural control and cognitive workload during various gaze tasks in healthy young and older people (Roh et al., 2021), used the ICA to quantify cognitive workload as well. As they managed to show significant differences in cognitive activity with gaze tasks in young participants, they could not conclude on an effect of the gaze conditions in older people. Although we could not conclude on the effect of our conditions on the ICA either in this population, studies using this index among older people are clearly lacking to already conclude on the non applicability of the ICA/IPA in this population. Indeed, the frequency analysis of the pupil signal was computed here at perfect intelligibility. Therefore, it might be possible that the IPA could not depict the differences in cognitive effort at such high performance. Moreover, the ICA seems to be task-dependant (Rerhaye, Blaser, and Alexander, 2018). As the ICA has proven itself to be a good indicator for measuring cognitive workload in arithmetic tasks (Marshall, 2002), language processing (in either single (Demberg and Sayeed, 2016) and dual task paradigms (Demberg, 2013; Vogels, Demberg, and Kray, 2018)), or mental rotation tasks (Rerhaye, Blaser, and Alexander, 2018), it was not the case during a Stroop task (Rerhaye, Blaser, and Alexander, 2018). Then, our task might not have been suited for this kind of analysis as well (although involving language).

Compared to baseline-related analysis, the use of ICA/IPA is still at early stages and researchers are already trying to improve the methods to evaluate cognitive effort through this index (Duchowski et al., 2020; Fehringer, 2021). The ICA/IPA has been shown to offer a light-independent indicator of cognitive load that is really useful in cross-modal, ecologic situations (for instance in dual-task settings, while driving on a simulator). However, for now, according to our results, the "classic" baseline-related methods of analysis of the pupillometric signal seem better suited

for the assessment of listening effort during a word-in-noise recognition task, and especially among older hearing-impaired listeners.

Chapter 3

Empirical studies

As different types of measures have been used to assess listening effort, they do not always agree with each other, sometimes giving inconsistent results. They seem then to tap into different underlying mechanisms of listening effort. One of the objectives of this thesis work was to compare and investigate the relationship between these different measures. The present chapter will focus on two empirical studies in which subjective, behavioral and objective measures have been concurrently used to assess listening effort. The first section will present results obtained during the study described on Chapter 2, conducted among hearing-impaired patients, using subjective and pupillometric measures. The second section will present results of a study conducted among healthy young adults, using subjective measures, as well as pupillometry and scalp electroencephalography as objective measures.

3.1 Study 1: Application to the assessment of listening effort among hearing impaired patients

In addition to the methodological investigation, this work aimed at highlighting objective measures contribution in comparison with subjective measures. Results presented in this section were obtained from data acquired during the experiment presented on Chapter 2, a quick reminder of the experimental method will be presented in the next part of this report.

3.1.1 Materials and methods

Thirty participants (15 male, 15 female) aged between 29 and 91 years old (mean: 70 years old) were recruited among hearing-impaired patients of a hearing-aid dispenser. Participants were screened for major cognitive alterations and dementia using the MoCA test (7.2) (<http://www.mocatest.org/>) (Nasreddine and Patel, 2016) and had a mean hearing loss (Pure Tone Average at 500, 1000, 2000 and 4000 Hz) of 44 dB HL in the better ear (SD = 13.5 dB HL) and 54.6 dB HL in the worse ear (SD = 14.9 dB HL). Participants were long-time users of hearing-aids (3.6 years on average), with an average 10-hour use per day. Participants completed a word-in-noise recognition test in which disyllabic words were presented in speech-shaped noise. Four different conditions were tested: (1) Quiet Aided (words presented at a high SNR with hearing-aids), (2) Quiet Unaided (words presented at a high SNR without hearing-aids), (3) Noise Aided (words presented at a lower SNR with hearing-aids), (4) Noise Unaided (words presented at a lower SNR without hearing-aids) (see Table 3.1). Participants' pupillary responses were recorded during the task (detailed procedure in the Material and Methods part of Chapter 2 section 1). For each condition, two lists of 12 disyllabic words were presented to the participant. At the end of each 12-word list, participants rated the perceived difficulty of the task using a 10-point visual analogue scale (VAS) (1: very easy task, 10: very difficult task). In addition to pupillometric measures and self-reported measures of difficulty (VAS score), participants' answers to a listening effort questionnaire adapted from the Effort Assessment Scale (EAS) (Alhanbali et al., 2017) were collected. This questionnaire aimed at measuring listening effort experienced by patients in their daily life with two subscores reflecting listening effort in quiet and noisy situations, as well as a global score (from 0 to 10). High scores depict high experienced listening effort in everyday life. Further statistics were conducted on the 20 participants included in the analyses (see Material and Methods part of Chapter 2 Section 1 for inclusion criteria).

Quiet	Noise
(1) Aided (2) Unaided	(3) Aided (4) Unaided

TABLE 3.1: Conditions tested.

3.1.2 Statistical analyses

Performance and VAS scores Statistics were conducted in order to find within-subject effects of noise and hearing-aid on participants' performance and VAS difficulty ratings. Participants' performance and difficulty ratings expressed as *rau* scores (Studebaker, 1985) were analyzed separately using a Linear Mixed-effects Model (LMM) to test within-subject effects of hearing-aid (Aided vs Unaided) and background noise (Quiet vs Noise). The models contained fixed-effects for the hearing-aid factor (Aided vs Unaided), the noise factor (Quiet vs Noise) and interaction between these two factors. A random-effect was also added to the models, to account for individual variance in intercept and slope for the noise factor (performance: $R^2m=0.27$, $R^2c=0.65$, subjective rating: $R^2m=0.3140$, $R^2c=0.8123$).

Correlations between subjective, behavioral and objective measures To express dependence between our measures, we computed a correlation matrix using Pearson's correlation criteria. For each condition, correlations between hearing loss of the better ear; subjective variables (listening effort questionnaire scores (in noise, quiet and global score), VAS difficulty scores); behavioral variables (speech perception scores); and objective variables (amplitude of mean pupil dilation during anticipation and processing of the word) were calculated. Correlations were computed using the "scipy" library from Python (Virtanen et al., 2020). We used Sherman and Funder's (2009) method to determine significant effect sizes. P-values associated with correlation coefficients were adjusted using Benjamini-Hochberg correction (Benjamini and Hochberg, 1995). Differences in correlations were assessed using Dunn and Clark's test (1969). The R "cocor" package (Diedenhofen and Musch, 2015) was used to compare correlations.

3.1.3 Results

Behavioral and subjective measures The listening effort questionnaire showed greater scores in noisy situations than in quiet ones (mean noise score: 6.17 (SEM=0.52), mean quiet score: 1.85 (SEM=0.26)). The mean global score reached a value of 4.6 (SEM=0.36). The speech perception task was successfully completed with a mean *rau* score of 95.3 (SEM=3.8) in the Quiet Aided condition, 93.8 (SEM=4) in the Quiet Unaided condition, 73.4 (SEM=3.7) in the Noise Aided condition and 77.6 (SEM=2.1) in the Noise Unaided condition. The subjective difficulty of the task was rated as follows (in *rau*): 17.2 (SEM=5.3) in the Quiet Aided condition, 14.1 (SEM=4.6) in the Quiet Unaided condition, 53.2 (SEM=5.9) in the Noise Aided condition and 40 (SEM=5.2) in the Noise Unaided condition. The type-II ANOVA indicated significant effect of noise on both performances and subjective ratings ($X^2(1, N=20)=22.18, p=2.5e-6$ and $X^2(1, N=20)=28.30, p=1.0e-7$ respectively). Participants performed better when words were presented in quiet (see Fig 3.1: Left). As expected, the task was perceived as easier when words were presented in quiet (see Fig 3.1: Right). A significant effect of aid was also found on subjective ratings ($X^2(1, N=20)=8.46, p=0.0036$) indicating that participants rated the task as easier when they were not wearing their hearing aids (see Fig 3.1: Right). No significant interaction was found between the hearing-aid factor and the noise factor.

Correlation between subjective, behavioral and objective measures Pearson's correlation coefficients obtained are shown in Figure 3.2. Sherman and Funder's (2009) method elicited a critical absolute value of effect size of $r=|0.2531|$ regarding the dependence between subjective, behavioral and objective variables. The mean of the absolute value of our observed effect sizes passed significance level ($r=|0.2531|, p=0.028$). A significant correlation was observed between better ear hearing loss and mean dilation in the anticipation window in the Noise Aided condition ($r=0.61, p=0.0478$), indicating that greater hearing losses at better ear were associated with an increased mean dilation during the anticipation period. Significant correlations were also observed between better ear hearing loss and performances in the Quiet conditions (Aided: $r=-0.63, p=0.0356$, Unaided: $r=-0.80, p=0.0009$), indicating that greater hearing losses at better ear were associated with poorer performances in the

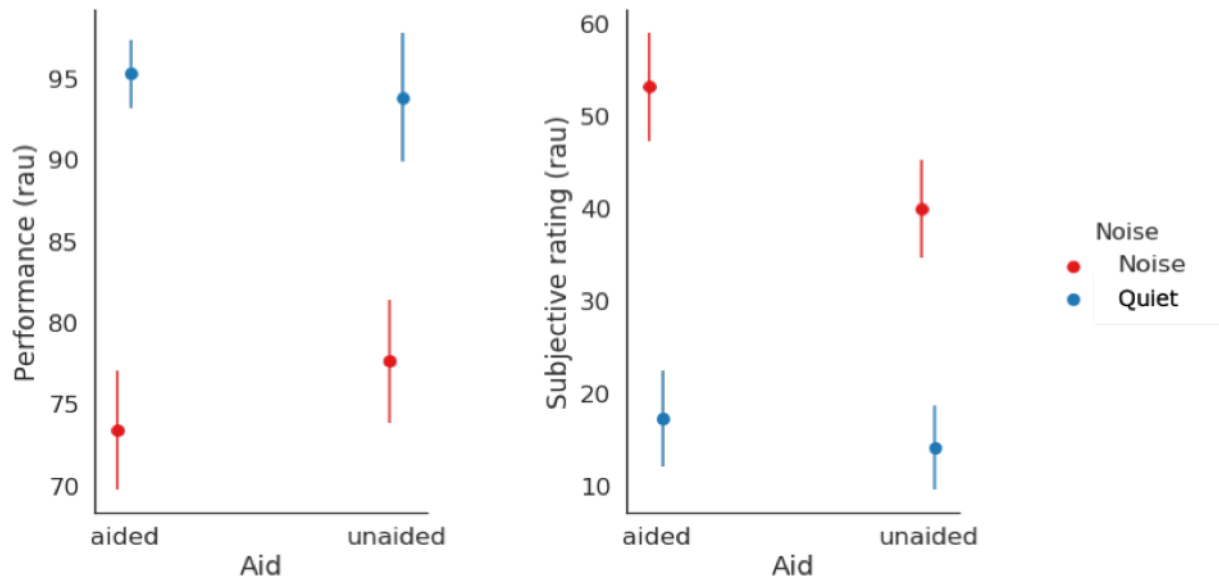


FIGURE 3.1: Left: Mean performance for each condition (N=20) (rau). Right: Participants subjective rating regarding the difficulty of the task for each condition (VAS score) (N=20) (rau). Error bars represent standard errors of the mean.

Quiet conditions. A significant correlation between better hearing loss and subjective ratings of difficulty (VAS score) was also found in the Quiet Aided condition ($r=0.67$, $p=0.0217$), suggesting that greater hearing loss were associated with higher subjective ratings of difficulty in the Quiet Aided condition. A correlation between subjective rating of difficulty (VAS score) and performance was found in the Quiet Aided condition ($r=-0.68$, $p=0.0217$), indicating that better performances were associated with lower ratings of difficulty. Finally, significant correlations between mean dilation in the anticipation window and mean dilation in the processing window were observed in several conditions (Quiet Aided: $r=0.66$, $p=0.0257$, Noise Aided: $r=0.78$, $p=0.0016$, Noise Unaided: $r=0.62$, $p=0.0384$), indicating that greater mean dilations in the anticipation window were associated with greater mean dilations in the processing window for these conditions. No significant differences were found between correlations.

3.1.4 Discussion

In the present study, we used a word-in-noise recognition test to assess listening effort among hearing-impaired patients. Four different conditions were tested: (1) Quiet Aided, (2) Quiet Unaided, (3) Noise Aided, (4) Noise Unaided; during which

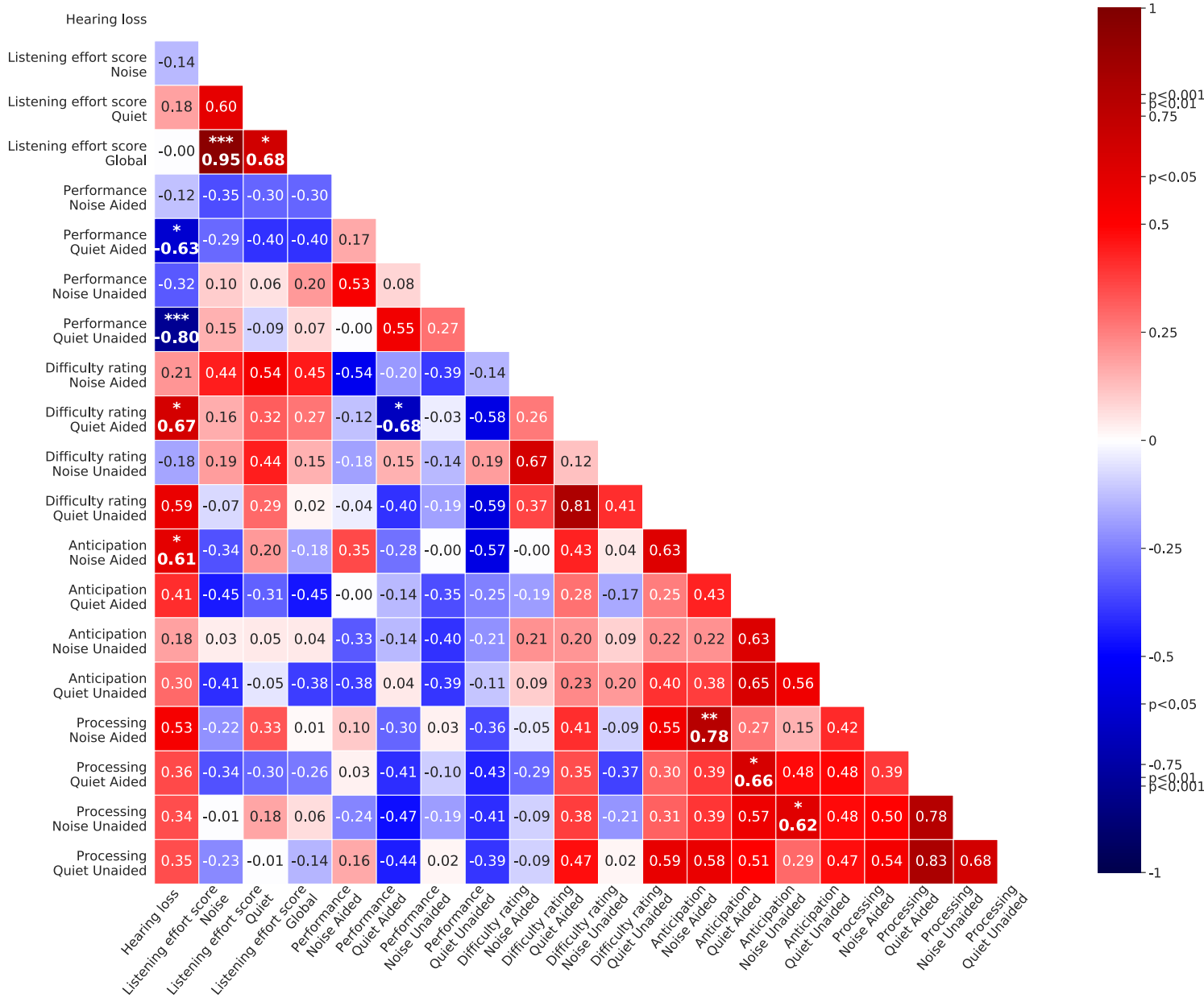


FIGURE 3.2: Pearson's correlation coefficients obtained between hearing loss of the better ear; subjective variables (listening effort questionnaire scores (in noise, quiet and global score), VAS difficulty scores); behavioral variables (speech perception scores); and objective variables (amplitude of mean pupil dilation during anticipation and processing of the word). Relevant significant correlations between objective and subjective variables are bolded. P-values were adjusted using Benjamini-Hochberg correction.

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

participants' pupillary responses and self-reported ratings of perceived difficulty were collected. Participants' self-reported listening effort in daily life was collected as well with a questionnaire resembling the EAS (Alhanbali et al., 2017).

As other studies that used longer stimuli (sentences) during speech-in-noise tasks (Koelewijn et al., 2014b, 2018; Ohlenforst et al., 2018; Wang et al., 2018b; Zekveld and Kramer, 2014; Zekveld, Kramer, and Festen, 2010, 2011), clear pupillary responses were obtained after the presentation of shorter stimuli such as disyllabic words. We also observed anticipation processes, accounting for attention mobilization during the word-in-noise recognition task, even when speech intelligibility was perfect, using pupillary responses (see Chapter 2 Section 1 for detailed results and discussion on pupillary responses). Further analyses were conducted in order to find effects of noise and hearing-aids on participants subjective rating of difficulty (VAS score) and performance during the task, as well as to investigate the potential relationship between hearing loss, task-related and everyday self-perceived listening effort, performance, and pupillary responses during the task.

As expected, greater performance was found when words were presented in the Quiet condition comparatively to the noisy condition. However, no statistically significant effect of hearing-aid was found on performance however. A common hypothesis regarding hearing-aids would be that they increase intelligibility, but studies did not always manage to verify this hypothesis (Brons, Houben, and Dreschler, 2014; Neher et al., 2014; Nordrum et al., 2006; Rovetti et al., 2019), and we could not reach such conclusions either. Regarding the subjective rating of the task, participants ratings were affected by the noise and perceived the task as easier when words were presented in the quiet condition. Moreover, a significant effect of hearing-aid was found indicating that the task was perceived as harder when participants were wearing their hearing-aids. Such counterintuitive results have also been found in literature (Brons, Houben, and Dreschler, 2014; Neher et al., 2014), following Ohlenforst et al. (2017a) comments regarding sparse results supporting the ability of hearing aids to reduce listening effort. However, as one of the main objective of this experiment was to evaluate the modulation of the pupillometric signal linked to listening effort even at perfect intelligibility, intensity levels were set individually to

get a 90% intelligibility score in silence without hearing-aids, in order to have a sufficient number of hit responses per condition per patient. Sound levels were then set relatively high (above the typical conversational level for speech) and the level of these sounds may have been unusually high (compared to everyday speech levels), when participants wore their hearing devices. It is therefore likely that such settings might have caused discomfort and signal distortions, as both the speech signal and the background noise were amplified by the hearing-aids (Agnew, 1998). This discomfort might have been transcribed through the task-related subjective ratings, as the task was rated as being more difficult with hearing-aid than without. However, this result is consistent with the interaction found between the factors noise and hearing-aid on mean pupil dilation measured during the anticipation window, showing that pupil dilation was greater in the Noise Aided than in the Noise Unaided condition (see Chapter 2 section 1).

