Characterization of audiovisual binding and fusion in the framework of audiovisual speech scene analysis

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ABSTRACT

The present doctoral work is focused on a tentative fusion between two separate concepts: Auditory Scene Analysis (ASA) and Audiovisual (AV) fusion in speech perception. We introduce "Audio Visual Speech Scene Analysis" (AVSSA) as an extension of the two-stage ASA model towards AV scenes, and we propose that a coherence index between the auditory and the visual input is computed prior to AV fusion, enabling to determine whether the sensory inputs should be bound together. This is the "two-stage model of AV fusion". Previous experiments on the modulation of the McGurk effect by AV coherent vs. incoherent contexts presented before the McGurk target have provided experimental evidence supporting the two-stage model. In this doctoral work, we further evaluate the AVSSA process within the two-stage architecture in various dimensions such as introducing noise, considering multiple sources, assessing neurophysiological correlates and testing in different populations.

A first set of experiments in younger adults was focused on behavioral characterization of the AV binding process by introducing noise and results showed that the participants were able to evaluate both the level of acoustic noise and AV coherence and to monitor the AV fusion accordingly. In a second set of behavioral experiments involving competing AV sources, we showed that the AVSSA process enables to evaluate the coherence between auditory and visual features within a complex scene, in order to properly associate the adequate components of a given AV speech source, and provide to the fusion process an assessment of the AV coherence of the extracted source. It also appears that the modulation of fusion depends on the attentional focus on one source or the other.

Then an EEG experiment aimed to display a neurophysiological marker of the binding and unbinding process and showed that an incoherent AV context could modulate the effect of the visual input on the N1/P2 component. The last set of experiments were focused on measurement of AV binding and its dynamics in the older population, and provided similar results as in younger adults though with a higher amount of unbinding. The whole set of results enabled better characterize the AVSSA process and were embedded in the proposal of an improved neurocognitive architecture for AV fusion in speech perception.

RESUME

Cette thèse porte sur l'intégration de deux concepts : l'Analyse de Scènes Auditives (ASA) et la fusion audiovisuelle (AV) en perception de parole. Nous introduisons "l'Analyse de Scènes de Parole Audio Visuelles" (AVSSA) comme une extension du modèle à deux étages caractéristique de l'ASA vers des scènes audiovisuelles et nous. proposons qu'un indice de cohérence entre modalités auditive et visuelle est calculé avant la fusion AV, ce qui permet de déterminer si les entrées sensorielles doivent être cognitivement liées : c'est le « modèle à deux étages » de la fusion AV. Des expériences antérieures sur la modulation de l'effet McGurk par des contextes AV cohérents vs. incohérents présentés avant la cible McGurk ont permis de valider le modèle à deux étages. Dans ce travail de thèse, nous étudions le processus AVSSA au sein de l'architecture à deux étages dans différentes dimensions telles que l'introduction de bruit, le mélange de sources AV, la recherche de corrélats neurophysiologiques et l'évaluation sur différentes populations.

Une première série d'expériences chez les jeunes adultes a permis la caractérisation du mécanisme de liage AV en introduisant du bruit et les résultats ont montré que les participants étaient en mesure d'évaluer à la fois le niveau de bruit acoustique et la cohérence AV et de contrôler la fusion AV en conséquence. Dans une deuxième série d'expériences comportementales impliquant une compétition entre sources AV, nous avons montré que l'AVSSA permet d'évaluer la cohérence entre caractéristiques visuelles et auditives dans une scène complexe, afin d'associer les composants adéquats d'une source de parole AV donné, et de fournir pour le processus de fusion une évaluation de la cohérence de la source AV extraite. Il apparaît également que la fusion dépend du focus attentionnel sur une source ou l'autre.

Puis une expérience EEG a cherché à mettre en évidence un marqueur neurophysiologique du processus de liage-déliage et a montré qu'un contexte AV incohérent peut moduler l'effet de l'entrée visuelle sur la composante N1 / P2. Une dernière série d'expériences a été axée sur l'évaluation du liage AV et de sa dynamique dans une population âgée, et a fourni des résultats similaires à ceux des adultes plus jeunes mais avec une plus grande dynamique de déliage. L'ensemble des résultats a permis de mieux caractériser le processus AVSSA et a été intégré dans la proposition d'une architecture neurocognitive améliorée pour la fusion AV dans la perception de la parole.

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ASA	Auditory Scene Analysis
AV	Audio Visual
AVSSA	Audio Visual Speech Scene Analysis
CASA	Computational auditory scene analysis
CI	Cochlear implants
EEG	Electroencephalogram
ERP	Event-related potentials
FLMP	Fuzzy Logical Model of Perception
MEG	Magnetoencephalography
MMN	Measured mismatch negativity
PACT	Perception-for-Action-Control Theory
PET	Positron emission tomography
RSVP	Rapid Serial Visual Presentation
SNR	Signal-to-noise ratio
STS	Superior temporal sulcus
TMS	Transcranial magnetic stimulation
VPAM	Vision Place Auditory Mode
WFLMP	Weighted Fuzzy Logical Model of Perception

Chapter 1

1. INTRODUCTION

In normal communication, speech is regularly heard in various types of background noise, which may mask the signal or compete for the attention of the listener. However, in most of the cases, speech perception will occur in an effortlessness manner in normal hearing population (that is the "cocktail party effect"). As Cherry (1953) explained, the cocktail party effect is a psychoacoustic phenomenon that enables the individual to attend selectively and identify one source of auditory input in a noisy environment. There are numerous attempts to explain this complex phenomenon from various backgrounds that include cognitive psychology, psychophysiology, neurobiology, physiology, biophysics, information technology, and engineering. In the cognitive psychology domain, the Auditory Scene Analysis (ASA) framework developed by Bregman (1990) has led to conceive the complex auditory processing of speech within a two-stage model of auditory perception.

The visual modality may also intervene in speech perception, particularly in adverse conditions – and the "cocktail party effect" generally involves the vision of the speaking partner. Audiovisual (AV) speech perception has been the focus of a large series of experimental and theoretical studies in the last thirty years, and led to the development of various models, which are all typically one-stage, from unisensory feature extraction to bimodal fusion and decision.

Our underlying framework consists in attempting to combine these two research fields into a single "Audiovisual Speech Scene Analysis" (AVSSA) architecture, based on what we call a "two-stage model of AV speech perception". The present work intends to further

explore this architecture experimentally in various directions. In the following of this introduction, we will successively review a number of facts and questions about ASA and AV speech perception. Then we will present our "two-stage model" and introduce the major questions and directions of this doctoral work.

1.1 AUDITORY SCENE ANALYSIS (ASA)

1.1.1 Primitives and schemas

ASA begins with a first stage in which the acoustic input is decomposed into a collection of time-frequency regions to which one can automatically attach "primitives" that are primary featural properties (e.g. in pitch, time, location, timbre, loudness). Global properties of continuity or coherence in one or the other primitive enable to group some of these time-frequency regions into possible coherent streams (groups). In a second stage, candidate organizations undergo a competitive process within which prior knowledge, context and/or task demands may operate, and the selected source is further processed and finally perceived. The ASA architecture put forward by Bregman explicitly capitalizes on the Gestalt laws of perceptual organization (Koffka, 1935) which are the basis for Visual Scene Analysis. The initial grouping process is based on primitives that are derived from Gestalt principles exploiting physical similarity, temporal proximity, spectro-temporal continuity, and more generally any cue related to "common fate". This primitive stage is considered pre-attentive and based on automatic bottom-up stream segregation.

Most of Bregman's works and studies by many others in the corresponding period typically from the 1980s to the 2000s were mainly focused on the characterization of primitives and automatic bottom-up stream segregation. The initial primitive-based grouping processes can be broadly classified as sequential grouping cues and simultaneous grouping cues. Sequential grouping cues (or temporal grouping) operate across time and are determined by similarities/continuities from one moment to the next which are available in the spectrum

(Bregman, 1990). Simultaneous grouping cues (or spectral grouping) operate across frequency in a given region of time and allow to group together simultaneous frequency components that come from a single source. A classical illustration of sequential grouping that consists of a sequence of tones with a particular pattern of time/frequency separation is displayed in Figure 1-1 (Bregman and Campbell, 1971; Van Noorden, 1975). In this auditory scene, whenever the frequency difference between the tones is small (Figure 1-1, top), perception comprises a single stream. In the case of larger frequency differences (Figure 1-1, bottom), the stimulus will be perceived as two segregated streams (Van Noorden, 1975).

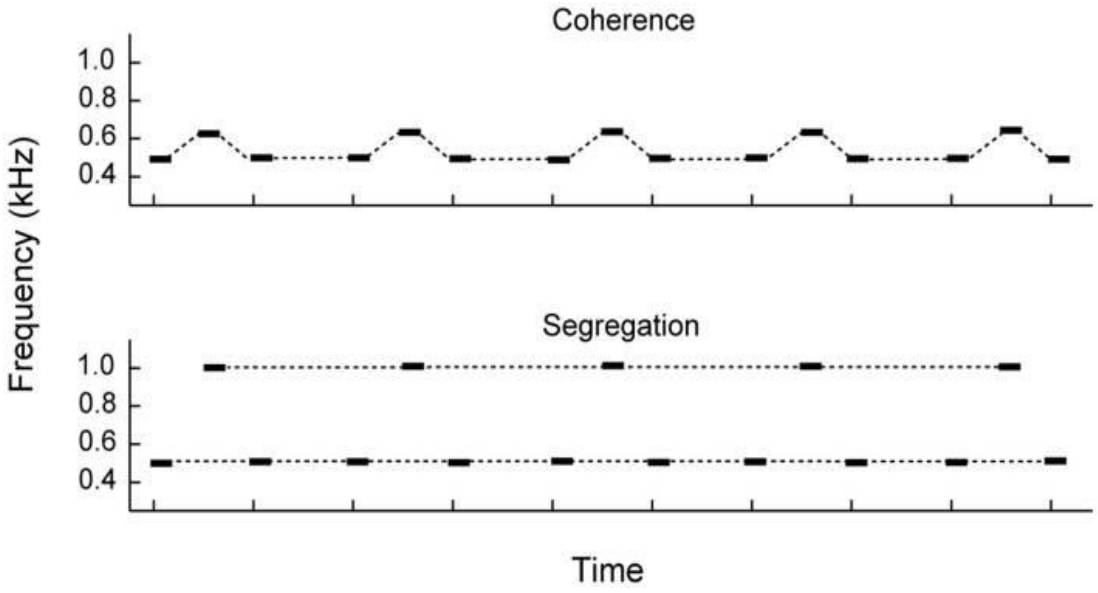

Figure 1-1 Example of an auditory stream segregation experiment. Taken from (Snyder *et al.*, 2012).

However, ASA would also comprise "schemas", that are learned patterns stored in memory, enabling both to extract adequate information from the scene in a top-down process, and to associate the extracted streams to a decision process enabling to attribute meaning to the corresponding acoustic data. This second schema-based decision stage would be permeable to conscious attention, contrary to the first primitive-based grouping stage. The role of schemas and top-down extraction processes could become particularly useful in unfavorable signal-to-noise ratios (SNR) listening situations.