Interesting correlations were found between hearing loss on the better ear and performance, subjective task-related difficulty rating as well as mean pupil dilation in the anticipation window. Greater hearing losses at better ear were associated with performance in the Quiet conditions, but no correlation were found between hearing loss on the better ear and performance in the Noise conditions. This result suggests that the recognition of disyllabic words in quiet situations is directly related to the degree of hearing loss, whereas the recognition of disyllabic words in noise relies on other additional cognitive processes and could not only be explained by hearing loss. Indeed, in challenging listening situations, top-down voluntary attention processes and working memory are engaged to select and reconstruct accurately relevant auditory information (Pichora-Fuller et al., 2016; Rönnberg et al., 2013). The correlation found between self-reported difficulty rating during the task and the hearing loss on the better ear in the Quiet Aided condition, indicating that greater hearing loss was associated with greater perceived difficulty in this condition, supports the idea that hearing loss directly impacts the difficulty perceived in quiet situations, as well. This correlation was found when participants wore their hearing devices, but not in the Unaided condition, suggesting that the discomfort (thus making the task challenging) due to sounds distortions and amplification when wearing the hearing-aid, was transcribed in this measure, as mentioned earlier. Moreover, the correlation between

hearing loss on the better ear and mean pupil dilation in the anticipation window in the Noise Aided condition, indicating that greater hearing loss was associated with greater mean pupil dilation during anticipation in this condition, supports this idea as well. Indeed, the increased perceived difficulty while wearing hearing aids was also visible in pupil responses, as participants anticipated more in this condition. No link could have been established between self-reported listening effort in daily life (via EAS-like questionnaire) and other measures of listening effort. This result might be due to the fact that listening conditions (and especially noise levels) were not representative of real-life situations. Another explanation could be that daily-life effort and task-related effort are not evaluated in the same way by listeners. Everyday life self-report needs to evaluate effort along a wider period of time (and numerous daily situations) and therefore could be difficult to appreciate and be under (or over) estimated by participants (Kamil, Genther, and Lin, 2015). On the other hand, task-related subjective effort is easier to evaluate and focus on a specific moment and a specific situation.

In accordance with previous studies assessing listening effort in hearing-impaired (Desjardins, 2016), and normal-hearing populations (Zekveld, Kramer, and Festen, 2010), we did not find any correlation between objective measures (pupil responses) and performance, nor with subjective measures (task-related VAS score and listening effort questionnaire (EAS) score). This result suggests that the different measures used tap into different underlying dimensions, supporting the idea that listening effort is therefore multidimensional (Alhanbali et al., 2019). The assumption that the different measures explore different dimensions of listening effort is consistent with the multidimensional attention-related outputs described in Pichora-Fuller et al. (2016) FUEL model. Indeed, we managed to demonstrate anticipation processes during the task (even at perfect intelligibility), thanks to pupil responses, that could not have been shown using only speech perception performance.

Altogether, we managed to observe effects of listening effort on multiple measures when short stimuli such as disyllabic word were presented during a word-in-noise recognition test. Indeed, we could observe main effects of noise and hearing-aids on participant's performance, task-related subjective difficulty ratings, and pupil responses as well. Notably, we could observe significant modulations of the pupil

responses linked to anticipation processes, even at perfect intelligibility, confirming the relevance and complementarity of objective measures (such as pupillometry) in the assessment of listening effort. Moreover, the lack of correlations between objective, behavioral and subjective measures, suggesting that these measures explore different underlying dimensions of listening effort, support the idea that listening effort is a multidimensional concept, rather than a single one.

3.2 Study 2: Influence of auditory selective attention on auditory information processing and listening effort

The present study will focus on auditory selective attention processes in listening effort, in another experimental setting. Attention processes of listening effort will be investigated in a young and healthy population during a discrimination task, in which non-verbal target stimuli will be presented in noise. In addition to pupillary responses, electrophysiological activity (scalp EEG) has been recorded during the experiment, in order to collect effort-related biological markers at different levels of the auditory pathway and explore their complementarity during the investigation of effortful listening. Data analyzed in this study were acquired before the beginning of the PhD.

3.2.1 Introduction

As the acoustic environment becomes more and more complex, the ability to select relevant information among irrelevant noise becomes crucial. Sophisticated top-down processes, such as auditory selective attention, allow us to enhance target signals and ignore less important stimuli. These processes are thus needed in noisy environments, whilst having a conversation or trying to focus on a specific sound target for instance, and require the engagement of cognitive resources. Physiological responses associated with this cognitive effort engaged whilst listening in noise, have been investigated at different levels of the human auditory system using different techniques.

The processing of auditory information involves both ascending and descending systems. The descending system, also known as efferent system, comprises multiple cortical and subcortical loops, the most peripheral of which being represented within the brainstem by the olivocochlear bundle (Rasmussen, 1946). This olivocochlear bundle is composed of the medial olivocochlear system, consisting of neurons that originate in the brainstem, project to the cochlea, and connect to the outer hair cells that are the core element of the cochlear amplifier (Guinan, 2006). Functional aspects of the cochlea amplifier can be explored by otoacoustic emissions (OAEs), which are

minute sounds produced by the activation of outer hair cells when a sound wave enters the inner ear (Kemp, 1978). By studying OAEs amplitude changes, researchers were able to show that the most peripheral stage of the hearing system could be modulated by selective attention, amplification in the cochlea being adapted according to the relevance of the stimulation (Boer and Thornton, 2007; Dragicevic et al., 2019; Francis, 2012; Giard et al., 1994; Smith, Aouad, and Keil, 2012; Wittekindt, Kaiser, and Abel, 2014).

At the cortical level, auditory selective attention has been widely investigated using scalp EEG and the dichotic paradigm (Ambler, Fisicaro, and Proctor, 1976; Hillyard et al., 1973; Näätänen, Gaillard, and Mäntysalo, 1978). Typically, subjects were instructed to detect occasional target stimuli in a series of tones presented to one ear, and to ignore a concurrent sequence of tones to the opposite ear, with no overlap between ears. Auditory selective attention was found to modulate the processing of stimuli according to their relevance by increasing sensory responses to relevant sounds (see Giard et al., 2000, for review). Effect of attention on auditory processing can be indexed by increased sensory responses to relevant sounds such as fronto-central N1, N2, P2 and parietal P3b (Kok, 2001; Patel and Azzam, 2005; Polich, 2007). Top-down anticipatory attention can be indexed by the deployment of a frontally distributed event-related potential (ERP) during the expectancy of an imperative event: the contingent negative variation (CNV) (Brunia and Boxtel, 2001). Importantly, the CNV amplitude increases with task difficulty and attentional load (Bidet-Caulet et al., 2015) and can be used as an index of the cognitive effort. Auditory selective attention processes have also been linked to specific brain oscillations such as parietal alpha oscillations (8-12 Hz) (Klimesch, 2012). Alpha power has been associated with task load and difficulty, with increased alpha power in task-irrelevant regions during demanding situations (Klimesch, Sauseng, and Hanslmayr, 2007; Mazaheri and Picton, 2005). Relevant cortical regions, on the other hand, show decreases in alpha power, i.e. increased region excitability, enabling active stimulus processing (Hanslmayr, Staudigl, and Fellner, 2012; Yordanova, Kolev, and Polich, 2001). Therefore, alpha rhythms seem to play an inhibitory role during selective attention in complex configurations (Foxe and Snyder, 2011; Jensen and Mazaheri, 2010; Strauß, Wöstmann, and Obleser, 2014; Weisz

et al., 2011). Alpha oscillations have also been shown to be involved in top-down anticipatory processes, with alpha decrease prior to stimulation facilitating processing in the relevant incoming modality (Foxe, Simpson, and Ahlfors, 1998; Fu et al., 2001). In addition to top-down attentional processes, alpha power has been used to quantify cognitive effort (Holm et al., 2009; Jensen et al., 2002), and therefore can be used to quantify listening effort as well. Indeed, Obleser and Weisz (2012) found increased alpha power with acoustic degradation over posterior region during a word comprehension-rating task. Another study showed that challenging listening conditions induced similar alpha power as high working memory load (Obleser et al., 2012). Moreover, alpha power modulations were related to participant's reported rating of listening effort, during a number comparison task in which target uttered digits were masked with continuous speech (Wöstmann et al., 2015). In this study, participants who elicited weaker alpha modulations as task complexity increased, reported greater effort when listening to digits in noise.

In addition to electrophysiological measures, pupil responses have been widely used as an objective marker of load and effort during cognitive tasks (Beatty, 1982; Beatty, 1980; Beatty and Wagoner, 1978; Hess and Polt, 1964; Kahneman, 1973; Kahneman and Beatty, 1966), in particular to assess listening effort (see Zekveld, Koelewijn, and Kramer, 2018, for review). Changes in pupil size are known to be linked to the activation of the locus-coeruleus-norepinephrine (LC-NE) system (Aston-Jones and Cohen, 2005) associated with arousal and attention (Benarroch, 2009). Pupil activity can be examined in two ways: tonic and phasic. Tonic activity refers to overall baseline level characterising general alertness during task, while phasic activity refers to quicker burst-like responses associated with specific stimulations. Regarding phasic activity, studies showed greater evoked pupil dilation associated with lower intelligibility levels and Signal-to-Noise ratios (SNR) during sentence recognition tasks (Kramer et al., 1997; Zekveld and Kramer, 2014; Zekveld, Kramer, and Festen, 2010; Zekveld et al., 2011, 2014b). Some studies increased cognitive demands using tasks requiring divided attention: sentences were presented in noise (single-talker masker or speech-shaped noise) simultaneously in both ears and participants were asked to ignore one or repeat both sentences. Results showed a greater pupil dilation in the most challenging conditions: dual-target task over

single target task (Koelewijn, Versfeld, and Kramer, 2017; Koelewijn et al., 2014b, 2015), interfering talker masker over energetic masker (Koelewijn et al., 2012b). Increased pupil responses were also observed when task difficulty was modulated using linguistically challenging conditions (Engelhardt, Ferreira, and Patsenko, 2010; Kuchinsky et al., 2013, 2014; Piquado, Isaacowitz, and Wingfield, 2010). In addition to effortful listening, auditory attention switching was also assessed by means of pupillometry during a detection task in which participants had to detect a specific uttered letter during the presentation of two concurrent streams. Results revealed greater phasic dilation when participants had to switch attention between streams compared to conditions that did not required a shifting of attention (McCloy, Larson, and Lee, 2018; McCloy et al., 2017). As well as divided or switched attention processes, sustained attention has an effect on pupil behavior. Indeed, increased continuous pupil dilation was observed during the monitoring of several streams of tones during a long period of time (25 seconds auditory scenes) (Zhao et al., 2019). In the visual modality, general alertness during sustained attention has been investigated using tonic pupil activity. Increased tonic activity was found with increased intrinsic alertness to relevant stimuli during a psychomotor vigilance task (Unsworth, Robison, and Miller, 2018), and with increased difficulty during a target-search task (Irons, Jeon, and Leber, 2017). Similarly in the auditory domain, hearing-impaired participants elicited an greater overall tonic activity during a lexical decision task compared to normal-hearing subjects (Wagner et al., 2019), suggesting that the hearing-impaired listeners showed greater alertness during the task and engaged more resources to complete it.

In light of the previous studies, ERPs, cortical oscillations and pupil dilation are useful to objectively evaluate listening effort and attentional load. Links between these physiological measures have been investigated to better understand processes underlying effortful listening. Indeed, the simultaneous occurrence of the P3 components and the LC-NE system activation suggests complementary cognitive processes induced when tracking significant stimuli (see Nieuwenhuis, De Geus, and Aston-Jones, 2011, for review). This hypothesis has been validated during auditory oddball task in which elicited parietal P3 component (P3b) was sensitive to changes in pupil tonic activity during task engagement (Murphy et al., 2011). Hong et al. (2014)

reached the same conclusion regarding the link between tonic activity and parietal P3 component and also found a linear relationship between baseline level and N2 amplitude, suggesting influence of LC activity on early processing of target stimuli. Phasic LC-NE activity on the other hand, does not seem to index same processes as ERP components since no correlation was found between electrophysiological responses and evoked pupil dilation (Hong, Walz, and Sajda, 2014; Murphy et al., 2011). Prestimulus alpha power though, was significantly related to phasic pupil dilation (Hong, Walz, and Sajda, 2014) suggesting a link between attention state prior to stimulation and post-stimulus phasic LC activation. Further studies attempted to link cortical oscillations and pupil dilation, unfortunately leading to contradictory results. Studies assessing listening effort during a degraded speech recognition task did not find any correlation between alpha power modulations and evoked pupil dilation in young normal-hearing participants (McMahon et al., 2016; Miles et al., 2017). A recent exploratory study concluded the same way for hearing-aid users while listening to concurrent speech streams (Seifi Ala et al., 2020) suggesting that these two measures arise independently and express different cognitive processes.

The present study aims at bringing more information on how these objective measures change and complement each other during the assessment of effortful listening, and at obtaining a better understanding of the different cognitive processes assessed by these measures. To this purpose, young and healthy participants performed an auditory discrimination task in which two stimuli were presented in noise with two levels of difficulty. The paradigm used in this study was originally designed for the coregistration of three signals: EEG, pupil dilation and OAEs (see Kemp, 1998, 2002; Kemp, Ryan, and Bray, 1990, for complementary information on OAEs). The paradigm used in this study was then designed to meet all the requirements of the three different methods and was inspired from the paradigm used by Francis (2012). Target stimuli were presented embedded in repetitive auditory clicks, that were OAEs elicitors, but also perceived as noise to ignore during the task. The present report will focus only on electrophysiological and pupil responses elicited by the task.

3.2.2 Material and methods

Participants

Twenty-three subjects (16 females), aged from 19 to 26, were recruited for the study, that was undertaken in conformity with laws and regulations of biomedical research involving human subjects in France (CPP authorization number 11/090; AFFSSAP edict number 2014-039). Written informed consent was obtained for each participant and participants were paid 10 euros per hour for their time. Subjects were right-handed, healthy adults (mostly university students) without any hearing, neurological nor psychiatric disorders.

Protocol

The protocol lasted between 7 and 10 hours per subject (including short breaks between tests), and was divided into 3 sessions, each one performed on different days:

- A screening session (3 hours), involving administrative aspects, health and auditory questionnaires, audiometric screening including OAEs and auditory efferent reflex, laterality and dichotic test, and screening for the ability to perform the auditory discrimination task.
- A training session (1 to 2 hours), designed to firstly, adapt the parameters used for the auditory discrimination task to the subject's ability, using an adaptive procedure and secondly, to train the subject on the task.
- The main session (4 to 5 hours) consisted in simultaneously recording OAEs, EEG, and pupil dilation during the auditory discrimination task.

Auditory discrimination task

The core of this study consisted of an auditory discrimination task in which subjects were presented with two auditory stimuli (S1 and S2) that sounded like frog croaks, via the sound system of a computer, using Presentation software (Presentation 17.1, Neurobehavioral Systems). Participants were asked to click on the left mouse button if the two stimuli were the same, or on the right mouse button if

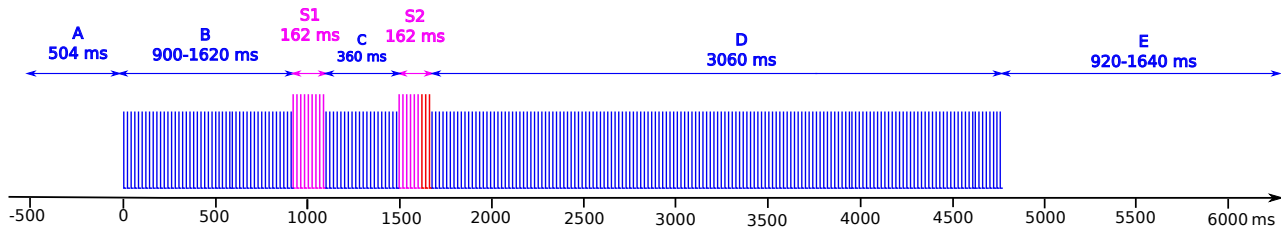


FIGURE 3.3: Trial time course. The trial duration is fixed at 6800 ms. Periods B and E have variable durations, compensating for each other in order to get 6800 ms trials. The trial is presented here with a period B of 900 ms and a period E of 1640 ms with a sS combination (the first stimuli has 9 tonebursts at frequency F1, the second stimuli is a complex F1-F2 series with the last 3 tonebursts at frequency F2).

the two stimuli were different. The stimuli were created in the wav format using the Python programming language (Python 2.7, Python Software Foundation). The “frog croaks” were composed of nine 3-cycles long tonebursts separated by 18 ms of silence. The 9 tonebursts were either all at the same frequency (F1=1500 Hz) (frog croak s) or with the last 3 of them with a greater frequency (F2) than 1500 Hz (frog croak S). F2 was adjusted for each subject, between 1510 Hz and 2300 Hz, so that all subjects could perform the task at a similar level of difficulty. The 2 frog croaks were separated by 360 ms and randomly and equally presented in 4 different combinations (ss, SS, sS, Ss). Same kind of trials were a combination of two identical tonebursts (ss or SS) and different trials always included one standard sound s and one complex F1-F2 series (sS or Ss).

The task-relevant stimulation was embedded in a continuous stream of 100 μ s long clicks, each one separated by 18 ms of silence, used as both stimuli to elicit OAEs and background noise (as heard by the subject) (see Fig.3.3). To avoid the influence of expectation relying on the beginning of the click sounds and not on the task itself (i.e. on the frog croaks), the number of clicks preceding S1 (period B in Fig.3.3) was variable, changing from 50 to 90 clicks (which corresponded to 900 to 1620 ms). The variability of Period B was compensated in period E (silence), in order to have a constant trial duration of 6800 ms. Each trial was then composed as follows:

- Period A: 504 ms of silence (fixed)
- Period B: 900 to 1620 ms click train (variable)
- S1: 162 ms "frog croak" (fixed)

- Period C: 360 ms click train (fixed)
- S2: 162 ms "frog croak" (fixed)
- Period D: 3060 ms click train (fixed)
- Period E: 920 to 1640 ms of silence (variable)

During the main session, subjects were presented with trials of 6800 ms with features corresponding to those presented in Fig.3.3. In the task introduction during the screening and in the training session, periods A, D and E were shortened so that trial lasted 3900 ms and we added trials without noise, where click trains were substituted by corresponding periods of silence.