1.1.2 Computational auditory scene analysis (CASA)

The cognitive processes that are supposed to be involved in ASA have inspired since the 80s the development of computational models in the framework of what was called Computational Auditory Scene Analysis "CASA". The objective is to elaborate "machine perception" systems for sound separation with many potential applications including hearing prostheses, noise-robust automatic speech recognition, etc. The goal of CASA is to mimic computationally the ASA process applied on an acoustic scene typically recorded through one or two microphones (Rosenthal and Okuno, 1998). CASA follows the conceptual ASA architecture with two stages consisting of "primitive labeling" which is followed by "grouping" in competing streams before separation or identification of one or several streams. The process typically begins with sound analysis at the level of the peripheral auditory system reproducing time-frequency representation of the auditory activity at the output of the cochlea or within the primary fibers in the auditory nerve. This is followed by the extraction of primitive features such as periodicity, onsets, offsets, amplitude modulation, or frequency modulation. Once extracted, features enable the segmentation of the scene into coherent pieces and then grouping mechanisms hopefully associate segments from the same sound source, and combine them to form a separate sound stream (Wang and Brown, 2006). Specific recognition algorithms may then be applied to the extracted streams taking into account the fact that the information may be incomplete [missing data schemes, glimpsing processes, (Cooke *et al.*, 2001; Cooke, 2006)]. There have been a lot of proposals of CASA systems over the years, varying in their architecture, biological motivation, and grouping process, but all of them obey the two-stage architecture introduced by Bregman and others for defining the ASA mechanisms in auditory perception: firstly extract sources in the scene, secondly identify the extracted sources.

1.2 Role of Vision in Audio Visual Speech Perception

In the process of speech perception, the incoming auditory signal plays a significant role, but other cues are also available, basically visual and also possibly tactile cues. It makes speech perception a multisensory rather than unisensory process, requiring multisensory integration. Whenever the auditory signal is compromised due to external (e.g. noise) or internal factors (e.g. hearing impairment), the additional cues from the visual or possibly tactile modality seem to be always beneficial. In most instances, the presentation of visual stimuli in addition to the auditory input significantly improves the efficiency of speech perception. In the following sections, some of the main aspects of the role of visual cues in AV speech perception will be discussed.

1.2.1 Contribution of visual cues to intelligibility

After a number of informal and qualitative reports about the efficiency of lip-reading in adverse listening condition, the first study quantifying the gain provided by visual cues for speech perception in noise was published by Sumby and Pollack (1954). These authors reported the benefits of visual cues by measuring speech intelligibility at SNRs with and without visual speech information in addition to the auditory signal. They showed that intelligibility scores were improved due to visual speech cues, and this improvement was larger at low SNRs. They concluded that visual cues were mostly utilized in poor SNR conditions associated with lower auditory intelligibility. They claimed that the presence of visual information associated with the sight of the speaker's face would enhance the transmitted signal and hence increase intelligibility, which naturally makes the visual contribution more significant as the SNR is decreased.

These findings were replicated and supported by many similar studies. All of these studies confirmed that listeners with normal hearing benefit from the availability of visual information during speech comprehension tasks whenever auditory information is degraded

(Erber, 1969; MacLeod and Summerfield, 1990; Grant and Braida, 1991; Benoit *et al.*, 1994; Sommers *et al.*, 2005; Ross *et al.*, 2007). The benefit of vision could be due to a number of phonetic cues that are available in the visual signal itself (Summerfield, 1987; Grant and Seitz, 1998; Grant *et al.*, 1998). For example, when acoustic cues in place of articulation of a consonant within a syllable (e.g. /ba/) are degraded, visual cues about bilabial closure available on the speaker's face naturally increase intelligibility. This is what is called "lip-reading" or "speech reading". However, vision can intervene in other ways. For example, Munhall *et al.* (2004) showed that rhythmic facial and head movements may provide cues conveying information about the speech envelope. Indeed, head and eyebrow movements as well as lip, jaw and cheek movements are known to be systematically associated with speech amplitude and fundamental frequency (Munhall *et al.*, 2001; Munhall *et al.*, 2004).

The visual input also appears to be beneficial to speech detection and cue extraction. Listeners are able to better detect speech that is masked by noise when the auditory input is accompanied by its visual counterpart (Grant and Seitz, 2000; Kim and Davis, 2003; Bernstein *et al.*, 2004; Kim and Davis, 2004). In their two first experiments, Grant and Seitz (2000) presented spoken sentences in three conditions: auditory-only (A), AV matched (AV_M) and AV unmatched (AV_{UM}). They found improved detection thresholds only when the audio and visual signals matched. There were no differences between the AV_{UM} condition and the A condition (see Figure 1-2a) for detection thresholds. In the second experiment, similar results were obtained when upcoming auditory stimuli were presented with orthographically matched stimuli (see Figure 1-2b). However, the gain provided by the visual orthographic input was much lower (in the second experiment) than the gain provided by the visually matched lip dynamics (in the first experiment). These results suggest that addition of visual information cued participants about the content of the auditory stream, which was beneficial for detection.

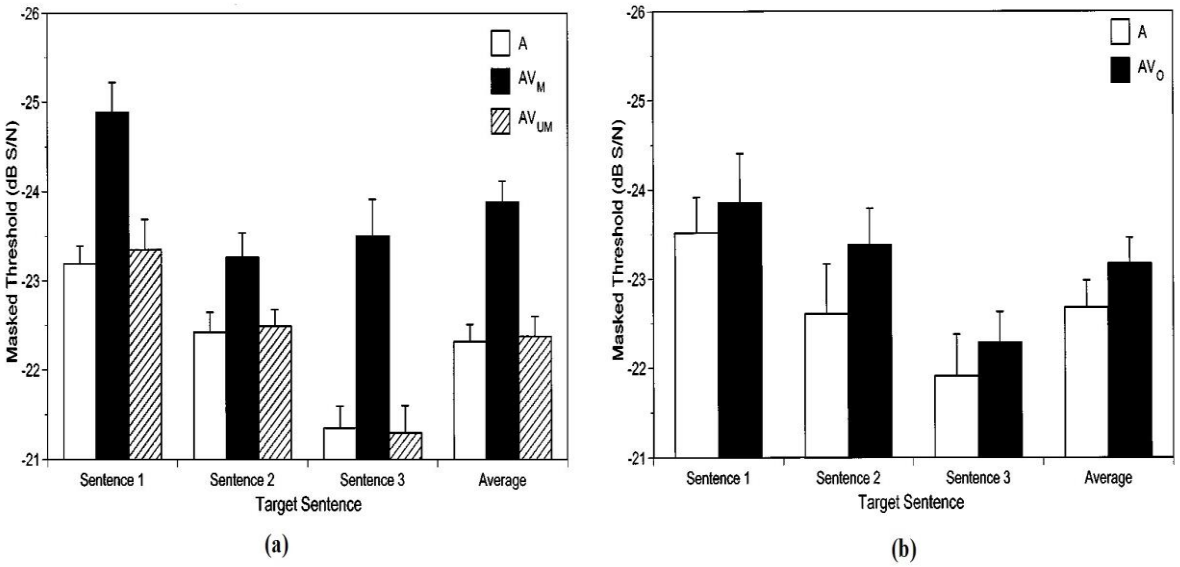

Figure 1-2 Experimental results of Grant and Seitz (2000). a) SNR for speech detection thresholds as a function of listening condition and target sentence. A=audio only; AV_M=matching video; AV_{UM}=unmatched video. b) SNR for speech detection thresholds as a function of listening condition and target sentence. A=audio only; AV_O=matching orthography. Taken from (Grant and Seitz, 2000).

Experiments from Kim and Davis (2003; 2004) and Bernstein *et al.* (2004) provided further confirmation and extension of the effect, showing that it persists even in a foreign language and hence does not depend on understanding speech (Kim and Davis, 2003), while it disappears or decreases for various manipulations of the audio [e.g. time-reversal or replacement by a synthesizer, (Kim and Davis, 2004)] or video input [e.g. replacement of the talker's face by various kinds of non-speech video stimuli driven by the audio envelope, (Bernstein *et al.*, 2004)]. Importantly, Schwartz *et al.* (2004) showed that the enhanced detection of auditory cues thanks to visual timing information also resulted in a gain in intelligibility in noise. They indeed showed that visual information providing no direct lip-reading cue could improve the recognition of a voiced vs. unvoiced plosive in a consonant-vowel syllable thanks to a timing cue enabling the listener to better extract prevoicing.

The speech detection AV advantage provides information about possible levels at which AV interactions might take place in speech processing as it will be discussed in detail in a

next section. It shows that the coherence of AV fluctuations in time may be exploited by the auditory system to detect important auditory information. Interestingly, AV interactions based on the coherence of AV information can operate on the other way round, from audition to vision, as displayed by the study by Alsius and Munhall (2013), in which a visible talking face, hidden to consciousness by a specific trick based on continuous flash suppression, was made visible again thanks to coherent auditory speech material.

The enhancement of speech perception by speech reading can be witnessed even when the signal is clearly audible and intact but difficult to understand [e.g. perception of a native language when presented using a non-native speech accent (Reisberg *et al.*, 1987; Arnold and Hill, 2001)]. Arnold and Hill (2001) showed that the listener comprehension increases with the presence of visual speech information in passages difficult to understand (see also Reisberg *et al.*, 1987). The visual cues increase understanding of non-native language speech sounds even when the target auditory speech is clear (Davis and Kim, 2004; Navarra and Soto-Faraco, 2007). For example, Navarra and Soto-Faraco (2007) showed that native Spanish-dominant bilingual speakers of Spanish and Catalan found it difficult to distinguish the Catalan phonemes /e/ and /ɛ/ in a unisensory auditory task ("phonological deafness"), but with the addition of visual information the listeners did show discrimination ability.

1.2.2 The McGurk effect and its variations with experimental factors

The most widely used stimuli to display AV integration in clear condition is the so-called "McGurk effect". McGurk and MacDonald (1976) discovered this robust multisensory illusion occurring with AV speech, in which the integration of visual information occurs even when the acoustic speech signal is perfectly intelligible and even when observers are completely aware of the possible illusion. In the classical paradigm, an audio bilabial sound /ba/ dubbed onto a visual velar sound /ga/ may be perceived as an alveolar plosive /da/ or a voiced dental fricative /ða/. This phenomenon has now been widely used, in exploring a robust

cross-modal fusion of discrepant inputs and also as a tool for understanding theoretical issues in AV speech perception. The McGurk effect is dependent on many variables, and previous findings provide important information on the variables that alter or eliminate the effect. It can be influenced by many internal factors (e.g. hearing loss) as well as external factors such as noise in audio or visual condition (e.g. auditory noise).

Firstly it varies with the speaker [some speakers provide more visible stimuli than others, see (Cienkowski and Carney, 2002)] and more importantly, it varies with the listener since the McGurk effect is characterized by large inter-subjective variability (Schwartz, 2010). It also depends on the language: for example, Dutch, English, Spanish, German and Italian listeners experience a robust McGurk effect, while it appears weaker for Japanese and Chinese listeners (Sekiyama and Tohkura, 1991; Sekiyama, 1994; Fuster-Duran, 1995; Bovo *et al.*, 2009; Wu, 2009). In the case of hard of hearing populations the size of the McGurk effect increases and individuals with cochlear implants (CI) show a higher McGurk effect than persons with normal hearing (Schorr *et al.*, 2005; Rouger *et al.*, 2008). The susceptibility of the McGurk illusion also varies across age, since young children display a lesser McGurk effect than adults (McGurk and MacDonald, 1976; Massaro *et al.*, 1986; Tremblay *et al.*, 2007; Sekiyama and Burnham, 2008). The McGurk effect seems robust to changes in speaker identity or localization between the auditory and the visual component (Green *et al.*, 1991; Bertelson *et al.*, 1994). However, the effect is decreased when there is asynchrony between the audio and visual input (Massaro and Cohen, 1993; Munhall *et al.*, 1996; Jones and Callan, 2003), though it persists unchanged within a rather large "temporal AV integration window" typically from 100 ms audio lead to 200 ms audio lag (Van Wassenhove *et al.*, 2007).

Importantly, the McGurk effect largely depends on the audibility of the auditory input, related to noise or to the listener's auditory abilities. Indeed, the McGurk effect decreases when the extraneous noise is visual, whereas it increases when the noise is auditory

(Sekiyama and Tohkura, 1991; Sekiyama, 1994; Fixmer and Hawkins, 1998; Kim and Davis, 2011). For example, the addition of auditory noise increased the McGurk effect in the Japanese population and produced a stronger effect than in silence (Sekiyama and Tohkura, 1991). For native speakers of English tested in English language, Hardison (1996) found a similar result in one of their experiments. Fixmer and Hawkins (1998) showed that the rate of McGurk responses increased with auditory noise and decreased with visual noise. These outcomes could receive two different interpretations. Firstly, these results could be due to increased ambiguity of the noisy component, which would automatically decrease its role in the fusion process: this is the "unisensory" hypothesis. In the second, "multisensory" interpretation, noise plays a role at the level of fusion, and produces changes in the respective weights of the auditory and visual input in the fusion process, hence the increase vs. decrease of McGurk responses for noisy auditory vs. visual inputs. These two interpretations will be specifically discussed and tested in Chapter 3.

From this literature, it appears that even though the McGurk is robust in nature, there may appear significant amounts of differences in the strength of the McGurk effect from one experimental condition to another. Altogether, the effect appears as a strong marker of AV fusion and as a powerful paradigm for studying the AV speech perception architecture in the human brain.

1.2.3 Contribution of visual cues in older adults and hearing-impaired listeners

The contribution of visual speech cues also depends on the efficiency of the auditory system, and hence it has been systematically studied in individuals with hearing loss (Walden *et al.*, 1993; Grant *et al.*, 1998; Bernstein *et al.*, 2000; Auer and Bernstein, 2007; Tye-Murray *et al.*, 2007) and in individuals with CI, who are often also trained to utilize visible speech cues to aid comprehension of spoken speech (Lachs *et al.*, 2001; Strelnikov *et al.*, 2009). For example, Walden *et al.* (2001) showed that hearing-impaired individuals with hearing aids

had better comprehension of AV speech stimuli even in an unaided auditory presentation than the aided auditory alone comprehension. Altogether, these studies converge on the fact that since audition is less efficient in these subjects, the role of the visual input appears more important in AV fusion than in normal hearing subjects.

The processing of AV stimuli depends on both peripheral organs and central processing mechanisms. As age increases, there might be significant changes in all sensory systems as well as in the efficiency of cognitive functions (Baltes and Lindenberger, 1997; Pichora-Fuller and Singh, 2006). In spite of a general deficit in the unisensory modalities, the literature suggests that older adults could actually exhibit greater multisensory integration when compared with younger adults (see Mozolic *et al.*, 2012 for review). As in younger adults, the advantage of additional visual information during speech processing has also been displayed in older adults, even though there could be differences in the overall amount of the benefit from the bimodal presentation. Indeed, a number of studies suggest an aging-related increase in the McGurk effect (Thompson, 1995; Behne *et al.*, 2007; Setti *et al.*, 2013). However, the control of the effective auditory receptive level is crucial in these experiments. Indeed, considering what we showed in the previous section about the reinforcement of the McGurk effect and the increased role of the visual input when the amount of auditory noise increases, it is hard to know for sure if the increase in the McGurk effect comes from just a difference in audibility of the stimuli with the hearing loss associated with aging, or from a difference in AV fusion, with an increased weight of the visual input with aging.

However, the difference in McGurk effect between young and older adults was not observed in some well-controlled studies with a precise calibration of the individual auditory SNR ratio (Cienkowski and Carney, 2002; Sommers *et al.*, 2005). Sommers *et al.* (2005) assessed the effect of age on the ability to benefit from AV speech in normal hearing young and older adults. The subjects were presented with consonant, word, and sentence identification

tasks in all three sensory modalities (A, V, and AV). Results displayed no age differences in the ability to benefit from combining auditory and visual speech signals after controlling for age differences in both the visual and the auditory acuity. Other studies obtained a similar pattern of results on AV performance as a function of sensory modality, in which the performance on bimodal condition was better (Walden *et al.*, 1993; Cienkowski and Carney, 2002; Hay-McCutcheon *et al.*, 2005; Tye-Murray *et al.*, 2007). Altogether, these studies converge to claim that older adults benefit from an additional visual signal at a level comparable to younger adults when auditory and visual acuities are adequately controlled.

However, in a recent paper, Sekiyama *et al.* (2014) compared AV speech perception between young and older adults by controlling the variables that had been reported to affect the results of previous results (e.g. age limit and speech material). They conducted two experiments in which the young and older adults were compared either under the same auditory SNRs or in calibrated SNRs. The visual influence was larger in the older adults when it is compared with the younger adults not only in the same SNRs condition, but this effect was seen even in calibrated SNRs. They claim that native Japanese speaking older adults used more visual speech information when compared wuth the younger adults, and were more susceptible to the McGurk effect when tested with stimuli containing equivalently intelligible auditory speech. They correlate this difference in behavior to a slower auditory processing in older subjects, and relate this correlation to the so-called "visual priming hypothesis" according to which the visual contribution would be larger when a subject processes visual speech faster than auditory speech compared to those who process both visual and auditory speech at the same speed (Sekiyama and Burnham, 2008).

Further works have attempted to disentangle the respective contributions of peripheral vs. cognitive processes in multisensory integration in older adults. For example, Laurienti *et al.* (2006) suggest that the aging brain adapts to changes in the sensory organs in order to

enhance as much as possible the robustness of multisensory perception. They compared multisensory speech discrimination scores between older and younger adults. The reaction time was better in older adults for AV stimuli. Similarly, Setti *et al.* (2013) assessed the efficiency of the McGurk illusion in older vs. younger adults. They created McGurk illusions using words, with a higher rate of AV illusions in older adults. Then, they asked participants to recall sentences that were matched with either the unisensory or the McGurk percept. Older adults recalled more "McGurk sentences" than younger ones. This higher susceptibility to the McGurk effect in older adults could be due to perceptual rather than cognitive process. Hugenschmidt *et al.* (2009) assessed the role of selective attention on AV perception with a cued multisensory discrimination task aiming to show that the capacity of multisensory integration can be reduced by attending to a single sensory modality. They found greater multisensory integration in older adults than in younger adults in all conditions and concluded that age-related decline in top-down mechanisms does not affect the integration process. However further studies are needed to assess more in detail the possible role of the cognitive decline in AV integration.

Altogether, the individual variations of the McGurk effect with sensory and cognitive processes associated with age or deafness are hence particularly relevant to better understand how AV interactions proceed in the human brain.

1.3 AV FUSION AND ITS MODELS

The first models of speech processing developed in the second half of the last century were mainly based on the acoustics of speech whereas the potential contributions of the visual speech input were essentially ignored. A number of theories and models emerged in the literature in the last forty years to provide possible cognitive architectures for AV speech integration. The major question in these models concerns the levels at which visual speech information integrates with auditory speech before integration occurs.

1.3.1 Possible architectures for AV fusion

The studies in the 1980s and 1990s considered that AV fusion could be either "early" or "late", that is it would occur earlier or later than the phonological categorization of the speech inputs (for review, Summerfield, 1987; Schwartz *et al.*, 1998). Early fusion would require a pre-phonetic common representation for integration while late fusion would be done at the level of phonemic labels. Based on the literature on sensory interactions in cognitive psychology, and on sensor fusion in information processing, and capitalizing on the previous architectures introduced by Summerfield (1987), Schwartz *et al.* (1998) proposed four basic models of AV speech perception (see Figure 1-3).

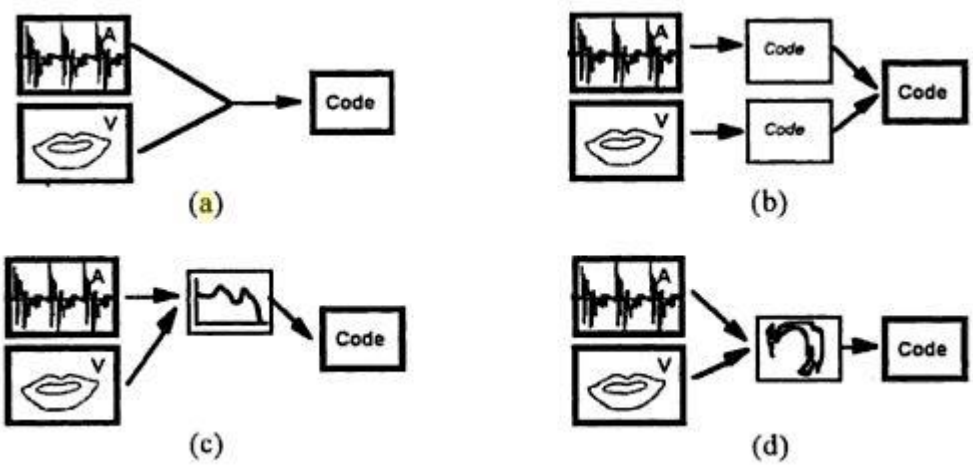

Figure 1-3 The four basic models of AV integration. a) Direct Identification (DI), b) Separate Identification (SI), c) Dominant Recoding (DR), d) Motor Recoding (MR). Taken from (Schwartz *et al.*, 1998).

In a Direct Identification model (Figure 1-3a), AV speech integration coincides with the decision stage. This type of model implies that sensory-specific information is in a common readable format within the integration stage but also simplifies the amount of processing that needs to be achieved from the sensory-specific channels since no transformation is required before the AV decision process applies. This model could be considered as an early model of integration – though with no common representation of the auditory and visual inputs.

In the Separated Identification model (Figure 1-3b), the visual and the auditory inputs are separately recognized through two parallel identification processes. After this process, the fusion of the phonemes or phonetic features across each modality occurs. This is typically a late integration model. Fusion can operate on logical data, such as in the VPAM (Vision Place Auditory Mode) model, which assumes that each sensory channel operates on its specific phonetic features (place of articulation for vision, mode of articulation for audition). It can also process probabilistic data as typically seen in a number of AV speech recognition models [see reviews in (Schwartz *et al.*, 2009)]. The Fuzzy Logical Model of Perception (FLMP) that will be described in the next section belongs to this class of models.