Screening session

Questionnaires As efferent system activity is linked to auditory perception in noise (Micheyl et al., 1995), as well as to musical abilities (Perrot et al., 1999), all participants completed a series of questionnaires assessing their general health, hearing status (The Speech, Spatial and Qualities of Hearing Scale (SSQ) (Gatehouse and Noble, 2004), French version (Moulin, Pautz, and Richard, 2015)) and musical ability and practice. Handedness was assessed by Edinburgh Handedness Inventory (Oldfield, 1971) so that only right-handed participants would be included in the experiment.

Audiometry To ensure participants normal hearing acuity, hearing thresholds were measured in dB HL by 5 dB steps, at each half-octave frequencies between 250 and 8 kHz, using a COLSON K-15 audiometer. Moreover, hemispheric lateralization was checked using a Dichotic Listening Test (Test Dichotique, A. Moulin).

OAEs and auditory efferent recordings, Transient Evoked Otoacoustic Emissions (TEOAE) test and efferent reflex assessment Since further presented results will only focus on electrophysiological and pupil measures, these procedures will not be developed here. Participants who presented anomalies during these specific testings were excluded from further proceedings.

Introduction to auditory discrimination task During the screening, four blocks of 10 trials of the discrimination task (two blocks with silence followed by two blocks of background noise condition) were presented. The volume was established individually at 60 dB SPL, F1 frequency was set to 1500 Hz, and F2 frequency was set to 3000 Hz. The hit rate was expected to reach maximum or near maximum (9/10 or 10/10) in at least two out of the four presented blocks, and near-chance (6/10 and less) score was not to appear in any other than the first block. Subjects had to meet all of these criteria during the task to be included in further steps of the experiment.

Training session

The hybrid Parameter Estimation by Sequential Testing (PEST) (Hall, 1981; Taylor and Douglas Creelman, 1967) adaptive procedure was used to estimate the psychometric curve of each subject. From this curve, we could establish the correct F2 frequency for an appropriate difficulty level that will be used for the Main Session. In our experiment, we aimed to obtain two different difficulty levels that would correspond to performance level (percent correct responses) of about 70% for our difficult condition, and 90% or above for the easy version of the task. In accordance with refinements proposed by Hall (1974, 1981), we therefore implemented a hybrid PEST procedure for 0.75 threshold, which yielded a subject specific F2 frequency estimation, based on reconstructed psychometric curve.

Apart from the frequency values which followed the PEST settings, all other variables of stimuli (time preceding the first tonebursts series and variant out of 4 possible tonebursts series successions) were randomized. If the subject maintained the expected performance level for more than 30 trials, the presentation stopped and was repeated starting with value of final frequency + 100 Hz. This allowed us to obtain additional points on the psychometric function and balance the learning effect over the nearby frequencies. The exact duration of presented block was therefore dependent on the outcome of the randomization of trial type and individual performance of the subject. To ensure the training efficiency, the PEST session was always conducted at least one day before the main session and, at the most, one week before. The subject was seated in a quiet room and asked to perform the test with the

same equipment and at the same sound intensity level as in the introduction to the task described above.

Custom-written Presentation scenarios were programmed in six blocks. Each block lasted around 7 or 8 minutes. Three out of six corresponded to frog croaks stimuli without background noise and the other three corresponded to the same blocks with background noise. PEST procedure was performed using a shortened version of trials (shorter A, D and E periods in Fig 3.3). The number of blocks actually presented was adjusted for each participant so that the PEST session always lasted one hour (± 5 minutes).

Main session

Experimental setup During the main session, we simultaneously recorded transiently evoked otoacoustic emissions (description not developed here), pupil dilation and electroencephalography data with a customized set up. The subject was seated in a sound-attenuated and electrically shielded chamber in a comfortable armchair, all powered devices being placed at the adjacent room outside the experimentation box. The acoustic stimulation was presented to the right ear by Presentation software installed on a stationary computer, at output sampling rate of 44.1 kHz. The general experimental setup is presented on Figure 3.4.

Pupillometry Pupil dilation data were acquired with the use of Eyelink 1000 eye-tracking system (SR Research Ltd.) at a 500 Hz sampling rate using the “head-free” mode, the camera being equipped with 16 mm lenses and a desktop mount. The subject was seated at a 59 to 66 cm distance from the camera, behind which a carton board with 5 crosses for fixation points was placed. In most cases, we measured the right pupil dilation; exceptions were made for three subjects, in whom left eye tracking was more stable.

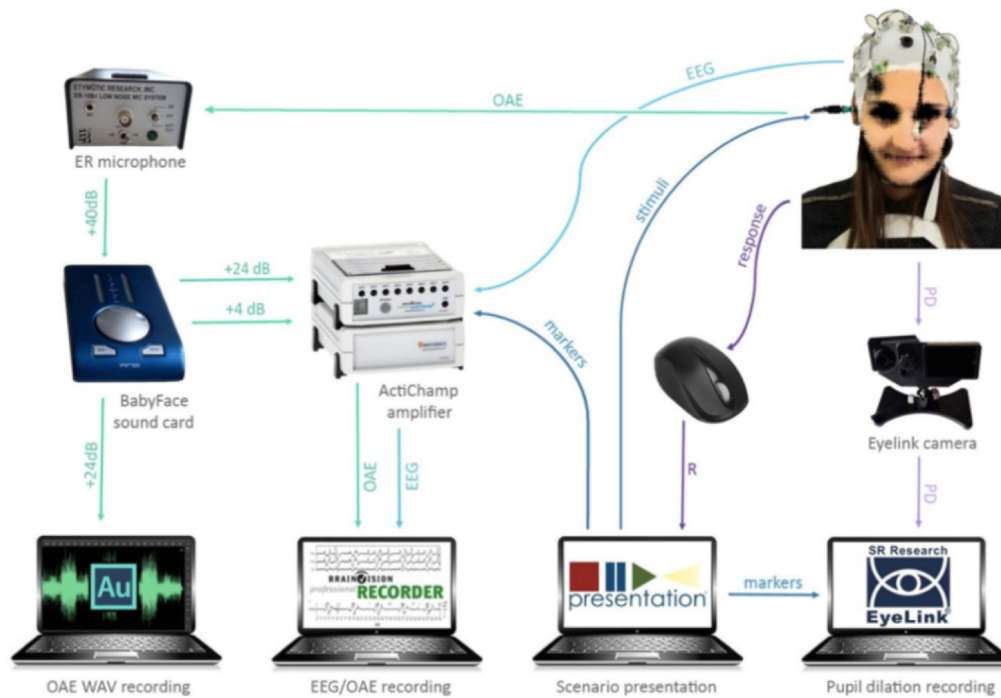


FIGURE 3.4: Experimental Setup

Electrophysiological recordings EEG data were recorded with the actiCHamp amplifier system powered with actiPower battery pack (Brain Products, Gilching, Germany). EEG was recorded from 30 active scalp electrodes mounted in an electrode-cap (EasyCap, Brain Products, Gilching, Germany) following a sub-set of the extended International 10–10 System. The recording setting comprised a forehead ground, a reference on the tip of the nose and electrooculography (EOG) data being acquired from an electrode placed on the external canthi of the left eye. Impedance level was limited to a maximum of 50 k Ω . A very high sampling rate was necessary for OAE recording, hence the sampling rate of 50 kHz was applied. No cut-off filters were applied for EEG channels whereas a band-pass filter of 500 Hz-20 kHz was used for the two OAE channels. Protocol set-up involved several steps:

- Setup of the pupil dilation recording. The luminosity was adapted for each subject, to be at the median portion of the psychometric curve of pupil dilation
- Online testing of the subject's OAEs at the desired sound intensity (60 dB SPL \pm 3 dB) by using the same trains of clicks than in the discrimination task (250 clicks separated by 18 ms)

- Presentation of a PEST block of 100 trials, starting at the frequency value determined from the PEST training session. This procedure enabled us to remind the task to the subject, to test the adequacy of performance on the equipment used during the recordings, as well as to gain additional points on the psychometric curve. Based on these data, the F2 frequencies associated with the two difficulty levels (0.7 for the difficult and 0.9 for the easy condition) were adjusted if necessary
- Setup of the EEG electrodes and impedance check.

Main recording The main recording lasted from 1 hour and a half to 2 hours. Sixteen blocks of 20 trials (8 of the difficult and 8 of the easy conditions, interlaced) were presented to the subject with Presentation software, each block preceded by the eye tracker camera calibration. All measures (EEG, pupil dilation, OAE recordings and behavioral data) were recorded for each block independently. Subjects performed the auditory discrimination task by pressing the mouse button (they had to click on the left button if S1 and S2 were the same, or to click on the right button if S1 and S2 were different) with their right hand. Participants were instructed to look at the central cross printed on the cardboard in front of them and to limit their movements during the block presentation. After each block, the subject was asked to rate the subjective difficulty level on a visual analogue scale from 0 to 10, where 0 meant very easy and 10 very difficult. This measure gave us additional information about the self-perceived effort. In case of an important deviation of performance from the level established in previous proceedings, one adaptation of the frequency value for each of the 0.7 or 0.9 level was admitted after the start of the session, usually after the second presentation of the corresponding condition block. This adjustment, though implemented rarely, ensured a better intra-individual difference between the two levels of difficulty (easy and difficult).

Data analysis

Behavioral data Individual performances were divided into correct (hit), incorrect, early and late responses. Responses were counted as correct or incorrect only when they occurred within the D period (see Fig.3.3), i.e. between the offset of the second

frog croak and the clicks offset (3060 ms). Responses that occurred before were considered as *early* and those that occurred after were counted as *late*. Reaction times were measured for correct trials as the time between the second frog croak (S2) onset and the subject's response (mouse single-click).

Electrophysiological data processing EEG data were preprocessed and analyzed using ELAN, a software bundle for electrophysiology data analysis developed at INSERM Brain Dynamics and Cognition team (Aguera et al., 2011). The signal refinement was initiated on the blocks separately using a band-pass filter between 0.1 and 140 Hz (Butterworth filter, order 2) and a down-sampling from 50 kHz to 1 kHz. The resulting blocks were then, together with their respective markers files, concatenated to obtain for each subject a single EEG file, which was further low-pass filtered to 40 Hz (Butterworth filter, order 3). Removal of the blink and saccade artefacts was performed by computing linear regression based on the EOG channel. This method appeared to be the most efficient, because blink correction using the classical Independent Component Analysis (ICA) method turned out to be unsuccessful on our data, despite numerous attempts. Following the regression, Fp1 electrode was no longer exploitable for all the subjects and was therefore excluded from the rest of the analyses. Moreover, six subjects presented at least one electrode channel that had to be interpolated before further analyses. Trials for which the dynamic range exceeded 45 μ V were automatically rejected. Around 20% of trials were excluded from the 23 participants data.

Event-related potentials (ERPs) were averaged, separately, for each stimulus event: clicks onset, S1 onset, S2 onset, and each condition: Easy-Same, Difficult-Same, Easy-Different and Difficult-Different. It is important to note that the acoustic content of S1 and S2 was identical in the Easy and Difficult conditions, in the Same trials, only. On one hand, the resulting files were low-pass filtered to 30 Hz (Butterworth filter, order 3) before baseline correction using the pre-event period (-100 to 0 ms), to observe transitory responses. On the other hand, data were low-pass filtered to 2 Hz (Butterworth filter, order 3) before baseline correction (using the same baseline period), to observe slow evoked responses.

In addition to ERP analysis, a time-frequency analysis was applied on electrophysiological data to investigate oscillatory activities. Time-frequency analyses aim at obtaining a power estimate of both evoked (phase-locked to stimulus onset) and induced (jittered in latency) activities in the time-frequency domain. To reduce the contribution of stimulus phase-locked responses, ERPs were first subtracted from 40Hz low-pass filtered data at the single-trial level before time-frequency transformation. A wavelet decomposition using complex Morlet's wavelet ($m=7$) with 1Hz frequency step was then applied on a -1000:7000 ms time window centered on clicks onset, a -3000:4000 ms time window centered on S1 onset and a -2000:2000 ms time window centered on subject's response. Time-frequency responses on single trials were then averaged across trials for each subject to get an estimate of induced oscillations in each condition (Easy-Same, Difficult-Same, Easy-Different and Difficult-Different). Transformed data were then baseline corrected using pre-clicks period (see period A on Fig 3.3) as baseline period. A visual inspection on the 3-40 Hz frequency range revealed that most oscillatory activity was contained between 9 and 10 Hz (see Fig 3.12), corresponding to alpha oscillations (generally defined on 8-12Hz frequency band). Alpha power time profiles on 9-10Hz frequency band were then computed and averaged for each trial event (clicks onset, S1 onset and participant's response) and condition (as alpha oscillations are slower responses than ERPs, responses were locked on S1 onset to observe processes involved during discrimination).

Pupil data processing All data processing and analysis were performed using Python (Python Software Foundation. Python Language Reference, version 3.7. Available at <http://www.python.org/>). Preprocessing of pupil data was performed using the "pypillometry" library (available at <https://ihrke.github.io/pypillometry/html/index.html>) (Mittner, 2020). Blink detection and interpolation techniques were based on Sebastiaan Mahtôt's work (Mathôt, 2013). Blinks and partial blinks were detected using zero values and pupil velocity profiles. The 'onset' of a blink is detected when the velocity value drops below a specific negative threshold (manually adjusted per recording). The 'reopening'

of the eyelid is detected when the velocity value exceeds a specific positive threshold (manually adjusted per recording). Using these elements, the blink is accurately detected and the blink period is then defined between the 'onset' and the complete 'reopening' of the eyelid. Blink events were then linearly interpolated from 60 ms before the starting point until 80 ms after the ending point of the blink. Margins were manually adjusted to get proper reconstruction of the signal when interpolation was not accurately performed (maximum 160ms before blink onset and 220ms after blink offset). Pupil data were then filtered using a low-pass 5th order Butterworth filter (cut-off frequency: 80 Hz) to remove high frequency artefacts. Trials containing more than 60% of interpolated data were rejected. Following this criterion, 1 participant was excluded from analysis due to too much missing and interpolated data. Around 17% of trials were excluded from the remaining data of 22 participants. A z-score transformation was applied at the single-trial level on entire trial once pupil data were preprocessed (McCloy et al., 2016; Nassar et al., 2012). The z-score transformation was followed by a baseline correction. The pre-clicks period (see period A on Fig.3.3) was used as baseline period, during which pupil dilation was averaged then subtracted from all data points of the signal. Aside from z-score transformation, pupil data were corrected using only baseline correction (with pre-clicks period used as the baseline period) to check if our previous methodological study's conclusions, regarding variability across conditions, were verified for this data set (see Chapter 2 section 1).

Statistical analysis

Behavioral data Participants' performances were expressed as percentage of correct responses then arcsin-transformed in order to normalize data distribution. Task performances were analyzed using a Linear Mixed-effects Model (LMM) to test within-subject effects of task difficulty (Easy vs Difficult) and stimuli type (Same vs Different). The model contained fixed-effects for the difficulty factor (Easy vs Difficult), the stimuli type factor (Same vs Different) and interaction between these two factors. A random-effect was also added to the model, to account for individual variance in intercept and slope for the stimuli type factor ($R^2_m=0.34$, $R^2_c=0.50$). A type-II

ANOVA (using type-II Wald X^2 test) was then applied to the model. Post-hoc pairwise comparisons were conducted using least-squares means testing. Analysis were conducted with R (R Development Core Team, 2020), the “lme4” package (Bates et al., 2015) was used to compute the model, the “car” package (Fox and Weisberg, 2019) was used to compute the type-II ANOVA and the “emmeans” package was used to compute least-squares means testing (Searle, Speed, and Milliken, 1980).

As well as for the percentage of correct responses, participants’ performances were analyzed using the sensitivity index d' . This index is the difference between normalized proportion of correct *different* answers over all *different* trials (CD rate) and normalized proportion of incorrect *different* answers over all *same* trials (ID rate): $Z(\text{CD rate}) - Z(\text{ID rate})$ (Macmillan and Douglas Creelman, 2005). In addition to the sensitivity index, the participants’ response bias was computed using the criterion c . This criterion is expressed as $-1/2(Z(\text{CD rate}) + Z(\text{ID rate}))$ (user’s guide to detection theory). Positive values indicate the tendency of answering “same” and negative values reflect the tendency of answering “different”. Sensitivities and response bias obtained in Easy and Difficult condition were compared using two-tailed t -tests.

Participants’ reaction time for correct responses were log-transformed in order to normalize data distribution. Reaction times were analyzed using a Linear Mixed-effects Model (LMM) to test within-subject effects of task difficulty (Easy vs Difficult) and stimuli type (Same vs Different). The model contained fixed-effects for the difficulty factor (Easy vs Difficult), the stimuli type factor (Same vs Different) and interaction between these two factors. A random-effect was also added to the model, to account for individual variance in intercept and slope for the stimuli type factor ($R^2_m=0.08$, $R^2_c=0.67$). A type-II ANOVA (using type-II Wald X^2 test) was then applied to the model. Post-hoc pairwise comparisons were conducted using least-squares means testing.

Finally, subjective ratings of perceived difficulty during the Easy and Difficult conditions were compared using a two-tailed t -test.

Electrophysiological data Statistical analyses were performed for each subject on ERP traces locked on each event (beginning of the clicks, S1 onset and S2 onset) using ELAN statistical tools. To limit assumptions on the location and latency of the

effects, we performed randomization tests for each of the 30 electrodes on several successive time windows, and corrected for multiple tests. In the temporal dimension, we used a randomization procedure (Blair and Karniski, 1993) to estimate the minimum number of consecutive time windows that must be significant for the effect to be globally significant in the entire time window of interest. For the spatial dimension, we considered as significant an effect visible at 3 or more adjacent electrodes. Easy and Difficult conditions were compared for the three events using permutation tests based on randomization ($n=1000$) (Edgington, 1964). ERP periods containing fast transitory responses (e.g. N1, N2) were tested point by point (every ms) while the periods of slower responses (e.g. P3b) were tested on successive 50 ms time windows. Fast transitory responses (e.g. N1, N2) were analyzed on the -100:360 ms time window locked on S2 onset. Slower transitory responses (e.g. P3b) were analyzed on the 360:1000 ms time window locked on S2 onset. To extract the effect of task difficulty independently of the acoustic content, ERPs to S2 in the Easy and Difficult conditions were compared in the Same trials only. Results obtained in All trials and Different trials are also presented but can be linked to differences in the F2 frequency. The same comparative statistical tool was used to compare alpha power elicited during Easy and Difficult conditions. Time profiles were compared on successive 50 ms time windows. Results were considered significant only when significant level of difference ($p<0.05$) were obtained on 3 or more adjacent electrodes.