If integration is early, it generally involves a common pre-phonetic representation, with two kinds of possibilities. Assuming a dominance of the auditory system in processing speech inputs, the Dominant Recoding (DR) model (Figure 1-3c) argues that visual information should be recoded in an auditory format (the dominant format) prior to being integrated with the auditory information. In the Motor Recoding Model (Figure 1-3d), the two inputs are projected into a common amodal space (which is neither auditory nor visual). They will be fused within this common space and this amodal space is supposed to be provided by the articulatory space of vocal tract configurations.

Motor Recoding models can be related to general theories invoking a central role of the perceptuo-motor relationship in speech perception. The most well-known are the Motor Theory of Speech Perception (Liberman *et al.*, 1967; Liberman and Mattingly, 1985) and the Direct Realist Theory variant (Fowler, 1986). The major claim of the Motor Theory is that the objects of speech perception are articulatory and not acoustic or auditory events. Articulatory events would be recovered by listeners as neuromotor commands applied to the articulators (referred as “intended gestures”) and not just visible articulatory movements or gestures. However, in the Direct Realist variant, the articulatory objects are real vocal tract

movements, or gestures rather than intended gestures. Both theories utilized the visual nature of speech perception as support and evidence for an amodal – and hence motor – theory of speech perception. Contrary to these theories, Auditory theories are based on the assumption that speech processing is primarily based on acoustic cues and auditory representations while knowledge about the way the articulatory system produces the sound would not play any role in perception (Diehl *et al.*, 2004). For example, the "Acoustic Invariance Theory" by Stevens and Blumstein (1978) assumes the existence of invariant acoustic patterns matching the phonetic features and providing the phonetic framework for the perceptual processing of speech sounds.

Recently, Schwartz *et al.* (2012a) proposed a sensory-motor theoretical framework (see also Skipper *et al.*, 2007) connecting perceptual shaping and motor procedural knowledge in multisensory speech processing and called it "Perception-for-Action-Control Theory" (PACT). Sensory-motor theories consider auditory frames as basic in the communication process but acknowledge the role of the sensory-motor link in the global architecture. According to PACT, speech perception is a group of mechanisms that enable the listener to understand as well as control the speaker's utterances in communication. PACT architecture for speech perception is shown in Figure 1-4. The two basic components in PACT are "developing units" and "extracting units". The "developing units" component (Figure 1-4, sensory-motor maps) is based on co-structuring of the motor and perceptual representations in development. This provides motor information for perception. The "extracting units" component (Figure 1-4, integration) is available for extraction and characterization of elementary pieces of information and would introduce motor knowledge in auditory or multisensory speech processing.

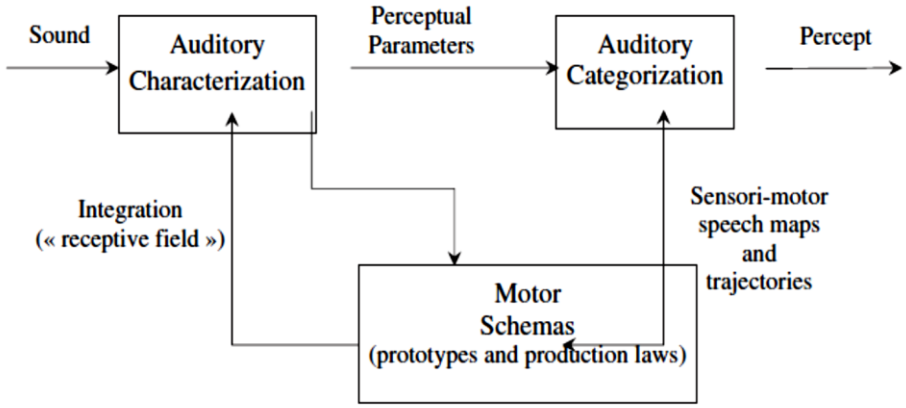

Figure 1-4 A PACT architecture for Speech Perception. Taken from (Schwartz *et al.*, 2012a).

1.3.2 Fuzzy Logical Model of Perception (FLMP)

In the 1980's and 1990's, the Massaro's group extensively studied AV fusion using mathematical modeling. They adapted to AV speech the FLMP that Massaro and colleagues had previously introduced as a very general model of perception, and tested for such problems as reading (Massaro, 1979; Oden, 1979; Massaro and Hary, 1986), auditory recognition of syllables and words, or visual perception (Massaro and Cohen, 1976; Oden and Massaro, 1978). This model progressively became the dominant model in AV speech integration until the late 1990's (Massaro, 1987; Massaro, 1998; Schwartz *et al.*, 2009).

The FLMP consists of three stages, Evaluation, Integration, and Decision (see Figure 1-5). This means that in very general terms, a given perceptual model that exploits a bundle of sensory inputs in order to take decisions about a set of possible labels is supposed to operate always the same: (1) first *evaluate* each sensory input in the likelihood of each label, (2) then *integrate* in a given way the likelihoods provided by each sensor about each label in order to obtain for each label a global likelihood taking into account likelihoods provided by all sensors (3) and finally *decide* in a probabilistic way driven by integrated likelihoods (that is, the probability of selecting a given label at the decision stage is proportional to the integrated likelihood of the corresponding label).

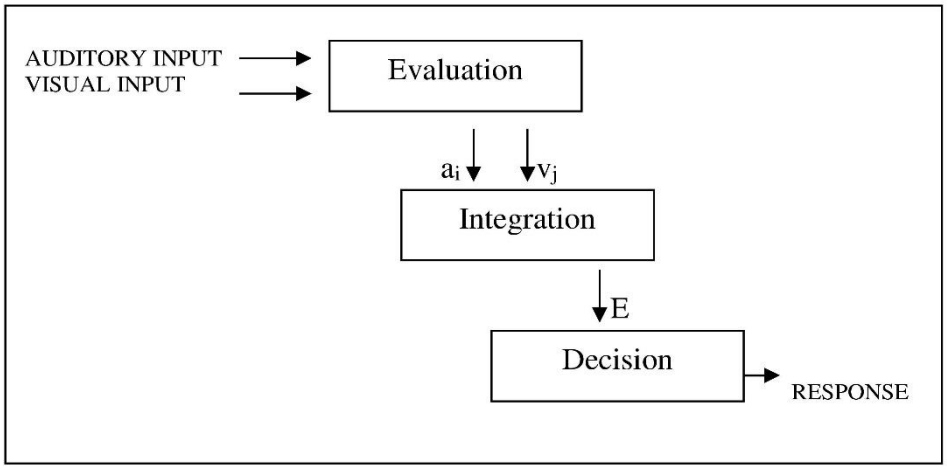

Figure 1-5 Summary of Massaro's FLMP model. Taken from (Chen and Massaro, 2004).

The adaptation of FLMP to AV speech perception was straightforward (Massaro, 1987; 1989; Massaro, 1998). In the first stage, speech sound and sight (vocal movements of the observed speaker) are analyzed in terms of the auditory features (a_i) and visual features (v_j) that are contained in the incoming stimulation. These features consist of degrees of support for each perceptual alternative, that is, a_i expresses the support for alternative (i) from the sound, and v_j the support for alternative (j) from the face. In the second stage, the feature information is integrated so that the decision process in the third stage can make use of the overall evidence (E) to classify the speech sound.

The FLMP, therefore, combines information at the level of degree of evidence for phonemes – which are typically the various alternatives for which evidence is searched within each modality – hence, it is a late integration model. A major characteristic of the FLMP is that the output of the integration process is just a multiplication of unisensory evidence: the AV evidence for phoneme (i) is the product of the auditory and visual evidence, $av_i=a_iv_i$. A consequence is that the final decision process, which provides probabilities of responses for each possible phonemic category, is computed in an automatic way:

$$P_{AV}(i) = av_i / \Sigma_{\square} av_j = a_i v_i / \Sigma_{\square} a_j v_j$$

That is, $P_{AV}(i)$ depends just on unisensory evidence a_i and v_i but not on any other factor such as the listener, the noise in the environment, the context or whatever else. In fact, the equation here above has an important property: if one modality is completely ambiguous, e.g. audition, with all values a_i equal to 1/N where N is the number of possible responses, then the AV probability depends only on the visual input: $P_{AV}(i) = v_i$. This is the way FLMP naturally adjusts its decision toward the decision of the least ambiguous modality.

FLMP has been shown to be efficient at simulating a number of experimental data related to the McGurk effect. This is why it has been so popular in the 90s. However, it received many criticisms related to its property to either over fit or be inappropriate for the purpose of predicting integration (Grant, 2002; Schwartz, 2006; 2010). We will see in the next sections what kinds of problems were posed to FLMP and possible solutions through a variant of FLMP, called WFLMP.

1.3.3 Non-automaticity and influence of cognitive factors on AV perception

AV fusion has long been considered to be automatic (Massaro, 1987; Soto-Faraco *et al.*, 2004). The line of evidence came from observations since McGurk and MacDonald (1976) that subjects experienced the McGurk illusion even when they were aware of the dubbing process. In the Massaro (1987) study, participants presented with an incongruent AV stimulus displayed no change in their responses despite specific instruction to focus on one or the other modality or to use both sources of information.

The hypothesis of automaticity in AV integration was tested by Soto-Faraco *et al.* (2004) in a modified (syllable) speeded classification paradigm. Participants were asked to perform a speeded classification of the first syllable of a disyllabic stimulus while ignoring the second syllable. However, variation in the second syllable happens to delay the subjects' responses, revealing a failure of the selective attention mechanism to focus on the first syllable. Interestingly, McGurk effects introduced in the second syllable also interfered with the speeded clas-

sification task. The authors interpreted this as showing that AV integration occurs prior to attentional selection. Hence, they concluded that these data provided evidence for automaticity.

However, the view on the automaticity of AV fusion has changed over the years (Talsma *et al.*, 2010). Indeed, a number of further studies suggest that AV speech integration can be modulated by attention. First of all, the mere fact that the strength of the McGurk effect seems to depend on language and culture (Sekiyama and Tohkura, 1991; Sekiyama, 1994; Fuster-Duran, 1995; Bovo *et al.*, 2009; Wu, 2009) suggests that fusion is not automatic but rather driven by cognitive biases that may act on the integration process. In a more direct way, a number of studies have manipulated the participants' attention and indeed shown that this influences the McGurk effect (Tiippana *et al.*, 2004; Alsius *et al.*, 2005; Talsma and Woldorff, 2005; Alsius *et al.*, 2007; Soto-Faraco and Alsius, 2007; Talsma *et al.*, 2007; Andersen *et al.*, 2009; Soto-Faraco and Alsius, 2009; Alsius and Soto-Faraco, 2011; Buchan and Munhall, 2011; Tiippana *et al.*, 2011; Alsius *et al.*, 2014).