Pupil data First, pupil activity was investigated at the trial level. Between-subject variability between conditions over time was inspected for each normalization method (z-score transformation and baseline correction) using the same methodology as described in Chapter 2 section 1. Pupil phasic activity (pupil dilation response) during task was then investigated. To do so, pupil data time series at trial level were compared using the same permutation test based on randomization ($n=1000$) as used for ERPs. Pupil dilation responses elicited during Easy and Difficult conditions for correct and incorrect responses were compared. As pupil dilation are relatively slow responses, permutation tests were performed on traces locked on S1 onset using 50 ms time windows.

To investigate pupil tonic activity, pupil activity was investigated at the block level. Pupil tonic activity was first analyzed. Pupil's dynamic during the whole block was first inspected using randomized permutation tests on pupil traces obtained during the complete block to compare the Easy and Difficult conditions. Same parameters were used for permutations tests ($n=1000$ permutations on 50 ms time windows). Baseline level during pre-clicks period (see period A on fig) was then computed for each trial, and blocks were divided in two parts: First, containing the first 10 trials of the block and Last, containing the last 10 trials of the block. Within-subject effects of task difficulty (Easy vs Difficult) and block part (First vs Last) on baseline levels were tested using a Linear Mixed-effects Model (LMM). The model contained fixed-effects for the difficulty factor (Easy vs Difficult), the block part (First vs Last) and interaction between these two factors. A random-effect was also added to the model, to account for individual variance in intercept and slope for the block part factor ($R^2_m=0.03$, $R^2_c=0.96$). A type-II ANOVA (using type-II Wald X^2 test) was then applied to the model. Post-hoc pairwise comparisons were conducted using least-squares means testing.

To explore the link between tonic and phasic pupil activities, we tested the impact of the block part on pupil phasic activity. Within-subject effects of task difficulty (Easy vs Difficult), response (Correct vs Incorrect) and block part (First vs Last) on peak pupil dilation were tested using a Linear Mixed-effects Model (LMM). The model contained fixed-effects for the difficulty factor (Easy vs Difficult), the response (Correct vs Incorrect), the block part (First vs Last) and interaction between these factors. A random-effect was also added to the model, to account for individual variance in intercept for any within-subject factor ($R^2_m=0.09$, $R^2_c=0.68$). A type-II ANOVA (using type-II Wald X^2 test) was then applied to the model.

Correlations between subjective and objective measures To investigate dependence between our measures, we computed a correlation matrix using Spearman's correlation criteria. Correlations between subjective and objective measures were computed for the difference in responses obtained between the Easy and Difficult condition. Objective measures comprised cortical responses (ERPs and alpha oscillations) and pupillary responses (phasic and tonic pupil activity). Subjective measures

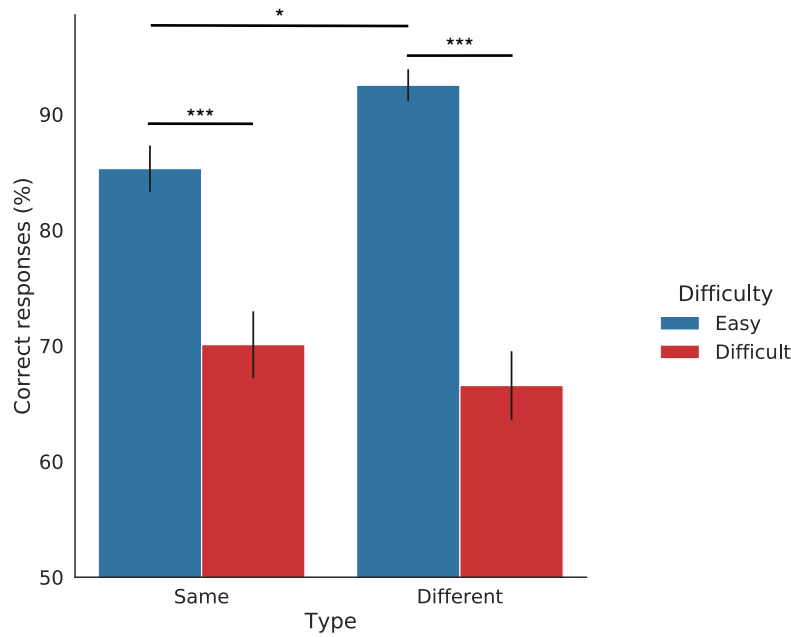


FIGURE 3.5: Mean percentage of correct responses for each condition and stimulus type. Errors bars represent standard errors of the mean.
*: $p < 0.05$, ***: $p < 0.001$

comprised sensitivity to the task, reaction times and subjective ratings regarding the difficulty of the task. Correlations were computed using the “scipy” library from Python (Virtanen et al., 2020). P-values associated with correlation coefficients were adjusted using Benjamini-Hochberg correction (Benjamini and Hochberg, 1995).

3.2.3 Results

Behavior

In agreement with the parameters set during PEST, mean performance (% of correct responses) during task for Easy condition reached 88.9% (SD=12.3%) and 68.3% (SD=20%) for Difficult condition. Statistical analyses showed an effect of difficulty on performance ($X^2(1, N=23)=114.54$, $p < 2e-16$) with better performance during Easy condition. A significant interaction between difficulty and type factors ($X^2(1, N=23)=9.49$, $p=0.0021$) was found as well. Post-hoc pairwise comparisons showed an effect of the stimuli type on the Easy condition only: the task was better performed when different stimuli were presented ($p=0.0285$) (see Fig 3.5).

In the same line, a significant effect of difficulty on sensitivity was found ($t=7.04$,

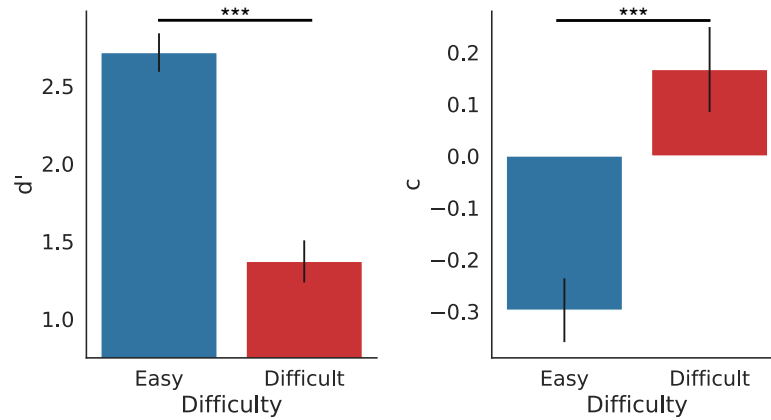


FIGURE 3.6: Left: Sensitivity. Right: Response bias for each condition. Errors bars represent standard errors of the mean.
***: $p < 0.001$

$p=4.56e-7$) with better sensitivity during Easy condition (see Fig 3.6 Left). One-sample t-test revealed that criterion c was different from 0 only in the Easy condition ($t=-4.35$, $p=2.57e-4$) and a significant effect of difficulty showed that participants were biased towards answering "different" in the Easy condition ($t=-5.27$, $p=2.76e-5$) (see Fig 3.6 Right).

Mean reaction times for correct responses reached 1014.5 ms (SD=249.8 ms) during the Easy condition and 1132.5 ms (SD=247 ms) during the Difficult condition. A significant effect of difficulty was found on reaction times for correct responses showing faster responses during the Easy condition ($X^2(1, N=23)=30.04$, $p=4.2e-8$). Statistical analyses revealed as well an interaction between difficulty and type factors ($X^2(1, N=23)=5.75$, $p=0.016$). Post-hoc pairwise comparisons showed an effect of the stimuli type on the Easy condition only: participants responded faster when different stimuli were presented ($p=0.032$) (see Fig 3.7).

Finally, mean difficulty rating reached 3.8 (SD=1.7) for Easy condition and 5.6 (SD=1.6) for Difficult condition. A two-tailed t-test revealed a significant difference between Easy and Difficult condition ($t=-6.4$, $p=1.93e-6$) with larger ratings in the Difficult condition (see Fig 3.8).

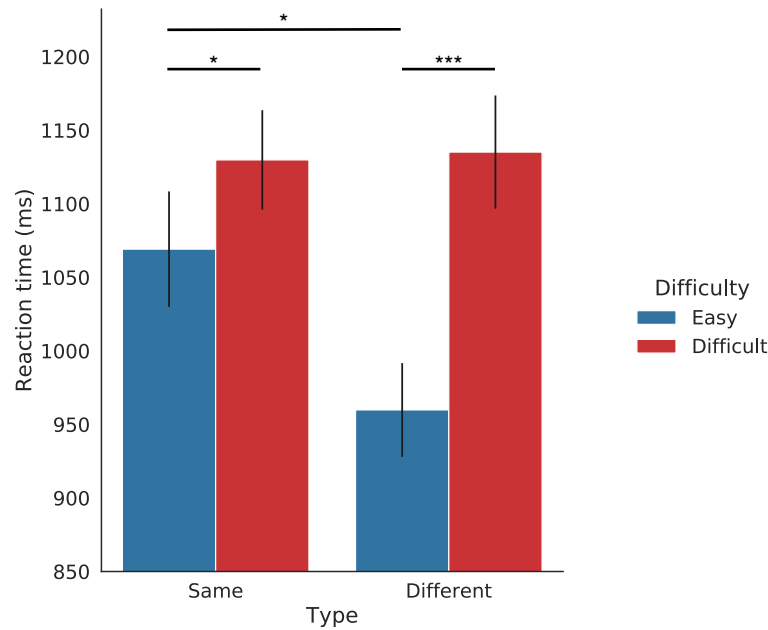


FIGURE 3.7: Mean reaction times (ms) for correct responses for each condition and stimulus type. Errors bars represent standard errors of the mean.
*: $p < 0.05$, ***: $p < 0.001$

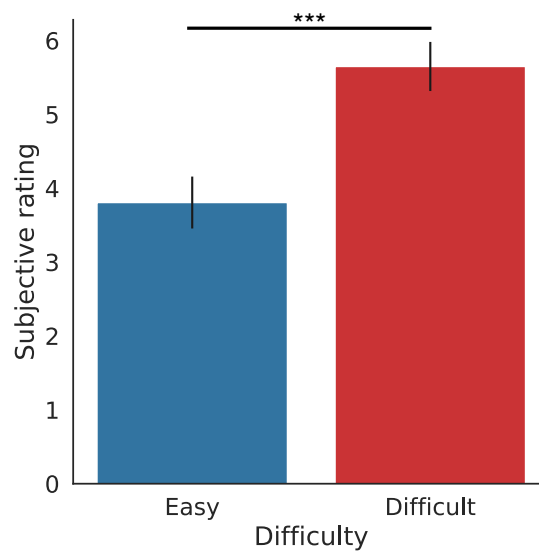


FIGURE 3.8: Mean subjective ratings of perceived difficulty for each condition. Errors bars represent standard errors of the mean.
***: $p < 0.001$

EEG markers

ERPs Evoked responses locked on clicks, S1 and S2 onsets were computed (see transitory responses on Fig 3.9). Clicks and S1 onset elicited transitory obligatory frontal N1-P2 responses and a frontal CNV was observed before S1 onset (see blue

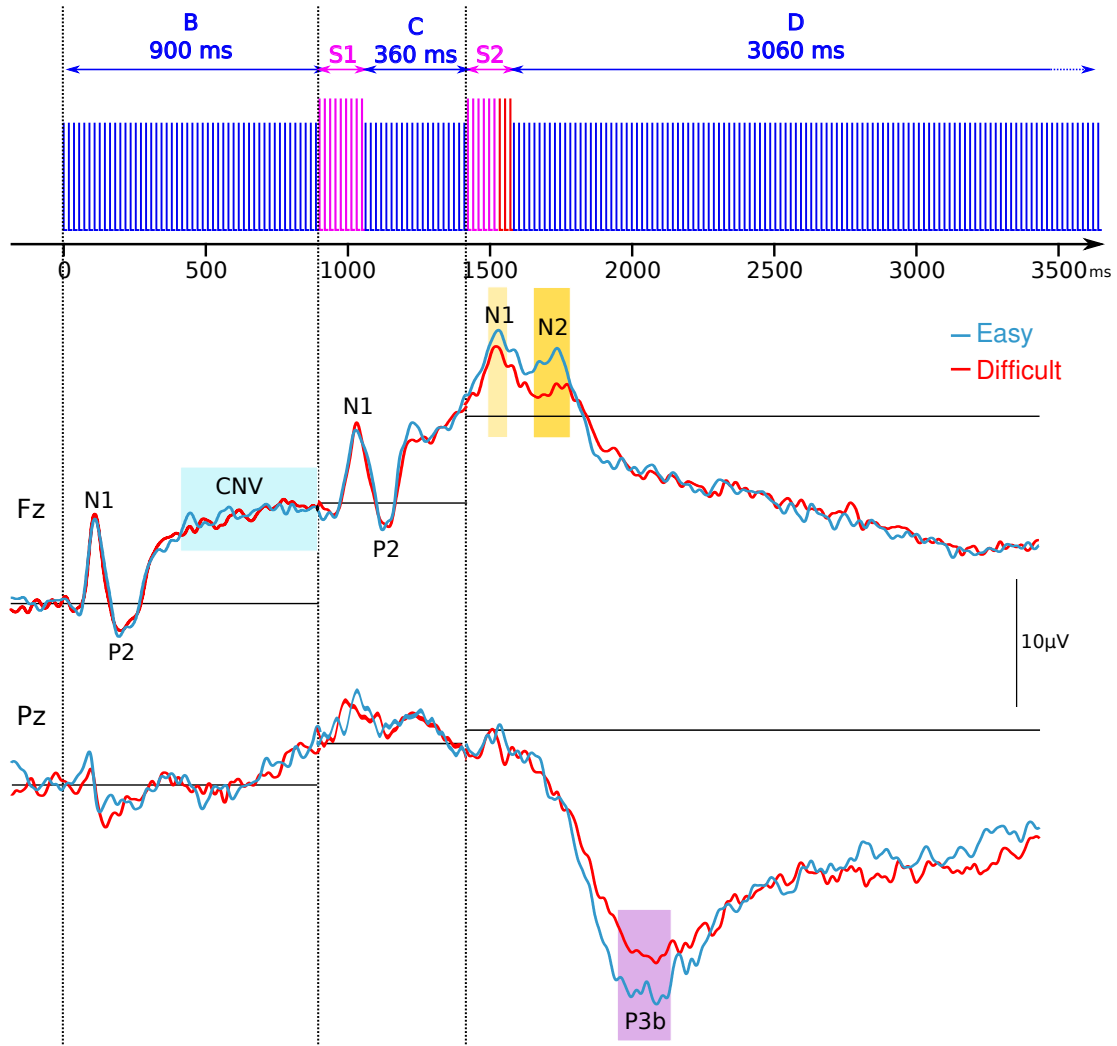


FIGURE 3.9: ERPs to each event onset (clicks, S1, S2) in Easy and Difficult conditions for all trials, at Fz (middle) and Pz (bottom) electrodes. Relevant part of the trial is displayed on top, with a timing relative to clicks onset. Shaded areas represent CNV, N1, N2 and P3b components. Dotted black lines represent events onset.

shaded area on Fig 3.9). However, transitory responses and frontal CNV showed no effect of difficulty before S2 onset. After S2 onset, significant modulations of frontal N1 (110-180 ms, see light yellow shaded area on Fig 3.9), N2 (225-350 ms, see dark yellow shaded area on Fig 3.9) and parietal P3 (P3b) components (425-680 ms, see purple shaded area on Fig 3.9) were found. Frontal N1, N2 and the P3b had greater amplitudes in Easy condition (see Fig 3.9). In a similar manner, after S2 onset, slow evoked responses showed similar modulations of P3b component, with greater P3b amplitudes during Easy trials. Further results will then focus on transitory evoked responses locked to S2 onset.

During *Same* trials, the significant modulation of the P3b only was preserved

(see Fig 3.10). In *Different* trials however, modulations of frontal N2 and central N1 components only passed significance level (see Fig 3.11), these ERP differences being probably related to the acoustic differences between the Easy and Difficult conditions in the *Different* trials. Thus, increasing task difficulty results in a smaller P3b response to the S2 stimulation.

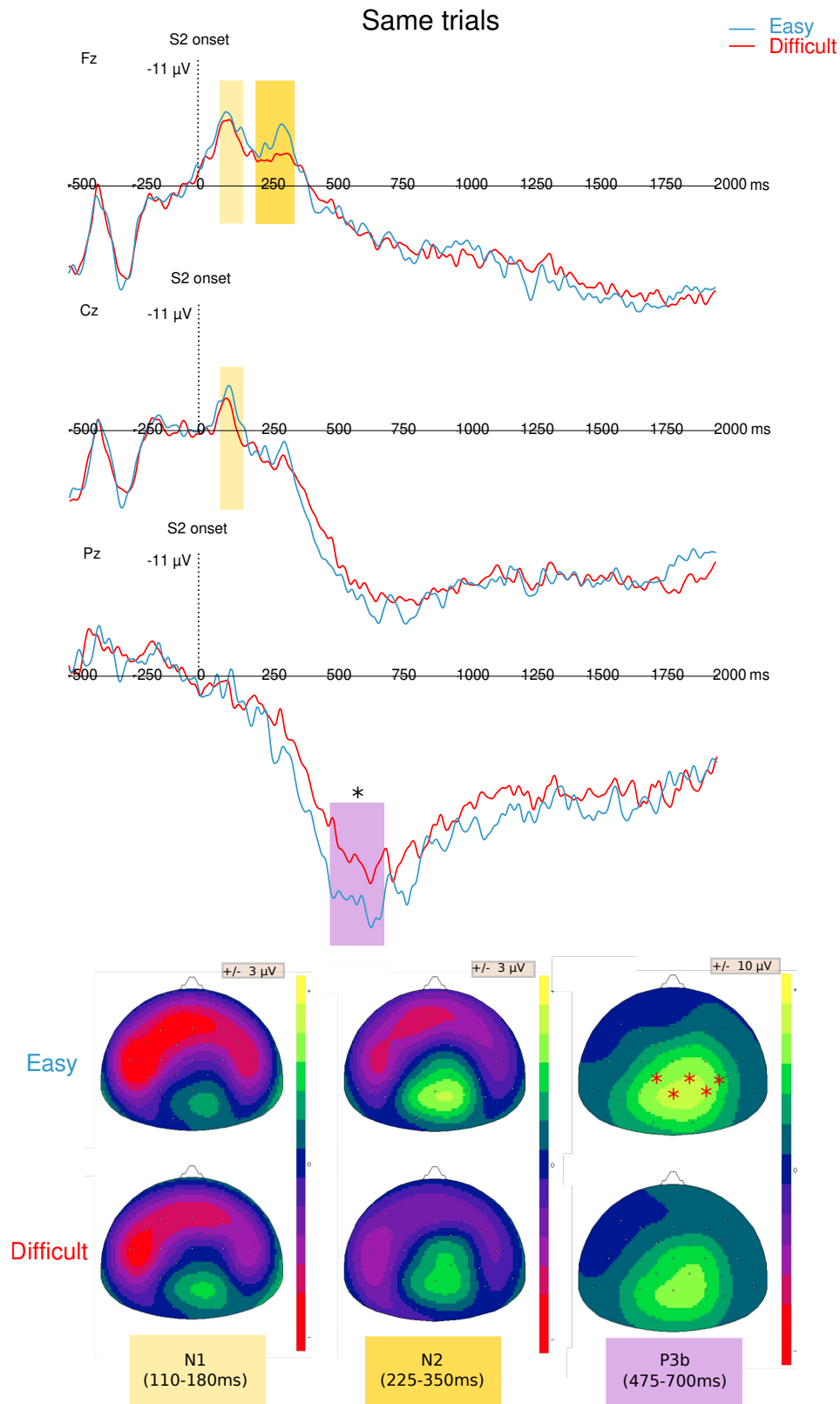


FIGURE 3.10: ERPs to S2 onset in Easy and Difficult conditions for *Same* trials only, at Fz (top), Cz (middle) and Pz (bottom) electrodes. Shaded areas represent N1, N2 and P3b components. Dotted black lines represent S2 onset. Topographic maps for each component are plotted in the lower panel of the figure. The color scale indicates a decreased potential in red (negative values), and an increased potential in yellow (positive values). Red stars on topographic maps indicated electrodes where the difference between Easy and Difficult conditions reached significance. *: $p < 0.05$

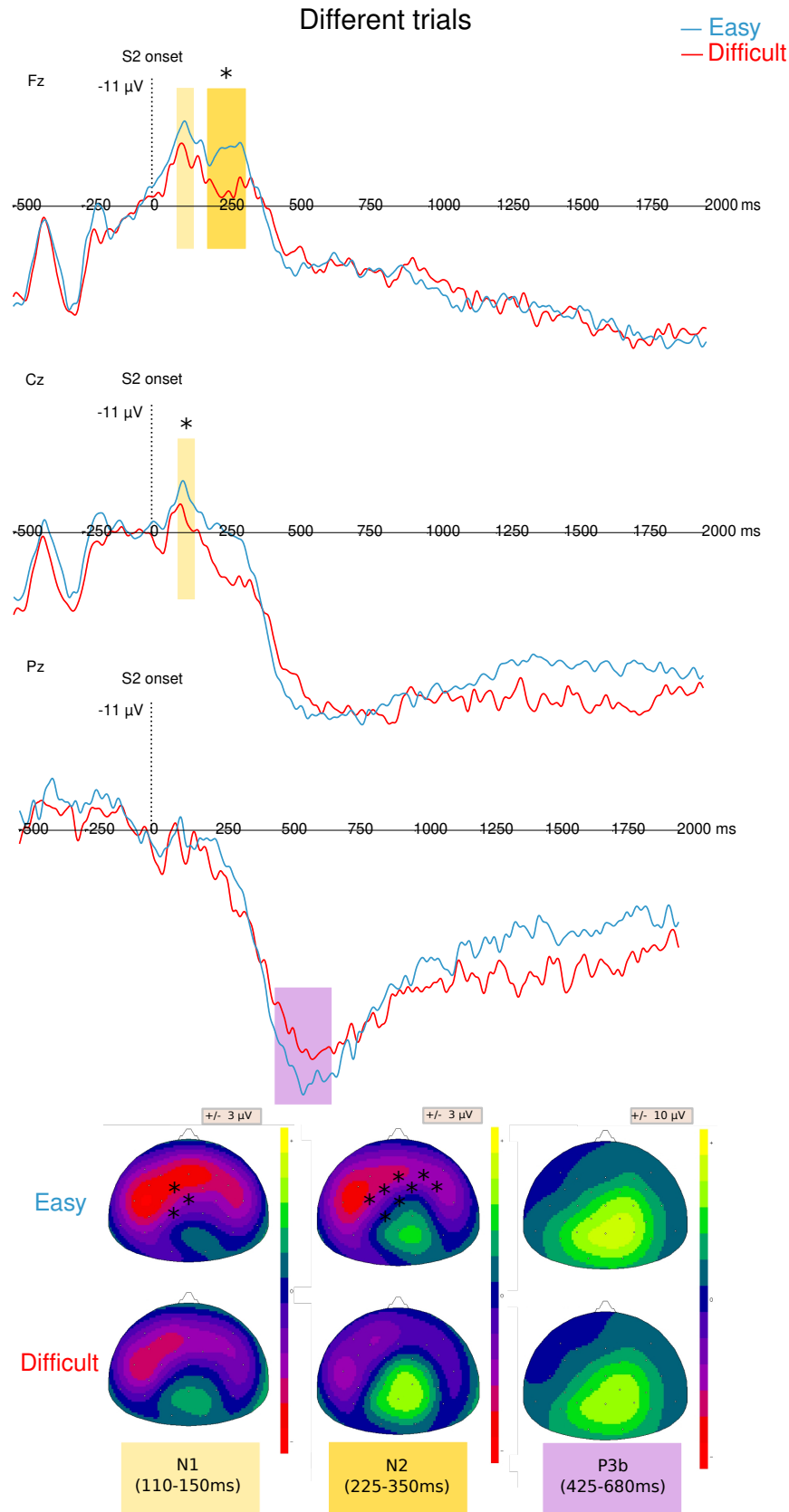


FIGURE 3.11: ERPs to S2 onset in Easy and Difficult conditions for *Different* trials only, Fz (top), Cz (middle) and Pz (bottom) electrodes. Shaded areas represent N1, N2 and P3b components. Dotted black lines represent S2 onset. Topographic maps for each component are plotted in the lower pannel of the figure. The color scale indicates a decreased potential in red (negative values), and an increased potential in yellow (positive values). Black stars on topographic maps indicated electrodes where the difference between Easy and Difficult conditions reached significance. *: $p < 0.05$

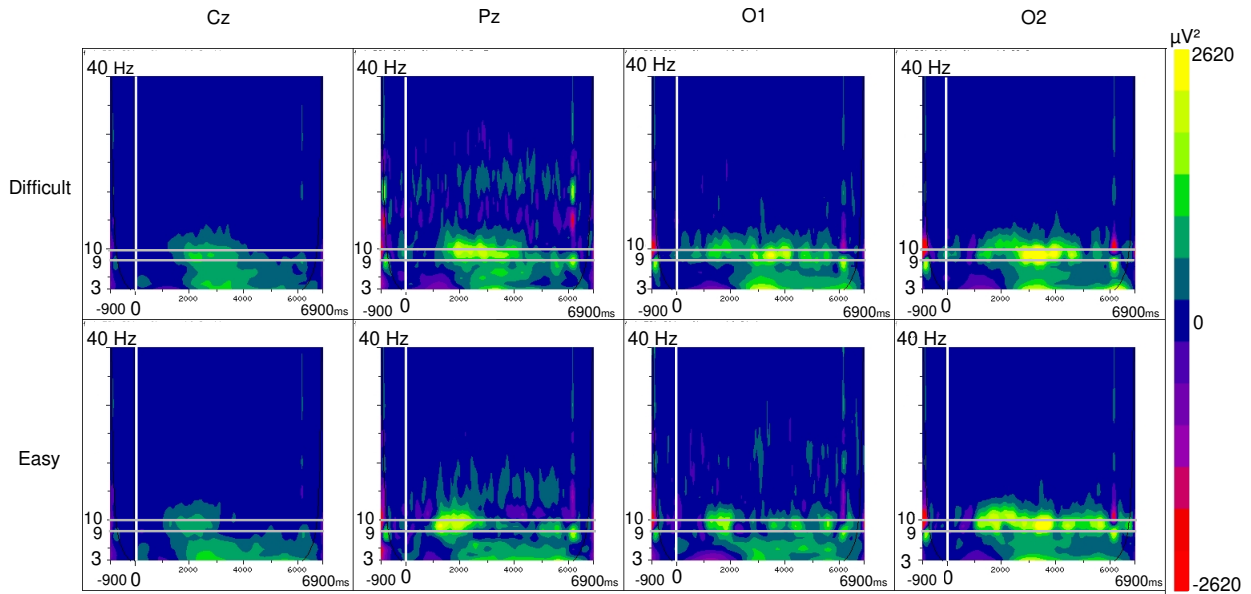


FIGURE 3.12: Alpha power induced after click onset in Easy and Difficult conditions. Time-frequency plots represent alpha power locked on the beginning of the clicks after baseline correction (baseline defined in the pre-clicks period: -504 to 0 ms). The color scale indicates a decrease in oscillatory power in red (negative values), and an increase in oscillatory power in yellow (positive values). White vertical line represents clicks onset. Horizontal grey lines represent the 9-10 Hz frequency band selected for analysis after visual inspection of time-frequency plots.

Alpha oscillations No effect of difficulty was found on alpha power between clicks and S1 onsets. After S1 onset, a larger increase in alpha power was found on centro-parietal electrodes during Difficult trials in the 1580-2000 ms time window when all trials were considered. During *Same* trials, an increase of alpha power was found in the Difficult condition on right electrodes in the 530-850 ms time window after S1 onset. During *Different* trials, alpha power was larger in the Difficult condition on left electrodes in the 1100-1870 ms time window after S1 onset, around participant's reaction time (see Fig 3.13). Alpha power around subject's response was then inspected. When only *Same* trials were considered, an increase of alpha power was found in the Difficult condition on right electrodes in the -580:-360 ms time window before subject's response. *Different* trials elicited an alpha desynchronization during the Easy condition on left electrodes in the -200-0 ms time window before subject's response (see Fig 3.14).

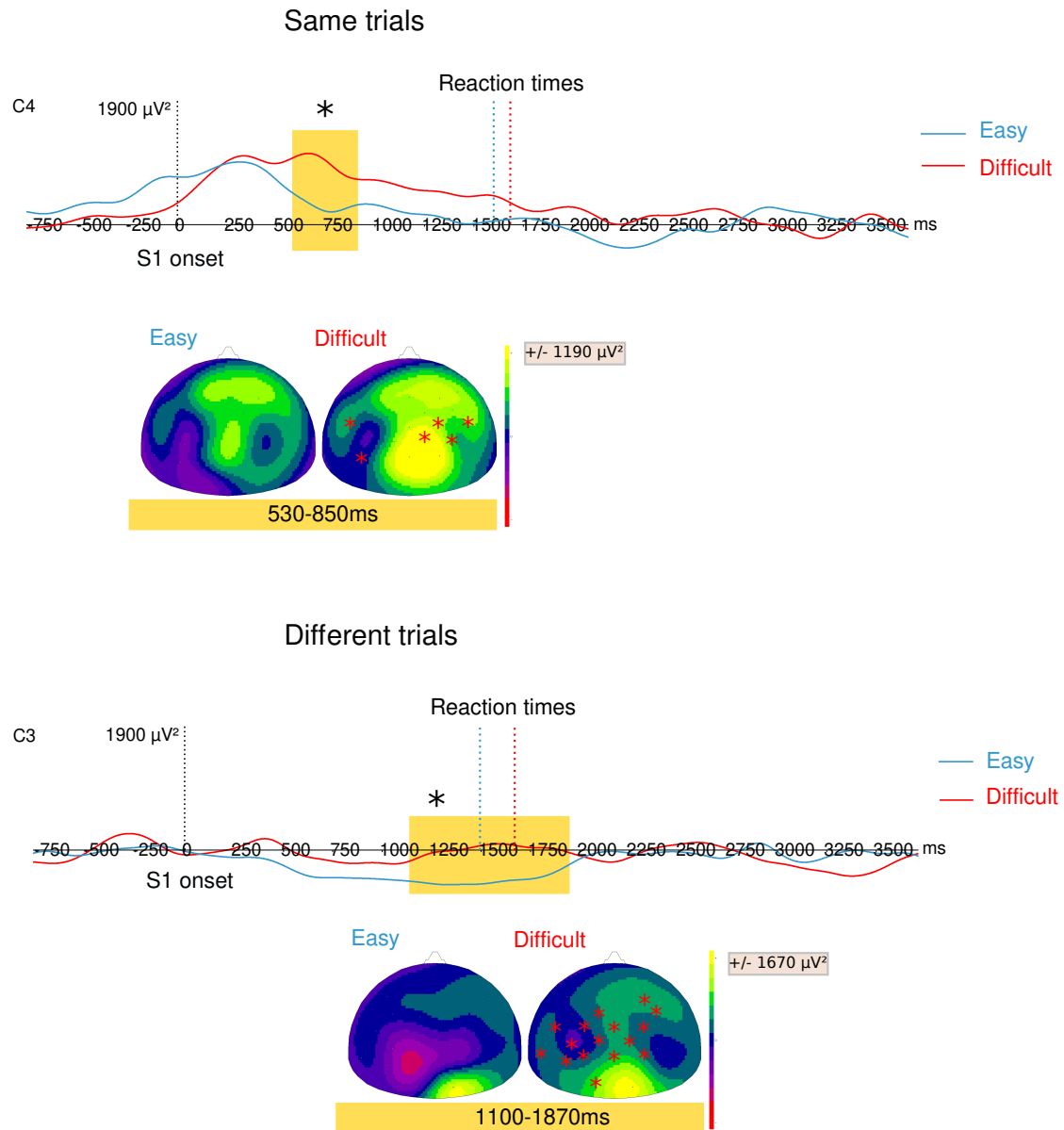
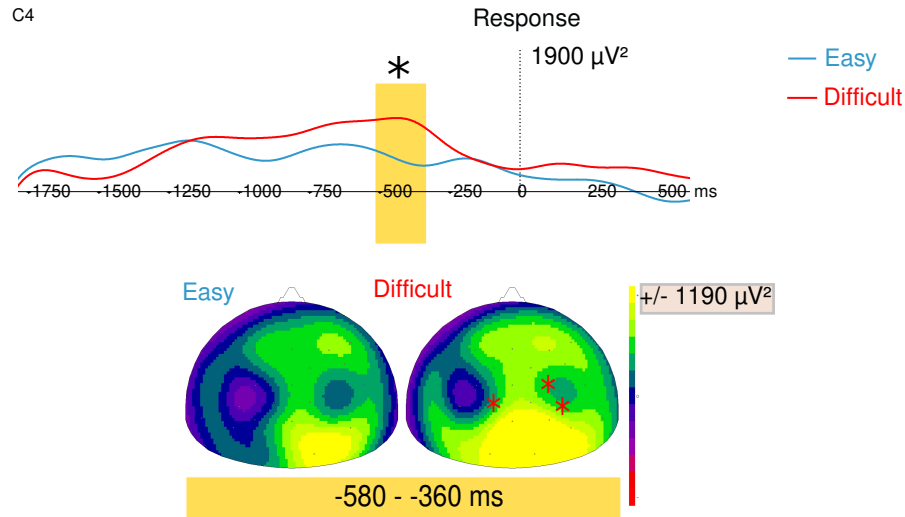


FIGURE 3.13: Time profiles of alpha oscillatory power in the 9-10 Hz frequency band locked at S1 onset and corresponding topographic maps for Easy and Difficult conditions in *Same* trials only at C4 electrode (upper panel) and for Easy and Difficult conditions in *Different* trials only at C3 electrode (lower panel). Dotted black line represent S1 onset. The color scale of topographic maps indicates a decrease in oscillatory power in red (negative values), and an increase in oscillatory power in yellow (positive values). Yellow shaded areas represent time windows with a significant difference between Easy and Difficult conditions. Red stars on topographic maps indicated electrodes where the difference between Easy and Difficult conditions reached significance.

*: $p < 0.05$

Same trials



Different trials

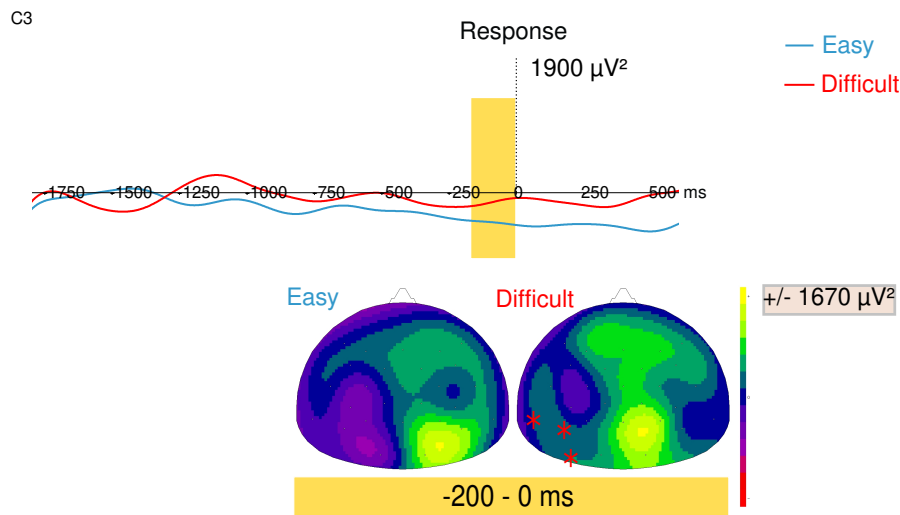


FIGURE 3.14: Time profiles of alpha oscillatory power in the 9-10 Hz frequency band locked at subject's response and corresponding topographic maps for Easy and Difficult conditions in *Same* trials only at C4 electrode (upper panel) and for Easy and Difficult conditions in *Different* trials only at C3 electrode (lower panel). Dotted black line represent subject's response. The color scale of topographic maps indicates a decrease in oscillatory power in red (negative values), and an increase in oscillatory power in yellow (positive values). Yellow shaded areas represent time windows with a significant difference between Easy and Difficult conditions. Red stars on topographic maps indicated electrodes where the difference between Easy and Difficult conditions reached significance.