In the first of these studies, Tiippana *et al.* (2004) attempted to direct the visual attention of the participants to either a face or to a concurrently presented leaf wandering on the face. The stimuli consisted of consonant-vowel-consonant conflicting stimuli designed to elicit the McGurk effect (audio /p/ dubbed on a video /k/, possibly perceived as the McGurk fusion /t/). During each trial, as an utterance was spoken, a semi-transparent leaf floated in front of the speaker's face, near the mouth, without obscuring it. The stimuli were the same in each attention condition; only the instructions differed by condition. In one condition the instructions were to attend to the face, and in the other, the instructions were to attend to the leaf. Tiippana *et al.* (2004) found fewer McGurk responses (i.e. responses differing from the auditory syllable) to incongruent stimuli when subjects were attending to the leaf instead of the face (see Figure 1-6)

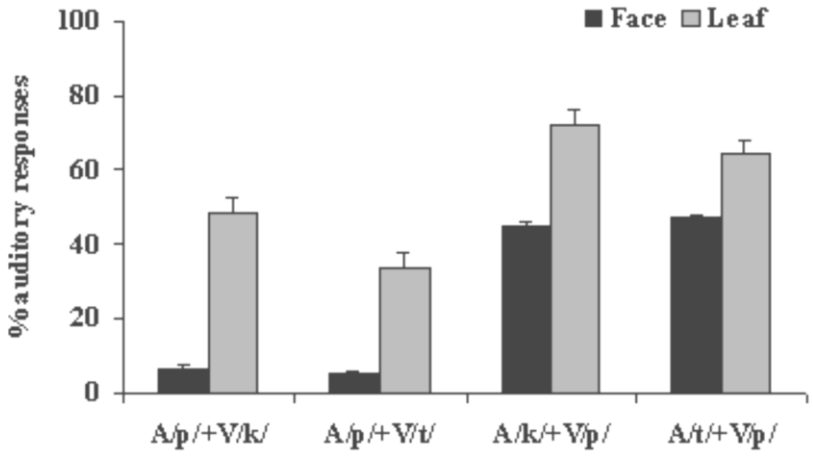

Figure 1-6 Experimental results of Tiippana *et al.* (2004). Percentage of auditory responses for four McGurk stimuli when a face or leaf was attended. Taken from (Tiippana *et al.*, 2004).

While the previous experiment consisted of attempting to divide the subject's attention between two different streams (the face and the leaf) in the scene in a given modality (vision), the strategy of the set of experiments proposed by Alsius, Soto-Faraco and coll. was different. It consisted in loading the AV speech perception task at hand (a classical McGurk paradigm) by asking the participants to perform a second task at the same time. The concurrent task was either auditory or visual (Alsius *et al.*, 2005) or even tactile (Alsius *et al.*, 2007). Interestingly, in all cases, the concurrent task appeared to decrease significantly and to a quite large extent the McGurk effect. The conclusion by the authors is that AV fusion does require a certain attentional state, and an additional cognitive load may decrease this attentional state and, therefore, decrease fusion. A similar conclusion was obtained by Buchan and Munhall (2012) who applied a working memory task in addition to the AV identification task at hand in the McGurk paradigm. Altogether these studies revealed that imposing high demands on the attentional system decreased the amount of AV fusion and hence denied the automaticity of the AV integration process.

1.3.4 Weighted Fuzzy Logical Model of Perception (WFLMP)

The data showing a modulation of the McGurk effect with age, language or attention seem to suggest that fusion is not automatic but rather controlled by the subject in a way depending on her/his cognitive state and cognitive requirements. However, the FLMP appears to be able to simulate the results of all these experiments, by assuming that the modulating factor actually changes the unisensory responses rather than the fusion process. Modulation of the unisensory response can often not be directly shown in the data, which may lead to an apparent contradiction in the interpretation of the experiment (Tiippana *et al.*, 2004). This is where the overfitting abilities of the FLMP play a dramatic role (Schwartz, 2006). This led Schwartz (2010) to introduce a Weighted Fuzzy Logical Model of Perception (WFLMP), in which fusion would also involve specific weights controlling the role of each modality in the fusion process. By comparing FLMP with WFLMP in a sounder model comparison framework based on Bayesian Model Selection rather than a comparison of Root Mean Square Error, Schwartz (2010) was able to show that individual or attentional processes can indeed modulate the McGurk effect. WFLMP then allows to introduce auditory and visual weights in the fusion process, that appear to depend on the subject's individual characteristics (Schwartz, 2010; Huyse *et al.*, 2013), attentional processes (Schwartz, 2010), or degradation of the auditory or visual input (Heckmann *et al.*, 2002; Huyse *et al.*, 2013).

1.4 Neural Correlates of AV Speech Perception

A number of studies have been searching for potential neuroanatomical and neurophysiological correlates of AV integration in speech perception. The development of neuroimaging techniques such as functional magnetic resonance imaging (fMRI), transcranial magnetic stimulation (TMS), positron emission tomography (PET), electroencephalography (EEG), and magnetoencephalography (MEG) has provided considerable improvement of our understanding of the processing of auditory, visual and AV speech in the human brain. In the

context of such modeling questions as the "early" versus "late" nature of AV integration, these studies have provided valuable information enabling to better localize multisensory brain areas and to better specify the temporal sequences of AV information processing.

These developments must be envisioned in the global movement of the neurosciences of multisensory integration, which progressively abandoned their traditional schema considering that perceptual processing stays unisensory in the primary sensory cortices and that multisensory interactions do not happen before the secondary cortices and associative areas. The conception is now completely different, well summarized by the quotation by Driver and Noesselt (2008) that "*In recent years the field of multisensory research has expanded and altered radically with the realization that multisensory influences are much more pervasive than classical views assumed and may even affect brain regions, neural responses, and judgments traditionally considered modality specific*".

1.4.1 Neuroanatomical architectures for multisensory integration

Let us first consider the basic findings of the neuroanatomy of auditory and visual speech perception in the human brain.

Auditory processing begins in the cortex with the Heschl's gyrus, planum temporale and associated auditory cortical regions in the superior temporal gyrus with further processing by anterior and posterior portions of the superior temporal sulcus (STS), before connecting inferior frontal regions through tempo-parietal regions in the "dorsal route" on one hand, and inferior temporal structures in the "ventral route" on the other side (Liegeois-Chauvel *et al.*, 1999; Hackett *et al.*, 2001; Belin *et al.*, 2002; Scott and Johnsrude, 2003; Poeppel *et al.*, 2004; Okada *et al.*, 2010). Visual speech is processed in the early visual areas in the occipital cortex (Ludman *et al.*, 2000; Sekiyama *et al.*, 2003; Hall *et al.*, 2005) before further processing in the posterior STS and then further front in the cortex, in the inferior frontal gyrus and premotor cortex (Puce *et al.*, 1998; Nishitani and Hari, 2002; Ruytjens *et al.*,

2006). Therefore, auditory and visual processing converge in two major sites of the language cortex, the posterior STS within Wernicke's area (supposed to be dedicated to speech comprehension) (Wernicke, 1969) and Broca's area (supposed to be dedicated to speech production) (Keller *et al.*, 2009).

The neuroanatomy of AV speech perception has been explored in many studies in the last 20 years, and these studies converge on a network for multisensory integration that includes cortical regions such as the anterior STS, the posterior STS (including temporal-parietal association cortex), the ventral and lateral intraparietal areas, the premotor cortex, and the prefrontal cortex. The AV integration network also comprises subcortical areas, that are the superior colliculus, claustrum, thalamus (including supra geniculate and medial pulvinar nuclei), and the amygdaloid complex [see Campbell (2008) and Calvert and Thesen (2004) for reviews].

A number of studies on the neural correlates of multisensory integration display the role of the superior temporal cortex for both speech and non-speech stimuli. More specifically, increased activation of the left posterior STS (pSTS) was observed in fMRI as well as TMS studies of the McGurk effect (Sekiyama *et al.*, 2003; Bernstein *et al.*, 2008; Beauchamp *et al.*, 2010; Benoit *et al.*, 2010; Irwin *et al.*, 2011; Nath *et al.*, 2011; Nath and Beauchamp, 2012; Szycik *et al.*, 2012). Beauchamp *et al.* (2010) showed that application of TMS on the left pSTS reduced the McGurk effect. Erickson *et al.* (2014), used fMRI to study brain areas involved in the processing of congruent and McGurk stimuli and distinguished pSTS areas with a specific role in integrating congruent AV signals and pSTG areas possibly involved in correcting incongruent percepts. The implication of the dorsal pathway in the perception of McGurk stimuli has been shown in several studies, including frontal and prefrontal areas, insula and parietal areas (Jones and Callan, 2003; Skipper *et al.*, 2007; Benoit *et al.*, 2010; Irwin *et al.*, 2011; Szycik *et al.*, 2012).

Recent fMRI and EEG studies suggest that AV speech interaction may occur at the earliest functional-anatomic stages of cortical processing (Besle *et al.*, 2004; Van Wassenhove *et al.*, 2005; Okada *et al.*, 2013). In a detailed review study, Ghazanfar and Schroeder (2006) conclude that multisensory integration involves both higher-order association areas as well as unisensory areas which were thought be unisensory in nature. Numerous fMRI studies have indeed reported multisensory interactions at the level of the visual or auditory cortices. Pure lip-reading (i.e., visual speech without auditory stimulation) activates the auditory cortex (Bernstein *et al.*, 2002; Calvert and Campbell, 2003; Hall *et al.*, 2005) and congruent visual speech increases the activity in response to auditory speech in the auditory cortex (Okada *et al.* (2013). These data contradict the traditional view that multisensory interactions do not occur in low-level unimodal sensory cortices.