*: $p < 0.05$

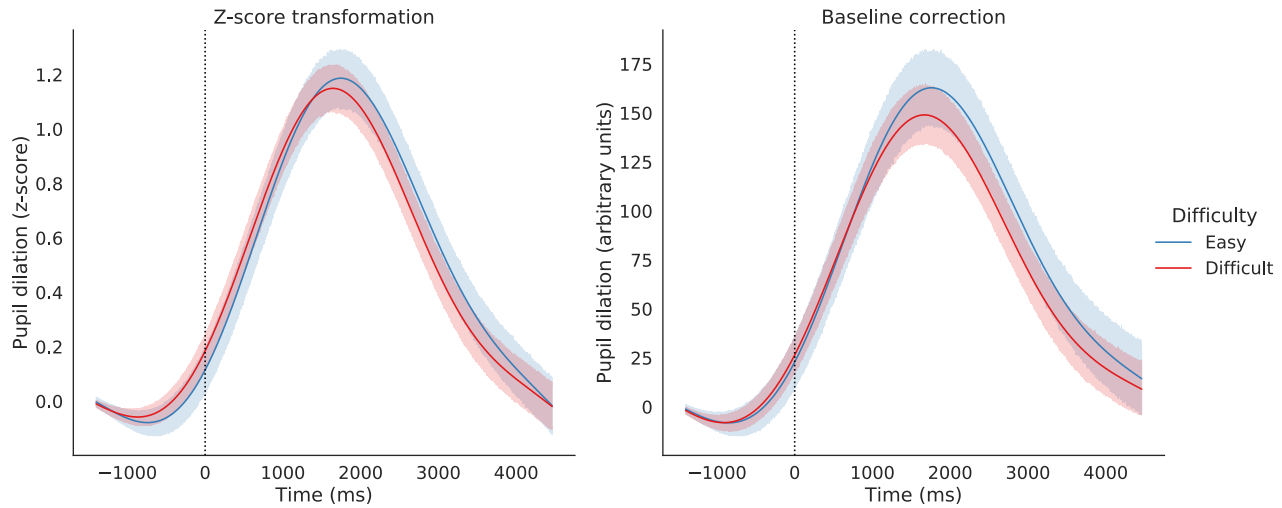


FIGURE 3.15: Pupil traces elicited by Easy and Difficult conditions obtained using z-score transformation followed by a baseline correction (left) or a baseline correction only (right). Shaded areas represent 95% confidence intervals.

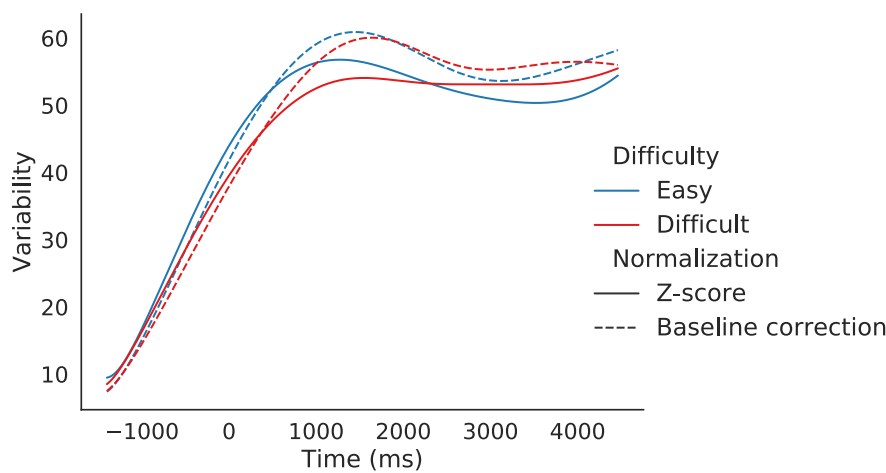


FIGURE 3.16: Variability over time for each condition per normalization method.

Task-Evoked pupil dilation

Inspection of pupil traces variability obtained with two normalization methods indicated that the variability was homogeneous across conditions (see Fig 3.15 and 3.16). However, z-score transformation provides less variability, especially around peak dilation. Further results will be then presented on z-score transformed data.

Comparative analysis on phasic pupil dilation at the trial level did not show any significant difference between Easy and Difficult condition when all responses were

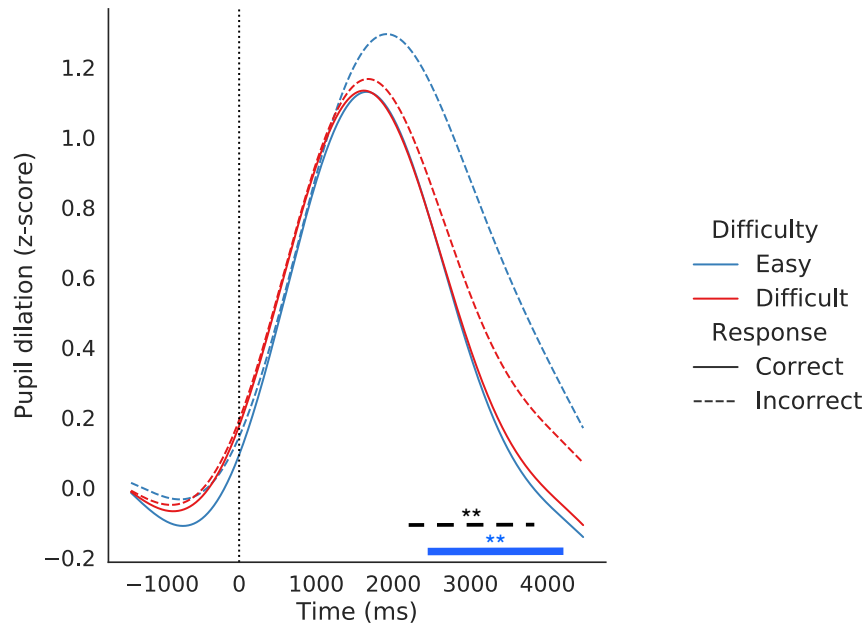


FIGURE 3.17: Pupil traces elicited by Easy and Difficult conditions for correct (solid line) and incorrect (dashed line) responses. Traces were computed using z-score transformation. S1 onset is noted with a vertical dotted black line. Horizontal lines represent time windows with significant differences (black dashed: Easy vs Difficult for incorrect responses, solid blue: incorrect vs correct responses during Easy condition).

**. $p < 0.01$

considered nor when only correct responses were considered. However, a significant difference between Easy and Difficult condition was found when participants did not respond correctly. Indeed, pupil dilation elicited during incorrect responses was greater in Easy condition compared to Difficult condition in the 2240-3750 ms time window after S1 onset ($p < 0.01$). Statistical analyses also revealed a significant difference in dilation between Correct and Incorrect response in the Easy condition, with greater dilation during incorrect response in the 2500-4150 ms time window ($p < 0.01$) after S1 onset. No difference in dilation was found when all conditions were averaged nor in the difficult condition (see Fig 3.17).

Randomized permutations on whole block traces revealed a significant difference in pupil size between Easy and Difficult blocks, with a greater pupil level during the second half of the block for the Difficult condition (see Fig 3.18). The linear model on baseline level during pre-clicks period revealed a main effect of block part, showing greater tonic activity in the first part of block ($X^2(1, N=22)=18.02$, $p=2.2e-5$). A main effect of difficulty ($X^2(1, N=22)=9.93$, $p=1.6e-3$), block part ($X^2(1, N=22)=18.02$, $p=2.2e-5$), as well as an interaction between these two factors ($X^2(1, N=22)=11.98$,

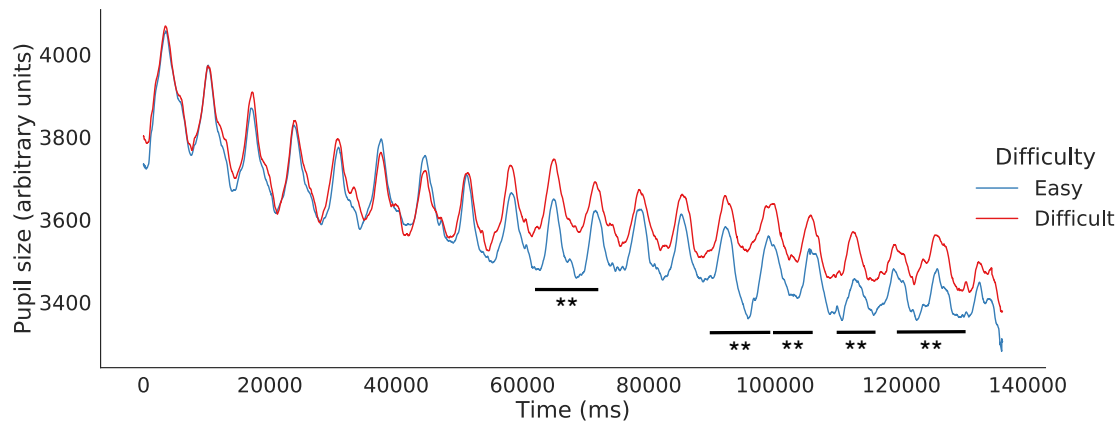


FIGURE 3.18: Pupil dynamic during the whole block for Easy and Difficult conditions. Horizontal lines represent time windows with significant difficulty differences.
**: $p < 0.01$

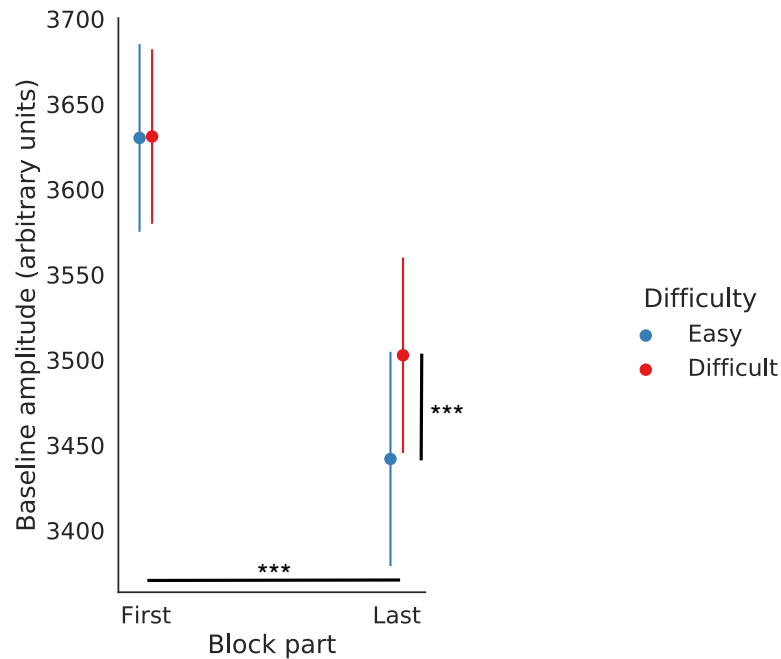


FIGURE 3.19: Mean baseline amplitude during the first and last parts of the block for Easy and Difficult conditions. Error bars represent standard errors of the mean.
***: $p < 0.001$

$p=5.4e-4$) were found. Post-hoc pairwise comparisons revealed an effect of difficulty during the last block only, with a greater pre-clicks level during the Difficult condition ($p < 0.001$) (see Fig 3.19). Regarding the impact of tonic activity on phasic activity, a main effect of the response ($X^2(1, N=22)=5.94$, $p=1.5e-2$) and the block part ($X^2(1, N=22)=37.08$, $p=1.1e-9$) were found on peak pupil dilation, showing greater

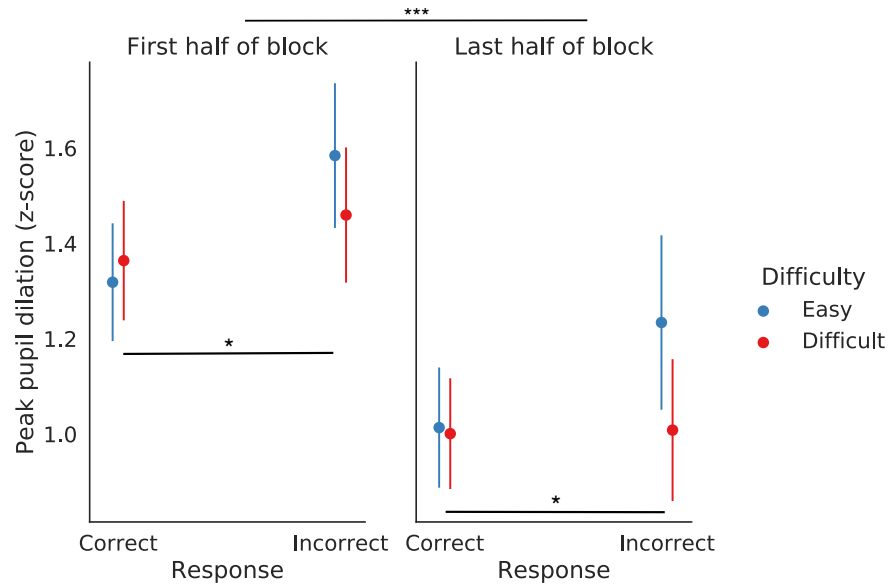


FIGURE 3.20: Mean peak pupil dilation during the first and last parts of the block for Correct and Incorrect responses in Easy and Difficult conditions. Error bars represent standard errors of the mean.

*: $p < 0.05$, ***: $p < 0.001$

dilation in the first half of the block, and for incorrect responses (see Fig 3.20). No interaction was found between difficulty, response or block part factors.

Correlation between subjective and objective measures

Spearman's correlation coefficients were computed on the difference between Easy and Difficult conditions between cortical responses (mean P3b amplitude on the Pz electrode in the 475:700 ms time window locked on S2 onset for *Same* trials only; mean alpha power on C4, CP2, CP6 electrodes in the 530:850 ms time window locked on S1 onset for *Same* trials only), pupillary responses (mean pupil dilation in the 2240:3750 ms time window locked on S1 onset for Incorrect trials only; mean pre-clicks amplitude during the second half of the block) and subjective measures (sensitivity, reaction times, subjective ratings). Spearman's correlation coefficients obtained are shown in Figure 3.21. A significant correlation was observed between the difference of subjective rating between the Easy and Difficult condition and the difference of sensitivity between the Easy and Difficult condition ($r=0.72$, $p=0.0031$), indicating that greater differences in perceived difficulty between the Easy and the Difficult condition were associated with greater differences in sensitivity between

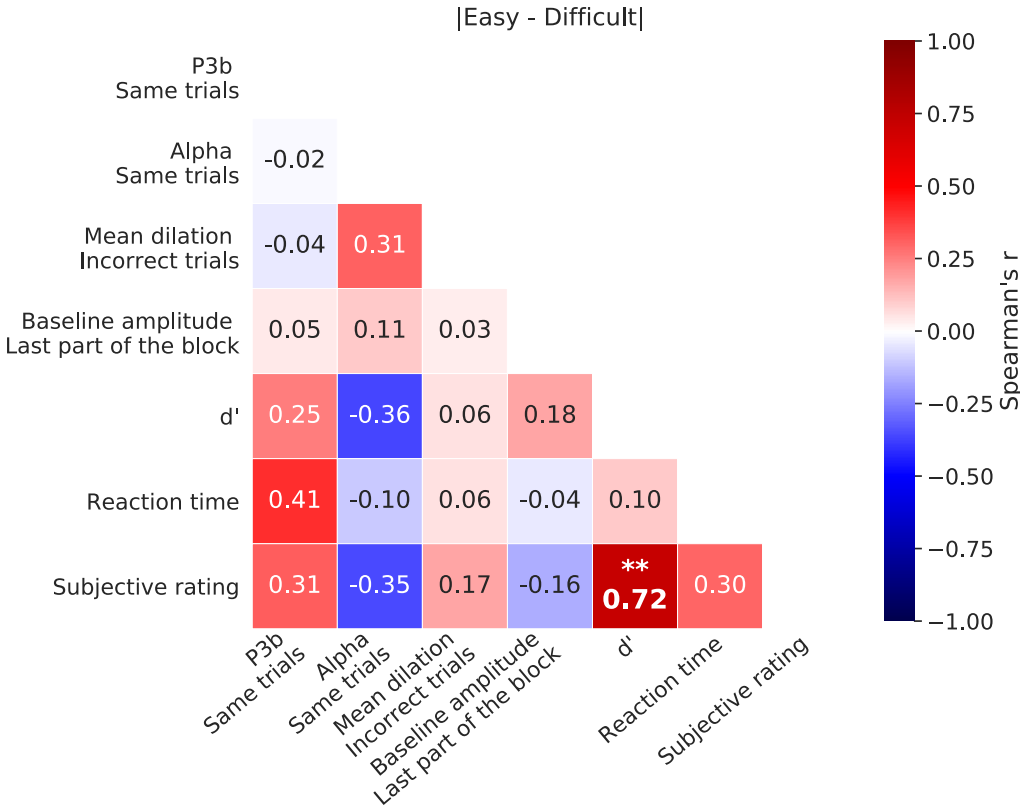


FIGURE 3.21: Spearman’s correlation coefficients computed between cortical responses (P3b amplitude, alpha power), pupil dilation (mean dilation, baseline amplitude) and subjective measures (sensitivity, reaction times, subjective ratings) obtained between the Easy and Difficult condition. The significant correlation between variables is bolded. P-values were adjusted using Benjamini-Hochberg correction.
**: $p < 0.01$

the Easy and the Difficult condition during the task. No correlation was found between objective measures, nor between objective and subjective measures.

3.2.4 Discussion

In this study, we aimed at exploring neural and pupillary correlates of effortful listening. To do so, participants performed an auditory discrimination task in which two tone-bursts stimuli (corresponding to target stimuli) were embedded in train of clicks (perceived as noise). Two difficulty levels were specifically designed to obtain a modulation of the cognitive demand. In Easy conditions, stimuli were designed so that participants could differentiate the two tone-bursts 90% of the time. In Difficult conditions, stimuli were designed so that participants’ performance reached 70%.

The behavioral results all agreed to indicate a significant difference between the

Difficult and the Easy conditions of the task. Indeed, difficult trials resulted in lower performances (see Fig 3.5), sensitivity (see Fig 3.6: Left) and longer reaction times in comparison with the easy ones (see Fig 3.7), reflecting the increase in task difficulty. These behavioural results were in agreement with the participants' self-assessment of the difficulty, as the difficult trials were perceived as more difficult (see Fig 3.8). As well as a difficulty effect, an interesting interaction was found between difficulty and stimuli type factor on subjects performance and reaction time. Indeed, stimuli type had an impact only in Easy condition, leading to higher performances and shorter reaction times when different stimuli were presented (see Fig 3.5 and 3.7 respectively). Participants response bias towards answering "different" in the Easy condition (see Fig 3.6: Right) brought more information on participants strategy during the task, showing a less conservative behavior in Easy conditions, accounting for previous observations in performance and reaction time.

At the cortical level, the difficulty of the task also had an impact on electrophysiological responses. Before S2 onset, transitory responses were not modulated by the difficulty of the task (see Fig 3.9). Contrary to our expectations, no difference in CNV amplitude was found between Easy and Difficult conditions. As more CNV would have been deployed if more top-down anticipation was engaged at the beginning of the clicks during Difficult conditions, we suppose here that participants used the beginning of the clicks as a temporal index before discrimination, regardless of the difficulty during the block. Whereas other studies observing CNV modulations used informative and uninformative cues (Berg et al., 2014; Bidet-Caulet et al., 2015; Kostandyan et al., 2019), in the present study, the beginning of the clicks did not stand as an informative cue regarding the difficulty of the task; nor the onset time of relevant sounds. Even though participants could have guessed the difficulty during the block, the fact that the beginning of the clicks were uninformative might explain the lack of modulations observed during anticipation. Another possible way to explain the lack of difference in CNV between the Easy and the Difficult condition would be that participants anticipated equally in the two conditions, their resources being already fully exploited in the Easy condition. Although no effect of difficulty was found during anticipation, ERP components elicited after S2 onset were affected by

this factor. Indeed, fronto-central N1,N2 and parietal P3b amplitudes were modulated by the difficulty of the task (see Fig 3.9). When all trials were considered, greater amplitudes were found for N1, N2 and P3b component during Easy condition. To better specify these effects, we compared responses obtained for Easy and Difficult condition in *Same* trials and *Different* trials separately. The modulation of P3b component with difficulty was conserved in *Same* trials (see Fig 3.10), but did not reach significance in *Different* trials (see Fig 3.11), though a tendency towards greater amplitude in Easy condition can be observed. The fact that less trials were included in the statistical analysis when isolating *Same* and *Different* trials might have been the reason why the difference between the two curves did not pass significance level. A larger P3b amplitude in the Easy condition suggests more attentional resources deployed in this condition (Kok, 2001; Polich, 2007), and is in line with previous findings of P3 amplitude decreases with lower stimulus discriminability (Kok, 2001; Parasuraman and Beatty, 1980), such as in the Difficult condition. This interpretation is in accordance with other studies that showed smaller P3b amplitudes in challenging conditions compared to easier ones during stimulus classification (Caclin et al., 2008), working-memory tasks (Pinal et al., 2014) and phonemic discrimination (Koerner et al., 2017). It is also consistent with behavioural results showing overall better performances, and lower ratings of the perceived difficulty of the task in the Easy condition. The modulation of N1 and N2 component with difficulty was observed in the *Different* trials only (see Fig 3.11). The enhanced N1 and N2 components in Easy vs. Difficult conditions for *Different* trials exclusively, suggest that these differences obtained were due to the habituation induced by the presentation of successive stimuli (Fruhstorfer, Soveri, and Järvillehto, 1970; Ritter, Vaughan, and Costa, 1968b; Woods and Elmasian, 1986), rather than to genuine attention effects. The more different the sounds, the weaker the habituation effect and the larger the responses to the second sound, leading to greater responses to S2 in the Easy condition, in which the acoustic difference between the two stimuli is more important than in the Difficult condition.

As we observed modulations of ERP components, oscillatory power were also affected by the difficulty of the task. Alpha synchronization was observed in parieto-occipital area during the task (see Fig 3.12). A previous study showed alpha power

modulation in prestimulus period during discrimination task with identical auditory stimuli (Wöstmann, Alavash, and Obleser, 2019), however, we did not find any modulation of alpha oscillations with difficulty during the anticipatory period. As for slow evoked responses, this result might be due to the uninformative character of the clicks or cognitive depletion already reached in Easy condition. We did find differences in alpha power after S1 onset though. When all trials were considered, differences in alpha power between Difficult and Easy conditions were localised in central and left electrodes. A significant increase of alpha power was observed in the Difficult condition in the 1580-2000 ms time window after S1 onset. As for ERPs analysis, we looked at oscillatory behaviour induced by the task during *Same* trials and *Different* trials separately. In *Same* trials only, statistical analyses revealed an increase in alpha power in the Difficult condition in the 530-850 ms time window after S1 onset mostly on right electrodes (see Fig 3.13: upper panel). In *Different* trials only, statistical analyses revealed an increase in alpha power in the Difficult condition in the 1100-1870 ms time window after S1 onset on left and central electrodes (see Fig 3.13: lower panel). In *Same* trials only, the timing and location of the increased alpha power in more challenging conditions are consistent with the hypothesis of alpha oscillations playing a key role in the inhibition of task-irrelevant stimulation (Payne and Sekuler, 2014). This effect located at central and occipital electrodes suggest an alpha synchronization in visual areas, resulting in the inhibition of these regions, being irrelevant during a purely auditory task. In *Different* trials, differences in alpha power were found during subjects responses (see Fig 3.13: lower panel). Moreover, topographic maps for *Different* trials indicated an alpha desynchronization in the Easy condition contralateral to the responding hand (see Fig 3.13: lower panel). The latency and topography at which differences in alpha power were found for *Different* trials might imply that the observed modulations observed are associated to the subject motor response (while clicking on mouse button to answer 'Same' or 'Different'). This was confirmed by the analysis of alpha power locked on subjects response. In *Same* trials, a larger increase in alpha power was found during the Difficult condition on right electrodes in the -580:-360 ms time window before subject response (see Fig 3.14: upper pannel). In the *Different* trials, the alpha power modulation did not persist, with only alpha desynchronization during the Easy condition on left posterior

electrodes (see Fig 3.14: lower panel). Therefore, the alpha increase in the Difficult condition seems to be rather related to a greater inhibition of irrelevant visual areas in the *Same* trials, while it seems to reflect enhanced motor preparation processes in the *Different* trials.

Pupil dilation, associated with cognitive effort through LC-NE activation, was also recorded during the task to obtain additional markers of effortful listening and get a better understanding of different cognitive processes involved. Phasic as well as tonic activities were analyzed as they reflect different aspects of processing during the task (Aston-Jones and Cohen, 2005). Statistical comparison of phasic dilation elicited with stimulus processing at the trial level revealed greater dilation in Easy conditions compared to Difficult ones for *Incorrect* responses only (see Fig 3.17). In Easy condition, phasic dilation was significantly larger when participants did not respond correctly (see Fig 3.17). The latter result confirmed previous results found during speech recognition task and auditory lexical decision task, with greater pupil responses when trials were incorrectly completed (Wagner et al., 2019; Zekveld, Kramer, and Festen, 2010). However the first outcome was not consistent with previous observation regarding task difficulty on pupil dilation, indicating greater dilation with increased cognitive load (Wel and Steenbergen, 2018; Zekveld and Kramer, 2014; Zekveld et al., 2014a, 2019; Zhao et al., 2019). As phasic dilation was expressed here relative to baseline, one explanation for this contradictory result would be that participants elicited a more aroused general state during Difficult condition with relatively greater baseline levels leading to necessarily weaker phasic dilation during stimulus processing. Indeed, large tonic pupil size has been repeatedly associated with small phasic pupil responses (Aston-Jones and Cohen, 2005; Eldar, Cohen, and Niv, 2013; Gilzenrat et al., 2010; Joshi et al., 2016; Murphy et al., 2011). To verify this hypothesis, tonic activity across blocks in Easy and Difficult conditions were compared. A decrease in pupil size throughout the block was observed and statistical comparison of whole block traces during Easy and Difficult conditions revealed greater pupil amplitudes in the Difficult condition in the second half of the block (see Fig 3.18) suggesting greater alertness in the more challenging condition during the second part of the block. Moreover the interaction between the difficulty and block part factor on baseline amplitudes confirmed that baseline

level was significantly larger in the Difficult condition during the second half of the block (see Fig 3.19). In light of these results, phasic activity was analyzed as well at the block level. While a main effect of the block part was found on peak pupil dilation, indicating greater peak pupil dilation in the first part of the block, no interaction between the difficulty and block part factors was found on pupil phasic activity (see Fig 3.20). Then, results obtained regarding phasic activity could not be explained here by the pupil tonic activity. However, interesting conclusions could be drawn with our results. Indeed, pupil size decrease with task progress in time has been associated with familiarization during the task (Polt, 1970) or fatigue and disengagement (Hopstaken et al., 2015a; Hopstaken et al., 2015b; McGarrigle et al., 2017b). Pupil patterns observed here are consistent with previous findings and replicate McGarrigle et al. (2017b) observations during a sustained listening task, with a reduced tonic state in the second part of the block compared to first one (see Fig 3.19). However, in the present study we found more decrease in tonic activity during the second half of the block for Easy conditions, whereas McGarrigle et al. (2017b) found the opposite. This might suggest that different processes were observed here. As habituation patterns are clearly observed here, the difference in pupil activity in the second half of the block might depict different strategies used during the task in the different conditions. Indeed, pupil size measurement have been used to assess explorative/exploitative behavior in several situations: "four-armed bandit" task with gradually changing payoff (Jepma and Nieuwenhuis, 2011), problem-solving task (Hayes and Petrov, 2015), or attentional set shifting task (Pajkossy et al., 2017). These previous studies revealed that slow decrease in pupil tonic activity was associated to gradual shift from explorative to exploitative behavior. Following this theory, our results might suggest that participant adopted an exploitative behavior at the middle of the block after guessing its difficulty, switching to a more aroused state in the Difficult condition engaging more cognitive demands. This interpretation would be consistent with participants subjective ratings regarding difficulty of the task, indicating a more challenging situation in the Difficult condition (see Fig 3.8), as well as with behavioural results regarding performance and reaction times (see Fig 3.5 and 3.7 respectively). Less decrease in tonic activity across trial numbers was also

observed by Wagner et al. (2019) during a linguistic task by hearing-impaired listeners compared to normal-hearing ones, suggesting more cognitive demands were deployed by hearing-impaired throughout the task. Though tonic activity has been used to assess cognitive load during working memory tasks (Mandrick et al., 2016; Peysakhovich, Vachon, and Dehais, 2017), this measure has been far less used to assess cognitive demands in effortful listening situations (compared to phasic dilation). Our findings reveal that processing and strategies during auditory stimuli discrimination in noise could be assessed by pupil baseline level throughout the task. This outcome confirms that it is a valid marker to assess listening effort and thus suggests that important information indexing effortful listening is contained within pupil tonic activity.

To assess the relationship between objective and subjective measures of listening effort, correlations between cortical responses, pupillary responses, sensitivity, reaction times and subjective ratings of difficulty in the Difficult vs. Easy conditions were computed. A significant correlation was found between the difference of subjective rating between the Easy and Difficult condition and the difference of sensitivity between the Easy and Difficult condition (see Fig 3.21). The positive correlation between the two measures indicated that greater differences in perceived difficulty between the Easy and the Difficult condition were associated with greater differences in sensitivity between the Easy and the Difficult condition during the task. This result indicates that the modulation of difficulty during the task was indeed perceived by participants and expressed through sensitivity. One of the aims of this study was to explore the relationship between the different measures of listening effort, and especially between cortical and pupillary responses, as well as between objective and subjective measures. No significant correlation was found between any cortical and pupillary measures (see Fig 3.21). As already observed in other listening effort studies (Alhanbali et al., 2019; McMahon et al., 2016; Miles et al., 2017; Seifi Ala et al., 2020), alpha power and phasic pupil activity were not correlated, suggesting that these responses express different cognitive processes engaged during effortful listening. No significant correlation was found between pupil tonic activity and cortical responses in the present study, neither between any objective and subjective measures. This absence of correlation between measures suggests

that each of them taps into a different dimension of listening effort, therefore supporting that listening effort is a multidimensional concept (Alhanbali et al., 2019).

In the present study, we were able to observe modulations in cognitive demands during stimuli discrimination in noise using electrophysiological recordings and pupil dilation. At the cortical level, we observed task-related P3b modulations with difficulty during *Same* trials showing a better processing of stimuli in the Easy condition. Alpha power modulations with difficulty during *Same* trials were found as well, showing more inhibition of irrelevant brain regions in the Difficult condition. Regarding pupil dilation, unexpected outcomes arose from phasic activity giving contradictory results with previous studies. However, tonic activity investigation gave us relevant information regarding cognitive demands during the task, revealing a more aroused state during the Difficult condition while completing the task. Difficulty in the task then induced a more aroused state with increased inhibition mechanisms, along with poorer processing of stimuli and performance, as well as greater response times compared to the easiest condition. The second analysis on pupil dilation, conducted throughout blocks rather than trials, was necessary to understand participants strategy and explain previous results on phasic dilation. We did not find any significant correlation between the different measures used to assess listening effort. Our results then suggest that listening effort is multidimensional and that these simultaneous measures are necessary to fully understand effortful listening. Indeed, by their different dynamics (fast transitory ERPs, slower alpha oscillations, and phasic or tonic pupil dilation), they seem to capture independent but complementary processes involved in listening effort. Their different analyses allowed us to explore responses elicited during the task at the trial-level as well as at the block-level and thus brought a complete investigation of cognitive resources deployed throughout the experiment. Moreover, the high signal-to-noise ratio of pupillometric measures allowed us to compare *Correct* and *Incorrect* trials, which was not possible with EEG signals due to few incorrect ones. In order to better understand cognitive processes involved throughout the task, further perspectives for this study may include complementary analyses on electrophysiological responses elicited during the first part and last part of the block.

Chapter 4

General discussion

The research presented in this PhD thesis deals with the investigation of listening effort through subjective, behavioral and objective (physiological) measures, with a focus on the use of pupillometry. The present work was divided in two axis. The first axis of this PhD work focused on the methodological investigation of the pupillometric signal during the assessment of listening effort. First, several baseline-related processing techniques were compared, then a frequency-based analysis was conducted on pupillary signal. The second axis focused on results of empirical studies in which several measurements (including pupillometry) were concurrently used to assess listening effort. First, the results obtained among hearing-impaired listeners during a word-in-noise task were presented. Then, listening effort was investigated among a young and healthy population during a tone discrimination task. Overall, the present work allows for new insights on 1) the use of pupillometry in the investigation of listening effort, and 2) the complementarity of subjective, behavioral and physiological measures during the assessment of listening effort, using different experimental setup among two distinct populations.

4.1 Relevance of the pupillometry technique

In the first study, pupillometry was used to assess listening effort among hearing-impaired patients during a word-in-noise recognition task in four conditions: (1) Quiet Aided (words presented at a high SNR with hearing-aids), (2) Quiet Unaided (words presented at a high SNR without hearing-aids), (3) Noise Aided (words presented at a lower SNR with hearing-aids). Several normalization techniques were applied on pupil data (subtractive baseline correction, proportional change from

baseline, within-trial mean scaling, grand mean scaling and z-score transformation). The different methods used resulted in similar results, however, the z-score transformation lead to an uniformed inter-subject variability between conditions, while greater differences in terms of variance were observed with other methods (both during anticipation and stimulus processing). In the second study, pupillometry was used to assess listening effort among young and healthy participants during a tone discrimination task with two levels of difficulty (Easy and Difficult). In this second study, the inter-subject variability in the pupillometric signal was homogeneous across conditions when applying subtractive baseline correction, as well as when a z-score transformation was applied. In light of these results, pupil patterns seem to vary less among a younger healthy population than an older hearing-impaired one, at least with the tasks and stimuli used here. Extra caution regarding the processing of the signal should be then accorded while using pupillometry among older hearing-impaired listeners.

As most studies that used pupillometry to assess listening effort focused mainly on the phasic response of the pupil during stimulus processing (Koelewijn et al., 2012b, 2014a; Kramer et al., 1997; Ohlenforst et al., 2018; Zekveld, Kramer, and Festen, 2010, 2011; Zekveld et al., 2014a,b), in the present studies, interesting results were observed at a different timing of the trial and on a different mode of the pupil response. Indeed, in the first study assessing listening effort among hearing-impaired patients, greater dilations in challenging conditions were observed during the anticipation period, but not during the processing of the stimulus. This result indicates that differences in listening effort are not systematically observed during the processing of the target stimulus and highlights the importance of anticipatory effects in the overall measure of listening effort during speech-in-noise tasks, especially when maximum intelligibility is reached. In the second study assessing listening effort among healthy young listeners during a tone discrimination task, important information regarding cognitive demands were observed within tonic activity of the pupil. Indeed, we could observe modulations of tonic activity throughout the block and greater baseline amplitudes were found during the second part of the block, suggesting greater alertness in the more challenging condition.

Pupillometry then clearly appears to be a relevant tool during the assessment of

listening effort. As it is relatively cheap and portable (compared to other physiological recording techniques), as well as noninvasive, pupil responses can be collected among several populations from children to older adults, with hearing-impairments or not. Despite variability in the signal across populations, robust normalization techniques can be applied in order to obtain consistent results regarding cognitive load and effort during different kinds of tasks engaging effortful listening. Indeed, in the studies presented in this PhD thesis, subtle changes related to attention processes (anticipation) or arousal state could be demonstrated thanks to this technique. Pupillometry therefore is a great asset in the investigation of listening effort, since it can capture attentional processes and modulation in arousal state that are closely related to listening effort (Pichora-Fuller et al., 2016).

4.2 Multidimensionality of listening effort

Listening effort is linked to the deployment of cognitive resources to understand an auditory message (McGarrigle et al., 2014). In challenging listening situations, cognitive processes such as selective attention (Pichora-Fuller et al., 2016) and working memory (Rönnberg, Holmer, and Rudner, 2019; Rönnberg et al., 2008, 2013) are engaged. Moreover, these cognitive resources are thought to be engaged depending on the arousal and motivational state of the listener (Pichora-Fuller et al., 2016). Different types of measure have been used such as, subjective, behavioral and objective ones, to investigate listening effort. Inconsistent relationships were sometimes found between these measure outcomes (Anderson Gosselin and Gagné, 2011; Larsby et al., 2005; Wendt, Dau, and Hjortkjær, 2016; Zekveld, Kramer, and Festen, 2010, 2011). It has also been shown that they were weakly correlated with each other (Alhanbali et al., 2019), suggesting that each measure tap into different underlying mechanisms of listening effort, supporting the idea that listening effort might be a multidimensional process. Indeed, in the first study assessing listening effort among hearing-impaired older adults, we did not find any correlation between self-assessed difficulty of the task and pupil responses. On one hand, pupil responses allowed for the observation of anticipation processes at a specific timing, even at perfect intelligibility. On the other hand, subjective measures described the overall perceived effort during

the task. In the second study, assessing listening effort among healthy young listeners, no correlation was either found between objective and subjective measures, nor between cortical and pupillary responses, suggesting that they tap into different processes. On one hand, modulations of the cortical responses were linked to the processing of the stimulation and the inhibition of the irrelevant sound source during discrimination. On the other hand, pupillary tonic activity brought information on participants arousal state and strategy during the task. Even though both tonic and phasic activity can be extracted from pupil responses (Aston-Jones and Cohen, 2005) and alpha oscillations (Klimesch, 1999), the recruitment of cognitive resources during effortful listening could be demonstrated here through alpha phasic activity only, and tonic pupil activity only. Moreover, the concurrent use of EEG and pupilometry allowed us to observe processes with different dynamics (fast transitory ERPs, slower alpha oscillations and pupil dilation). Results of both studies suggest that the different measures used complement each other and that their combination can help for the understanding of the different cognitive processes involved during effortful listening, among older hearing-impaired and young individuals, using verbal and non verbal stimuli.