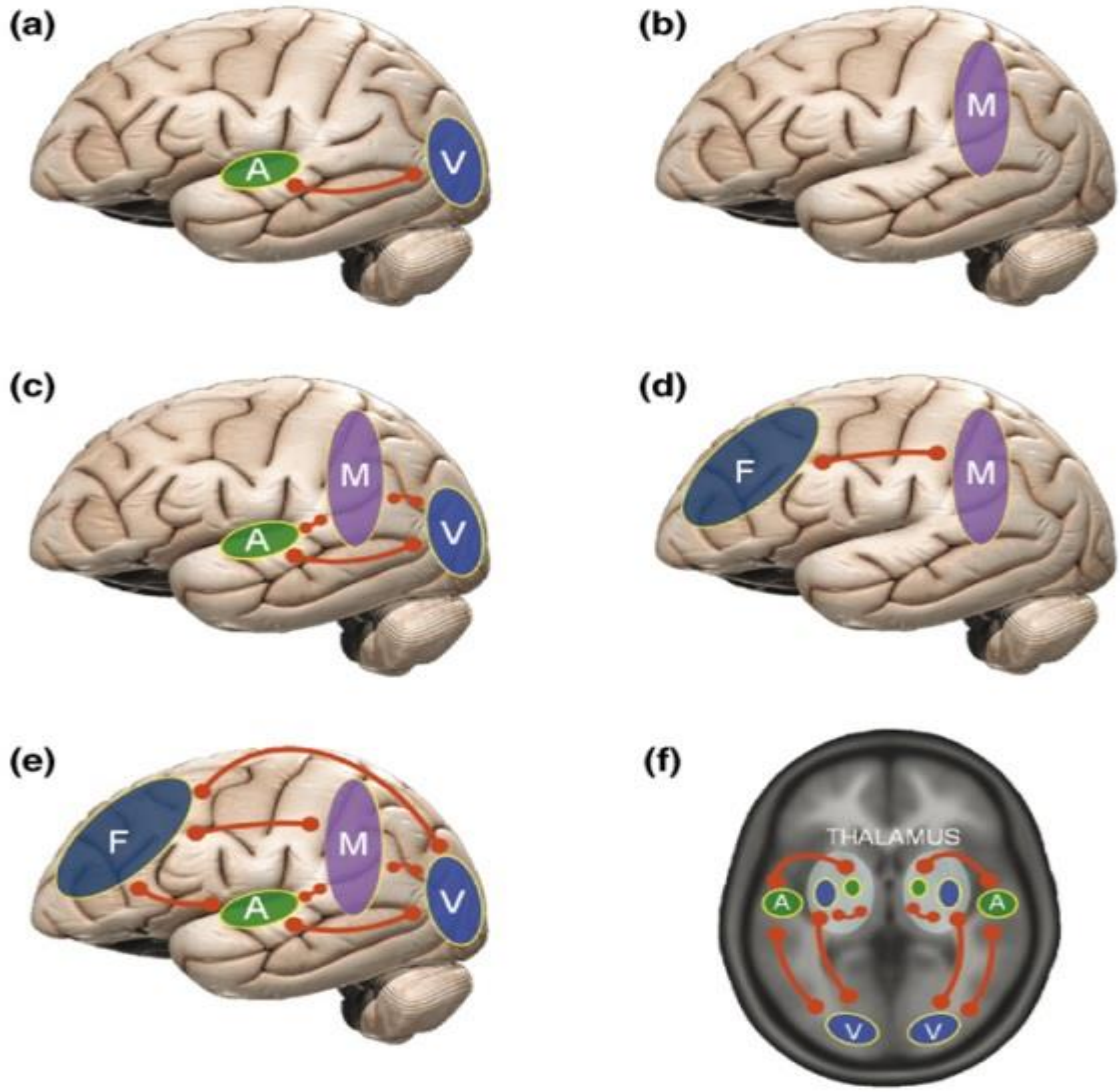

Figure 1-7 Hypothetical scenarios for cross-modal binding. Abbreviations: A = auditory cortex; V = visual cortex; M = higher-order multisensory regions; F = prefrontal cortex. Taken from (Senkowski *et al.*, 2008). See text for further explanation.

Overall, neuroanatomical studies hence indicate that there could be interactions at multiple levels in the brain during multisensory integration. This fits well with the global portrait proposed by Senkowski *et al.* (2008) for dealing with multisensory coherence in the human brain, with several possible scenarios regarding the interaction of "early" and higher-order regions (see Figure 1-7). In a first simple scenario (Figure 1-7a) the primary sensory organs i.e. auditory cortex and visual cortex directly connect for neural synchronization. In another

scenario (Figure 1-7b), multimodal associative regions such as superior temporal or parietal regions would mediate or be in charge of multisensory integration. An interplay between unisensory and associative regions is considered in Figure 1-7c with the neural interaction between unisensory areas associated with increased cortical oscillations in the multimodal regions in the brain. A fourth possible scenario includes the involvement of frontal and pre-frontal regions linked with parieto-temporal regions through an oscillatory coupling (Figure1-7d). Figure 1-7e depicts the most likely configuration, with the participation of all possible areas including higher multimodal cortical areas as well as early unisensory functional-anatomic stages. Finally, subcortical areas (e.g. Thalamic nuclei) could also be involved in the architecture (Figure 1-7f).

If we come back to the various architectures proposed for AV fusion, we could find possible connections between the proposed models and the possible underlying neuroanatomical networks. For example, the Direct Identification or Dominant Recoding models could be related to mechanisms of neural synchronization between unisensory areas (Figure 1-7a). Based on their fMRI study Skipper *et al.* (2005; 2007) also proposed a sensory-motor theoretical model for AV integration associated with a possible underlying cortical network (Figure 1-8).

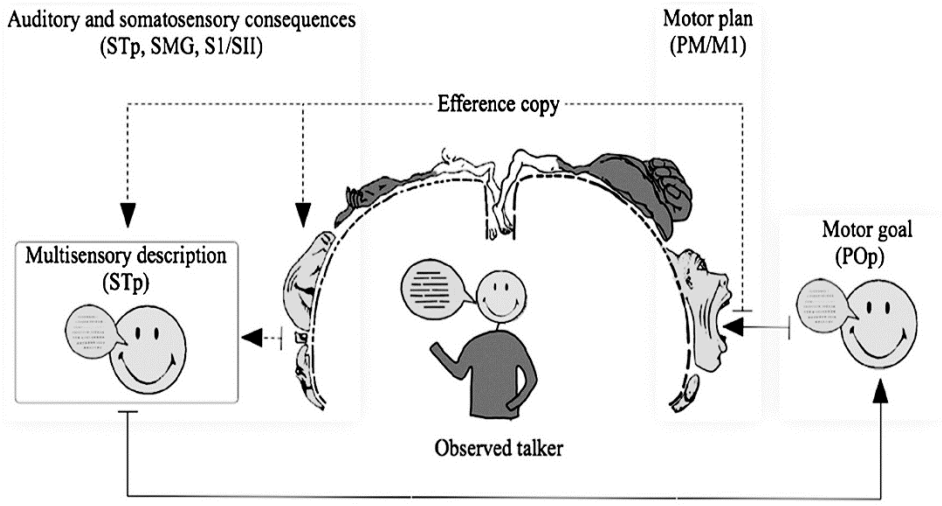

Figure 1-8 Sensory-motor theoretical model for AV integration. Taken from (Skipper *et al.*, 2007).

This model is based on an "analysis-by-synthesis" mechanism which would take place in the dorsal pathway. According to Skipper *et al.* (2007), the cortical regions responsible for processing of speech are "*visual areas, primary auditory cortex (A1), posterior superior temporal (STp) areas, supramarginal gyrus (SMG), somatosensory cortices (SI/SII), ventral premotor (PMv) cortex, and the pars opercularis (POp)"*. According to this model, the processing of speech begins in primary sensory areas such as the auditory and visual cortices, which should lead to multisensory representations as "multisensory hypotheses" in the multisensory STp areas. These "multisensory hypotheses" would specify a motor goal (STp / POp) mapped onto motor commands likely to have produced the observed movement, and these commands would be represented in a somatotopically organized manner, in the ventral premotor cortex PMv and the primary motor cortex M1. The motor commands would then generate predictions of auditory and somatosensory consequences, and these predictions would be combined with the primary hypothesis in (STp) for a final decision.

In summary, the neuroanatomical studies on AV integration suggest the involvement of both primary auditory and visual areas as well as several multisensory areas, with the possibility that pSTS could play a key role in elaborating a common representation before fusion. Furthermore, the involvement of frontal areas associated with motor knowledge suggests the existence of a perceptuo-motor link compatible with perceptuo-motor theories of speech perception (Skipper *et al.*, 2007; Schwartz *et al.*, 2012a)

1.4.2 Neurophysiological correlates of AV perception

Neuroimagery data coming from fMRI and PET provide a clear view of the network of cortical circuits involved in AV integration, but the lack of precise temporal information makes it difficult to derive from this network strong views about the underlying model, and more generally about the time course of AV speech perception. This limitation can be overcome by utilizing electrophysiological tools that measure electrical activity generated by

the neurons during multisensory perception and which ensure good temporal resolution at the level of the millisecond. Recent EEG and MEG studies focused on the influence of the visual input on the auditory event-related potentials (ERPs), notably on auditory N1 (negative peak, typically occurring around 100 ms after the sound onset) and P2 responses (positive peak, typically occurring around 200 ms after the sound onset) considered to be associated with the processing of the physical and featural attributes of the auditory speech stimulus prior to its categorization (Naatanen and Winkler, 1999).

In the last ten years, various studies consistently displayed an amplitude reduction of N1/P2 auditory responses together with a decrease in their onset latency, when the AV response was compared with the audio-only response. These studies generally involved consonant-vowel syllables uttered in isolation, with a natural advance of the visual input (associated with the phonation preparation) on the sound. Their results suggest that the visual input modulates and speeds up the neural processing of auditory ERPs as soon as 100 ms after the sound onset and that AV integration partly occurs at an early processing stage in the cortical auditory speech processing hierarchy (Besle *et al.*, 2004; Van Wassenhove *et al.*, 2005; Stekelenburg and Vroomen, 2007; Arnal *et al.*, 2009; Pilling, 2009; Vroomen and Stekelenburg, 2010; Stekelenburg and Vroomen, 2012; Alsius *et al.*, 2014; Baart *et al.*, 2014; Knowland *et al.*, 2014; Treille *et al.*, 2014a; b).

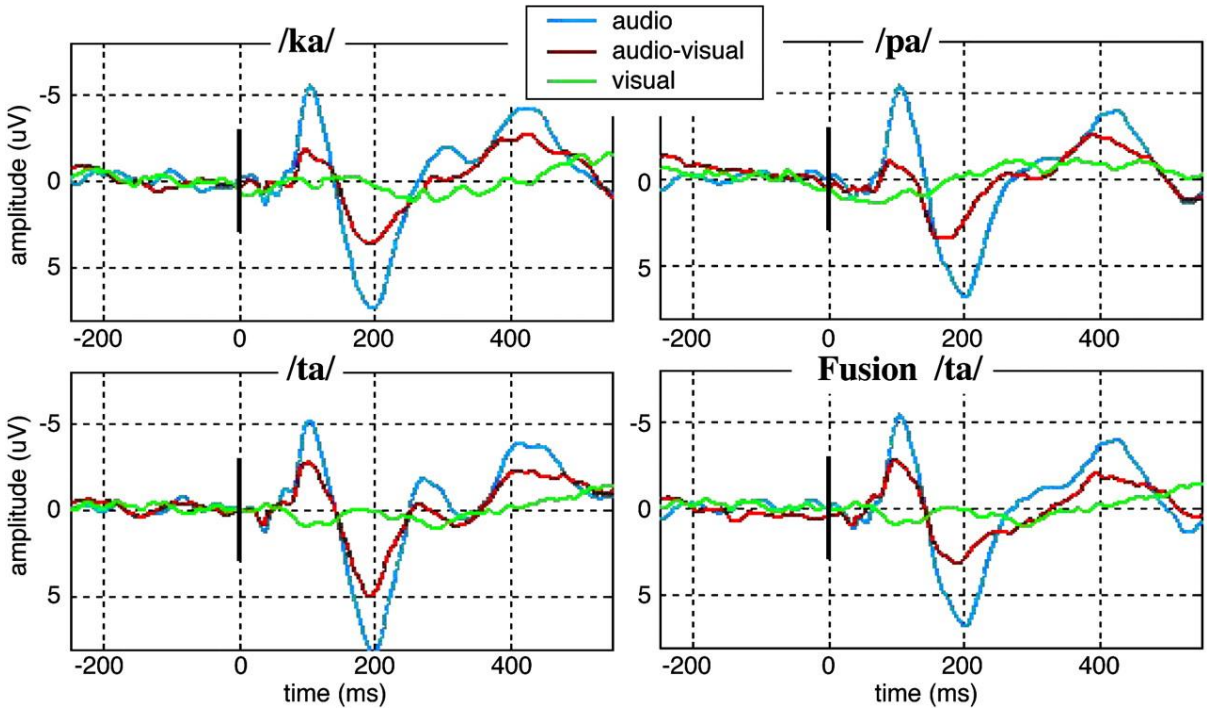

Figure 1-9 Experimental results of Van Wassenhove *et al.* (2005). The graph displays the average ERPs for four stimulus types. AV speech produced faster but smaller auditory ERPs compared to the auditory alone condition. Taken from (Van Wassenhove *et al.*, 2005).

Let us present one of the initial studies in some more detail. Van Wassenhove *et al.* (2005) measured EEG-based ERPs in response to occurrences of the syllables /ka/, /pa/ and /ta/ in audio, visual and AV (both congruent and incongruent) conditions (see Figure 1-9). They found that for the congruent stimuli, N1/P2 in the AV condition had decreased amplitude and shortened latency compared to the audio-only condition. For the incongruent stimuli, N1 and P2 in the AV condition had the same amplitude reduction, but without temporal facilitation. Interestingly, the temporal facilitation was restored in a condition of enhanced visual attention. The interpretation by the authors was that the visual information systematically influenced the key timing properties of the auditory responses, and auditory processing was facilitated when auditory information was reliably predicted from the visual information. The results supported in their view the ‘'Analysis-by-Synthesis” theory of auditory-visual speech perception (see also Skipper *et al.*, 2007) in the framework of theories of “predictive mechanisms” (Rao and Ballard, 1999; Friston, 2009). Such theories predict a

large visual effect on auditory ERP's for stimuli with salient visual dynamics generating strong predictions and large enhancement in syllable detection, as for the bilabial /pa/. On the contrary, we should observe less faciliation whenever the visual cues are weaker and provide a less salient sound predictor such as for the syllable /ka/ where lip movements are small in speech production. This is indeed what was obtained, with a larger effect of the visual input for /pa/ than for /ka/.

The role of temporal synchrony relations in the AV N1-P2 effect has then been clearly demonstrated by the studies of Pilling (2009) and Vroomen and Stekelenburg (2010) who showed that N1 and P2 amplitude modulations was altered with the introduction of temporal asynchronies in AV events. Many later EEG and MEG studies replicated the visual N1-P2 modulation effect, though with possible variations in the precise results.

In one of these studies, Arnal *et al.* (2009) recorded early visual M170, and auditory M100 (the MEG equivalent of the ERP N1/P2 response in EEG) evoked responses for both congruent and incongruent AV stimuli. The obtained data lead them to propose the "dual routing model" including a first direct connection between the visual input and the auditory cortex and a second route – compatible with most neuroanatomical studies – where feedback from STS would mediate the link between the auditory and the visual cortices. The visual reduction in amplitude and latency of the auditory M100 response, rapid and independent of AV congruence, would be based on visual motion cues conveyed by the direct link (first route). In the case of incongruent inputs, detection of incongruence, affecting the auditory responses as soon as 20 ms after latency shortening was detected on M100, suggests that the initial auditory facilitation by vision through the first route could be followed by a feedback signal from the second route. This would correspond to the error between the expected and actual auditory input (prediction error) computed in STS. This analysis was then confirmed by fMRI data showing that functional connectivity between auditory and visual areas was

rather dependent on AV synchrony while functional connectivity between STS and these areas was rather dependent on AV congruence. These results support the existence of multiple levels of multisensory integration in cortical speech processing.

In agreement with the proposal by Arnal *et al.* (2009), the visual modulation seems to obey different rules respectively for N1 and P2. For N1, it would just depend on the predictable advance of the image over the sound, even for incongruent auditory and visual inputs, and even for non-speech stimuli; while the P2 modulation would be speech specific and crucially depend on the phonetic content and congruence of the auditory and visual inputs (Stekelenburg and Vroomen, 2007; Vroomen and Stekelenburg, 2010).

Recently, Alsius *et al.* (2014) studied the effect of attentional load on AV speech perception using N1/P2 components with a Single vs. Dual task paradigm applied on the McGurk effect. In the Single task condition, participants were asked to identify McGurk stimuli regardless of the Rapid Serial Visual Presentation (RSVP) of line drawings, whereas, in the Dual task condition, participants were requested to perform the syllable identification task and also to detect repetitions in the RSVP. The McGurk effect was weaker in the Dual task than in the Single task condition, in agreement with the previous behavioral experiments by Alsius *et al.* (2005). Interestingly, the temporal facilitation of the N1/P2 complex for AV ERPs was smaller in the Dual than in the Single task condition (see Figure 1-10).

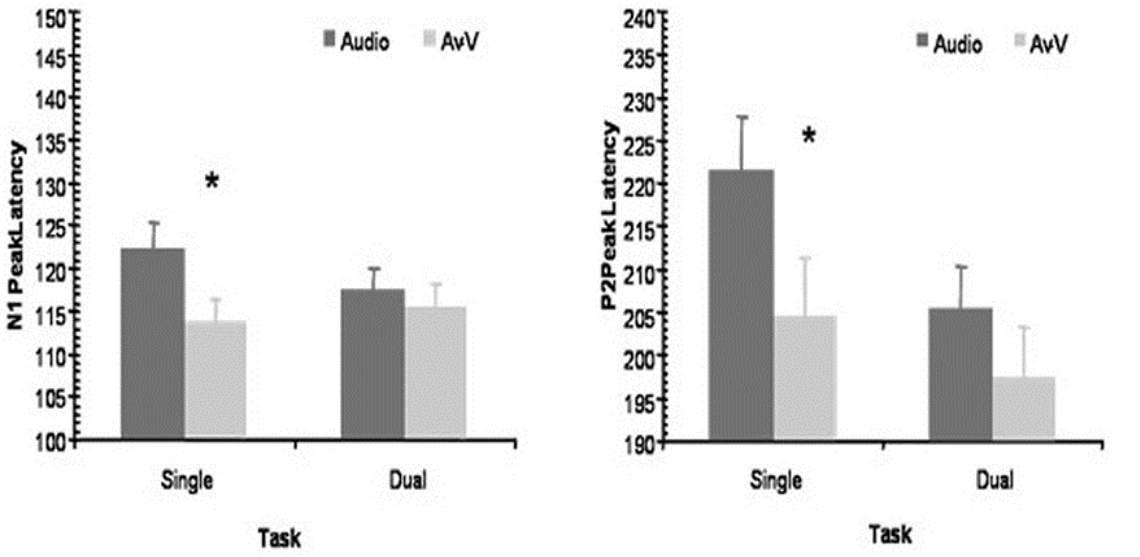

Figure 1-10 Experimental results of Alsius *et al.* (2014). The peak latencies of N1 and P2 were significantly reduced in the AV-V compared with the auditory condition in the Single task condition, but not in the Dual task condition. Taken from (Alsius *et al.*, 2014).

In addition to N1/P2 cortical measurements, the other well-known cortical measurement based on the measured mismatch negativity (MMN) was also exploited in AV speech perception. This paradigm, considered as pre-attentive and automatic, was first used in AV speech by Sams *et al.* (1991) in an MEG study. They elicited robust MMN by presenting congruent stimuli as "standard" stimuli and incongruent stimuli as "deviant" stimuli, though with a fixed auditory input. This was further replicated in EEG (Colin *et al.*, 2002b; Mottonen *et al.*, 2002; Mottonen *et al.*, 2004). Colin *et al.* (2002) suggested that such MMN effects were in favor of the hypothesis that AV interaction occurs at an early and pre-attentive stage in the perceptual process.

Overall, the data from neurophysiological studies indicate that AV interaction occurs at early stages of sensory processing – apart from possible "higher level" interactions. This suggests that there is some level of early integration in AV speech perception, and discard pure "late" integration models – though a combination of early and late stages remains, of course, compatible with experimental data.

1.5 Integrating ASA with AV fusion within a Two-Stage Model of AV Speech Perception

1.5.1 The one-stage architecture of AV speech perception

In most ecological instances the perception of speech is not unisensory but rather involves a multisensory process. Multisensory integration requires our brain to link information from different modalities and bind together coherent information across modalities. The question is to know if a multisensory scene is first perceptually organized modality by modality, before integration operates at a higher level, or if the perceptual organization directly captures the coherence between cues from various modalities for defining the perceptual streams of information.

It is classically considered that the binding process should first operate within each modality before fusion. This is the underlying basis of all current models of AV speech perception, presented in Section 1.3. This is what we call the "one-stage architecture" shown in Figure 1-11, in which the sensory processing is applied independently in the auditory and visual domains, and the fusion/decision process producing the final percept operates at the output of these unisensory cue extraction mechanisms.

Notice that the one-stage architecture stays compatible with the studies putting forward the role of attention in AV fusion: they just show that the fusion/decision stage could be partly regulated by the attentional state of the subject, in relation to any interfering stimulus or task (Tiippana *et al.*, 2004; Alsius *et al.*, 2005; Andersen *et al.*, 2009; Alsius and Soto-Faraco, 2011) (see Figure 1-11).

However, we will explore the assumption that multisensory binding mechanisms could operate before fusion, inducing intersensory interactions at the level of the scene analysis and cue extraction process before the fusion/decision stage.

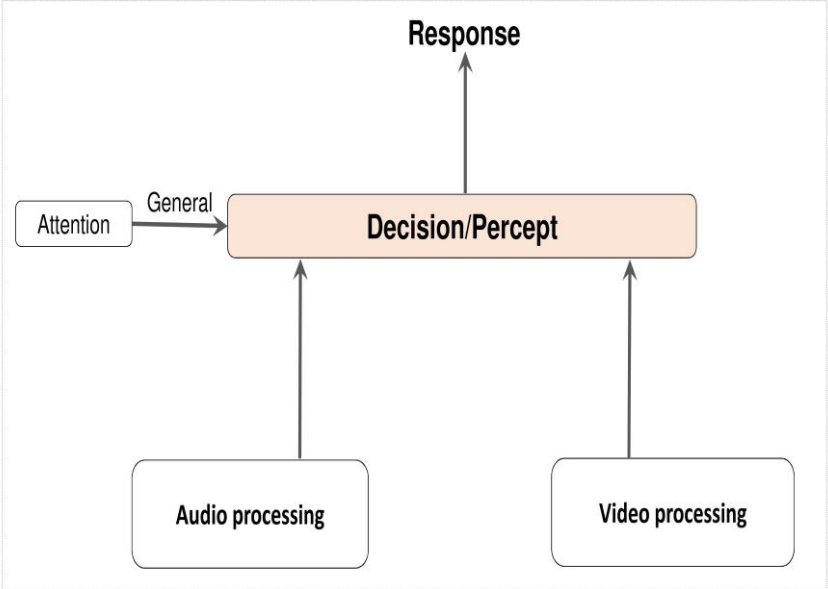

Figure 1-11 The one-stage model for AV fusion in speech perception.