Although many experiments were conducted on listening effort for decades, there is still no consensus on how to define it nor how to properly measure it (Strand et al., 2020). As listening effort arises from the recruitment of resources linked to a complex mixture of cognitive processes, it seems fair to assume that all the methods used to assess listening effort might not be investigating "listening effort" on its all, but rather assess specific subcomponents of listening effort (Alhanbali et al., 2019; Strand et al., 2020). Notably, the paradigms used in the present work mostly tapped into the top-down processes of selective attention during effortful listening (as anticipatory and inhibition processes were mostly observed in our results).

Another crucial element in effortful listening is its motivational and affective dimension. Indeed, it is essential to accurately measure and interpret the motivational and affective aspects of listening effort in order to understand how listening effort affects communication-related decisions, such as whether to continue participating in a conversation in a noisy environment (Francis and Love, 2019; Herrmann and Johnsrude, 2020; Pichora-Fuller et al., 2016). This dimension of listening effort can be

inferred through tonic pupil behavior, as it is associated with arousal states (Aston-Jones and Cohen, 2005). Modulations of arousal state were observed throughout the blocks of the experiment while assessing listening effort among healthy young listeners, however the very "experimental" aspect of the protocol did not resemble real-life situations at all, and thus the motivational effects of complex listening in common situations have probably not been captured. This dimension of effortful listening is usually not at the center of interest, however researchers recently raised even more awareness on its importance (Francis and Love, 2019; Herrmann and Johnsrude, 2020), broadening areas of interest and investigation in the study of listening effort.

The different measures used in the studies presented in this PhD thesis come with their benefits and their limits. The behavioral and subjective measures are easy to collect and interpret, and seem to capture listening effort in a global manner. However, they have limitations inherent in participant's judgment, that can lead to misestimation of the effort (Kamil, Genther, and Lin, 2015; Larsby et al., 2005). Pupillometry and EEG are objective techniques and allows to observe modulations in cognitive effort at different time landmarks and with different dynamics. However, they focus on specific processes linked to listening effort, such as processes of selective attention for instance. Moreover, studies using EEG and/or pupillometry require heavier experimental set ups and have specific constraints. EEG experiments require to repeat a great number of trials (over a hundred) because of the relatively low signal-to-noise ratio of the EEG signal. In pupillometry experiments, less trials are required to obtain usable signals (ten or twenty trials can suffice). Finally, several steps of processing have to be applied on the pupillometry and EEG signals before being interpreted.

Behavioral and subjective measures can easily be used among several populations, such as older hearing-impaired patients and healthy young adults. As cortical and pupil responses can also be collected via EEG and pupillometry among these populations, some considerations can be noted. EEG experimental set ups are relatively heavy (even more if they are coupled with pupillometry) and experiments usually last several hours. Such conditions can be really exhausting on participants (even more so on older hearing-impaired people) and then influence their cognitive

and arousal state. Pupillometry experiments however, imply less complex set ups and are shorter (they usually last around one hour), and thus can be less fatiguing for participants. Nevertheless, as aforementioned, extra caution have to be accorded to the processing of the pupil signal among older hearing-impaired patients.

Subjective, behavioral and objective measures presented in the different studies, allowed us to assess listening effort in both a word-in-noise recognition task and a tone (embedded in noise) discrimination task. Top-down attentional processes were observed in both tasks, even though we used shorter and simpler stimuli than sentences that are usually used in studies investigating listening effort. As we could observe attentional processes linked to listening effort in our data using EEG and pupillometry, these techniques have also been shown to be useful to capture the working-memory processes of listening effort (Obleser et al., 2012; Zekveld et al., 2019).

According to the results presented in this thesis, each measure seems then to contribute in its own manner in the assessment of listening effort, and complement each other regarding the understanding of effortful listening, during different tasks and among distinct populations.

4.3 Conclusion

This thesis focused on the investigation of listening effort using several measures (subjective, behavioral and physiological). This work highlighted the relevance of the use of pupillometry and its contribution for the study of listening effort among hearing-impaired patients and healthy young listeners. It also allowed for new insights on the use and processing of the pupillometric signal to properly explore effortful listening. Moreover, we showed the complementarity of subjective, behavioral and objective measures during the assessment of listening effort, each thought to tap into a specific aspect of listening effort, supporting the idea that listening effort is a multidimensional construct, and cannot probably be outlined with only one measure.

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Appendix A

Publications and scientific communications

International peer reviewed journal

- Seropian L., Ferschneider M., Cholvy F., Micheyl C., Bidet-Caulet A., Moulin A. (2021). Comparing methods of analysis in pupillometry: application to the assessment of listening effort in hearing-impaired patients. *Heliyon* (Under Review)

International congresses

- Seropian L., Popieul J., Soares-Boucaud I., Moulin A. Towards a French language version of the Children's Listening and Processing Skills Scale (ECLiPS). Poster selected for poster discussion at the 14th congress of the European Federation of Audiological Societies, 22-25 May 2019, Lisbon (Portugal). Abstract published in *Journal of Hearing Science*, 2019; 9(1) Supplement: 144:: ID: 03825 – P034.
- Seropian L., Ferschneider M., Cholvy F., Gallego S., Micheyl C., Moulin A. Pupillometry : new insights to effectively assess listening effort in hearing impaired people. Poster selected for poster discussion at the 14th congress of the European Federation of Audiological Societies, 22-25 May 2019, Lisbon (Portugal). Abstract published in *Journal of Hearing Science*, 2019; 9(1) Supplement: 149-150:: ID: 03901 – P079.

- Seropian L., Ferschneider M., Cholvy F., Gallego S., Moulin A. Self-reported listening effort measured by an extended version of the Effort Assessment Scale (EEAS). Poster presented at the 14th congress of the European Federation of Audiological Societies, 22-25 May 2019, Lisbon (Portugal). Abstract published in *Journal of Hearing Science*, 2019; 9(1) Supplement: 170:: ID: 03902 – P127.

National congresses

- Seropian L., Ferschneider M., Cholvy F., Gallego S., Michey C., Bidet-Caulet A., Moulin A. Pupillometry: new insights to effectively assess listening effort in hearing-impaired patients. Oral communication at the Congress of the Psychophysiology and Cognitive Neuroscience Society, 12-13 December 2019, Toulouse (France).
- Seropian L. Study of listening effort in normally hearing and hearing-impaired individuals using a combination of subjective and objective techniques. Flash talk at the NSCo doctoral school scientific day, 16 May 2019, Lyon (France).
- Seropian L., Ferschneider M., Cholvy F., Gallego S., Michey C., Bidet-Caulet A., Moulin A. Comparing methods of analysis in pupillometry: application to the assessment of listening effort in hearing-impaired patients. Poster presented at the online NSCo doctoral school scientific day, 29 January 2021.

Appendix B

Towards a French language version of the Children's Listening and Processing Skills Scale (ECLiPS)

Children with auditory processing disorders (APD), although displaying normal or near-normal hearing acuity, encounter listening difficulties characterized by poor perception of speech and non-speech sounds according to the British Society of Audiology (2018). Understanding speech in noisy environments, problems in locating the source of a signal, fail to response correctly to verbal information, frequently asking for repetition of information, reduced attention to auditory information and easy distraction are frequently reported symptoms of APD (American Academy of Audiology, 2010). Barry and Moore (2015) developed a scale to evaluate children's listening and processing skills (The Evaluation of Children's Listening and Processing Skills (ECLiPS)), that has been designed to be filled by a parent (or an adult close to the child). As there is no standard reference for the assessment of APD yet, the ECLiPS showed a possible role in supporting the assessment of children referred for APD (Barry et al., 2015). The scale has been validated and normed in English in the United Kingdom. This study aimed at validating a French language version of the scale. A French language version of the ECLiPS (F_ECLiPS) was first elaborated, then a pilot study was conducted during a French annual event aimed at people involved in learning disabilities. Sixty-seven participants (53 parents) completed the questionnaire. The group of 28 children diagnosed with speech language impairment and/or dyslexia reached a clear pathological score, and all the individuals

without learning disorders showed a normal score according to UK ranges. Overall, the F_ECLiPS was very well perceived by all respondents. The follow-up of this pilot study includes establishing French norms by age, including children below 6 years of age.

ID: 03825 - P034

Towards a French language version of the Children's Listening and Processing Skills Scale (ECLiPS)

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Key-words: Cultural adaptation of health related questionnaires; children's listening skills; Speech language impairment

Background: The Evaluation of Children's Listening and Processing Skills (ECLiPS) is a scale created by J. Barry and D. Moore which assesses listening and communication difficulties among children aged between 6 and 11. It has been designed to be filled by a parent or anyone close to the child (a teacher for instance). The scale is composed of 38 items phrased as statements of behaviors observable on a daily basis. The person completing the ECLiPS is asked to rate on a 5-point scale the extent to which they agree or disagree with each statement. The scale has been validated and normed in English in the United Kingdom. This study aims to validate a French language version of the scale, adapted to French culture.

Material and methods: A French language version of the ECLiPS (F_ECLiPS) was obtained, in agreement with the latest European guidelines pertaining to cultural adaptation of health related questionnaires. We used a translation committee and a focus group. In a pilot study, we asked people attending a French annual event aimed at people involved in learning disabilities (mostly families), to complete anonymously the F_ECLiPS on site. We added a 6-item questionnaire, rating from 0 to 10 how well participants perceived the F_ECLiPS, including duration, difficulty, relevance of the items, and global presentation.

Results: Sixty-seven participants (53 parents) completed the questionnaire. The mean duration of the F_ECLiPS completion was less than 7 minutes (SD=2 min). The relevance of the items was rated 7.5 (SD=2.7). For the 53 children aged between 6 and 11, the raw scores have been converted to normative scores, according to the UK norms. The scores concerning the group of 28 children diagnosed with speech language impairment and/or dyslexia reached a clear pathological score: 3.64 (SD=2.13) and all the individuals without learning disorders showed a normal score according to UK ranges. The normed global score was related to the rating of the ecological aspect: The greater were the difficulties identified by the ECLiPS, the more relevant the items were considered, suggesting that the chosen items were effectively pointing out challenging situations.

Conclusion: The F_ECLiPS was very well perceived by all respondents. The follow-up of this pilot study includes establishing French norms by age, including children below 6 years of age.

ID: 03831 - P035

Test-retest reliability of SinB as a screening tool for auditory processing disorders

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Keywords: auditory processing disorder, screening techniques, validation, pediatric audiology, speech-in-babble.

Background: The Greek Speech-in-Babble (SinB) recognition test is a novel speech-in-noise test that was lately evaluated under controlled audiology laboratory conditions, to be a valid tool for the assessment of central auditory processing competence. The current study aims to further explore its validity, this time as a screening tool, by estimating its test-retest reliability under appropriate conditions.

Material and methods: Ten health professionals coming from various disciplines administered the SinB test twice, under conditions similar to those encountered when using it as a screening tool, and test-retest reliability was assessed. Ninety-three Greek-speaking individuals; adults and children aged five years old and more, served as our study sample. The time interval between the two testing sessions ranged from two weeks to two months. The intraclass correlation coefficient (ICC) was calculated as the primary outcome measure.

Results: For the right ear, the average intraclass correlation coefficient (ICC) was 0.858 with a 95% confidence interval (CI) between 0.786 and 0.906, results consistent with 'good' to 'excellent' reliability. Slightly better conditions apply for the left ear, as the average ICC was 0.873 with 95% CI from 0.89 to 0.916, which shows 'excellent' reliability.

Conclusions: Our results suggest that the test may be effectively used, under analogous conditions, to evaluate a subject's hearing abilities in background competition. It could be thus used as a screening tool for populations considered as being at increased risk for Auditory Processing Disorders

Conflicts of interest: None declared.

ID: 03883 - P036

Detection and treatment of children with auditory processing disorder in Republic of Serbia

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Key word: auditory processing disorder, speech and language pathology

Towards a French language version of the Children's Listening and Processing Skills Scale (ECLiPS).

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Background

The Evaluation of Children's Listening and Processing Skills (ECLiPS) is a scale created by J. Barry and D. Moore which assesses listening and communication difficulties among children aged between 6 and 11¹. It has been designed to be filled by a parent or anyone close to the child (a teacher for instance). The scale has been validated and normed in English in the United Kingdom². This study aims to validate a French language version of the scale, adapted to French culture.

Methods

Prononce mal certains mots.

Par exemple - panier/poignet, mouton/bouton, jupe/zupe¹

Comprend mal quand vous vous adressez directement à lui/elle.

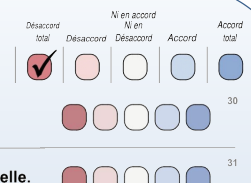


Figure 1: Example items translated to French language and adapted color code. Items: "Says some words wrong / For example - soldier/shoulder", "Mishears what you say directly to him/her". Color code: Strongly disagree to Strongly agree.

- A French language version of the ECLiPS (F_ECLiPS) was obtained, in agreement with the latest European guidelines³ pertaining to cultural adaptation of health related questionnaires. We used a translation committee and a focus group.
- The scale is composed of 38 items phrased as statements of behaviors observable on a daily basis. The person completing the F_ECLiPS is asked to rate on a 5-point scale the extent to which they agree or disagree with each statement.
- In a pilot study, we asked people attending a French annual event aimed at people involved in learning disabilities (mostly families), to complete anonymously the F_ECLiPS on site. We also added a 6-item questionnaire, rating from 0 to 10 how well participants perceived the F_ECLiPS, including duration, difficulty, relevance of the items, and global presentation.
- We also asked parents of 5 to 6 years old children in reception year to complete the questionnaire, to test whether the F_ECLiPS could be helpful to children below 6 years of age.

Results

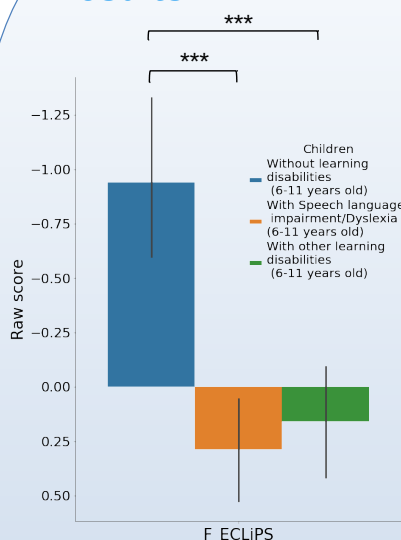
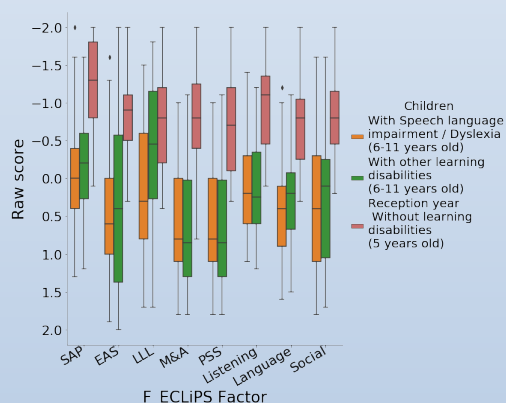


Figure 2: Global raw scores for three groups of 6 to 11 years old children with (N=47) and without (N=10) diagnosed learning disabilities. Black lines represent confidence intervals.

Raw scores are obtained by scoring items as follows: Strongly agree = 2, Agree = 1, Neither agree or disagree = 0, Disagree = -1, Strongly disagree = -2. The more parents "strongly agree" with items, the more the child is likely to experience processing difficulties on a daily basis.

Figure 3: Box plots comparing raw scores for each ECLiPS factors: Speech & Auditory processing (SAP), Environmental & Auditory Sensitivity (EAS), Language/Literacy/Laterality (LLL), Memory & Attention (M&A), Pragmatic & Social Skills (PSS), Listening, Language and Social. Boxes represent inter quartile ranges with medians. Black dots represent "outliers".



The scores concerning the group of children diagnosed with speech language impairment and/or dyslexia, as well as children with other learning disabilities, reach a clear pathological score whilst individuals without learning disorders show a normal score (Fig 2). This result is also confirmed for each ECLiPS factor compared for children with learning disabilities and children in reception year (Fig 3).

Conclusion

The F_ECLiPS was very well perceived by all respondents. The follow-up of this pilot study includes establishing French norms by age, including children below 6 years of age.

Results

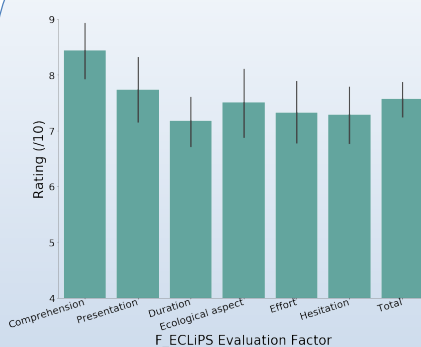


Figure 4: F_ECLiPS ratings given by participants (parents or close to the child, N=74) for each factor and F_ECLiPS global rating. Black lines represent confidence intervals.

- The mean duration of the F_ECLiPS completion is around 7 minutes (SD=2min). Comprehension and ecological aspect of items were very well rated (mean = 8.4/10, SD = 2.4 and mean = 7.5/10, SD = 2.6 respectively).
- A relation was observed between the global score and the rating of the ecological aspect of items. The greater were the difficulties identified by the ECLiPS, the more relevant the items tended to be considered ($r=0.21$, $p<0.09$), suggesting that the chosen items were effectively pointing out challenging situations.

References

- Barry, J. G., & Moore, D. R. (2014). Evaluation of Children's Listening and Processing Skills (ECLiPS). London, United Kingdom: MRC-T.
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