1.5.2 Binding multisensory information in AV scenes

In a recent special issue on multistability, Schwartz *et al.* (2012b) explored the question of multisensory binding in the field of multistable and multisensory patterns. Multistability refers to this phenomenon where a given sensory input may be equally well perceived in two ways, and, in consequence, the brain appears to switch regularly from one percept to the other. The most famous examples come from vision, with the Necker's cube or various figure/ground alternations as the Rubin's vase/face illusion; and with the binocular rivalry effect in which two different images presented one on each eye happen to be perceived in alternation at a more or less regular rhythm. In their introduction to the special issue, Schwartz *et al.* (2012b) recalled that multistability may occur in other sensory modalities such as audition (Denham and Winkler, 2006; Pressnitzer and Hupé, 2006) and explored the question of multisensory competing percepts.

It appears that multistable effects from one modality can influence the other modality (Hupé *et al.*, 2008; Munhall *et al.*, 2009; Conrad *et al.*, 2010) but in a way rather compatible with a view in which the perceptual organization would first be extracted separately in each

modality. A nice example is provided by the study of Munhall *et al.* (2009), where the authors presented a McGurk stimulus in which the speaker's face was embedded in the Rubin's visual vase/face bistability effect. The authors show that the visual input modifies the auditory percept only when the subject perceives the input as a face – and they conclude that visual binding occurs primarily to AV fusion. However, a contrary conclusion is proposed by Basirat *et al.* (2012) from their work on the verbal transformation effect. This effect is a speech multistability phenomenon, in which a given speech input repeated in loop may lead to the occurrence of a new percept, such as "life" being perceived as "fly". While the subject appears to switch regularly between one percept and the other, Basirat *et al.* (2012), show that the visual input participates to the switching competition, and conclude that in this case, AV organization is primary.

Apart from multistability, some behavioral and neurophysiological studies have suggested that the presentation of a visual stream can affect primary auditory streaming by enhancing segregation or integration (Rahne *et al.*, 2007; Marozeau *et al.*, 2010; Devergie *et al.*, 2011; Maddox *et al.*, 2015). For example Rahne *et al.* (2007) exploit MMN to determine whether an ambiguous sound organization could be driven toward an integrated or segregated percept by the simultaneous presentation of visual cues. They used the Van Noorden (1975) auditory stimuli presented in Figure 1-1, with a sequence of alternating low and high frequency sounds, which can be perceived as either one stream or two. The visual input was either synchronous with the low-frequency audio sequence, hence promoting segregation; or a sequence compatible in time with the alternating low-high audio sequence, hence promoting integration. The mismatching stimulus was an auditory variant introduced in the low-frequency stream. The authors found that the MMN was observed only when the visual pattern promoted stream segregation. Devergie *et al.* (2011) also found intersensory effects on scene organization in a behavioral experiment dealing with the possible benefit of lip-reading

in stream segregation. Their two experiments consisted of sequences of French vowels alternating in fundamental frequency F0, possibly resulting in segregation between the two F0-streams, in which subjects were instructed to identify the order of items in the 1st experiment and to detect disruption of temporal isochrony in the 2nd experiment. The visual speech gestures were synchronized with one auditory F0-sequence. In both experiments, the authors observed that visual cues did interfere in the task, hence playing a role in the stream segregation process. Recently, Maddox *et al.* (2015) studied the effect of AV temporal coherence on selective listening and confirmed that temporal cues provided by vision can help listeners to select one sound source from a mixture in the everyday multisource environment. This extends to AV speech a crucial observation in ASA, that coherence between two cues is crucial for stream formation – see for example the proposal by Shamma *et al.* (2011) that the temporal coherence between two auditory features (e.g. pitch, timbre, location) plays a major role in the auditory stream formation.

However, some other contradictory studies highlight cases where unimodal perceptual grouping appears to precede multisensory integration (Sanabria *et al.*, 2005; Keetels *et al.*, 2007). In a task of discrimination of spatial motion direction, Sanabria *et al.* (2005) displayed the influence of intramodal visual perceptual in the multisensory integration of motion information. In a temporal order judgment task, Keetels *et al.* (2007) showed that grouping of the auditory information took effect prior to intersensory pairing.

1.5.3 Elements in favor of a two-stage AV process in speech perception

Our portrait of the experimental data on AV speech perception in Sections 1.2 and 1.4 displayed a number of studies concluding that AV interactions could intervene at various stages of the speech decoding process.

Let us begin by the speech detection advantage, according to which visual cues appear to improve speech detection and cue extraction during AV perception (Grant and Seitz, 2000;

Kim and Davis, 2004; Schwartz *et al.*, 2004; Alsius and Munhall, 2013). The authors have related these AV interactions based on coherent AV fluctuations in time to the natural correlations between auditory and visual features in the speech signals.

To mention one of the most cited relevant studies, Chandrasekaran *et al.* (2009) attempted to characterize the natural statistics of AV speech in English and French. They observed strong correlations and close temporal correspondence between the envelope of the auditory signal and mouth opening area in the visual signal (see Figure 1-12). The speed of these observed temporal modulations of both the speech envelope and the mouth movements typically lies in the 2–7 Hz frequency range.

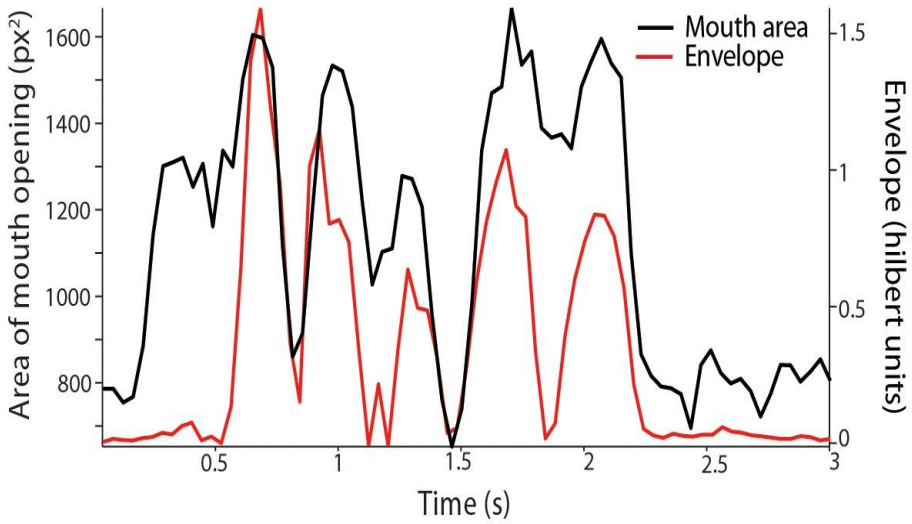

Figure 1-12 Illustration of AV correlation. Average correlations between mouth opening area and audio envelope. Taken from (Chandrasekaran *et al.*, 2009).

Similar results have been obtained in most of the AV correlation studies despite different choices of both the audio (e.g. acoustic envelope using wideband or narrowband filters) and video parameters (e.g. lip movements or facial features) (Yehia *et al.*, 1998; Barker and Berthommier, 1999; Jiang *et al.*, 2002; Craig *et al.*, 2008). Overall, these studies display and quantify the coherence between auditory and visual speech stimuli and suggest how this might enhance the processing and extraction of auditory cues for both detecting and under-

standing speech. This provides a scenario in which visual information would be available at an early stage of auditory processing and help reduce the spectral and temporal uncertainty prior to AV fusion.

This is also in line with the neurophysiological studies reported in Section 1.4.2 showing that visual speech can speed up the cortical processing of the auditory input as soon as 100 ms after the stimulus onset. Altogether, these data suggest that the visual speech flow could modulate ongoing auditory feature processing at various levels (Bernstein *et al.*, 2004; Bernstein *et al.*, 2008; Arnal *et al.*, 2009; Eskelund *et al.*, 2011).

1.5.4 A two-stage model for AV Speech Scene Analysis

It is in this context that Berthommier (2004) proposed that AV fusion could rely on a two-stage process, beginning by binding together the appropriate pieces of auditory and visual information, followed by integration *per se* (Figure 1-13). This provided a formalization of a proposal elaborated in Grenoble since the end of the 90s stating that ASA and multisensory interactions in speech perception should be combined into a single AVSSA process (Barker *et al.*, 1998; Berthommier, 2004; Schwartz *et al.*, 2004). The basic claim is that the two-stage analysis-and-decision process at work in ASA should be extended to AV speech scenes made of mixtures of auditory and visual speech sources. A first AV binding stage would involve segmenting the scene into AV elements, which should be segregated or grouped with respect to their common multisensory speech source, either by bottom-up AV primitives or by learnt top-down AV schemas. This AV binding stage would control the output of the later decision stage, and hence intervene on the output of the AV speech-in-noise or McGurk paradigms.

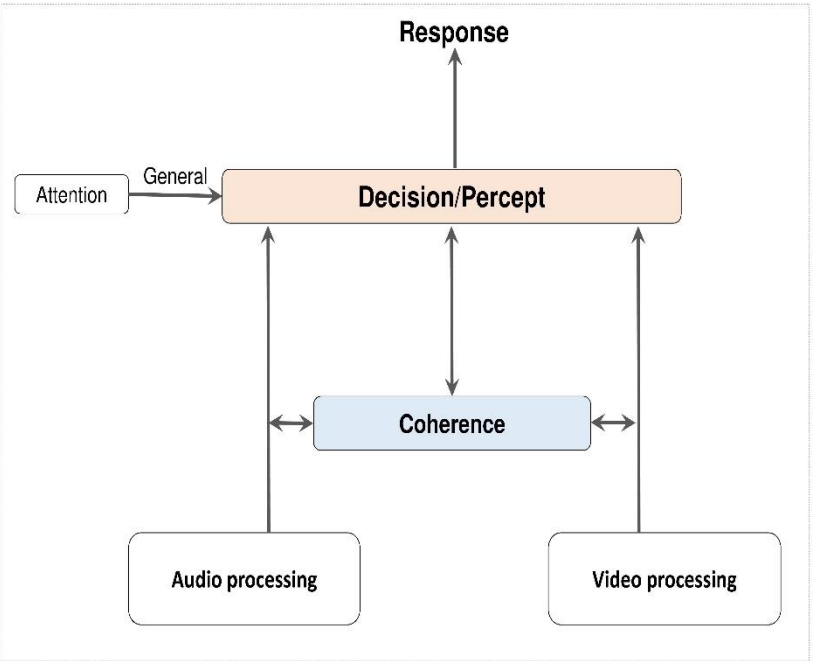

Figure 1-13 The two-stage model for AV fusion in speech perception.

1.5.5 Evidence in favor of the two-stage model

In a series of experiments, Nahorna *et al.* (2012) provided evidence for the hypothesized AV binding stage in the processing of AV speech. The basic assumption for all the experiments was that, if binding does indeed occur prior to AV integration, then it should be possible to either measure the amount of binding or find a way to reduce it. Altering or reducing the binding mechanism should reduce or eliminate the McGurk effect. This process of reduction of the binding mechanism was termed "unbinding".

The basic paradigm in all the experiments by Nahorna *et al.* (2012; 2015) consisted of designing various types of contextual AV stimuli before a McGurk target and to test if various amounts of incoherence in the context could lead to decrease or increase the amount of fusion within the McGurk target, as indexed by the amount of McGurk effect. In the first set of experiments demonstrating the efficiency of the paradigm in Nahorna *et al.* (2012), two types of context material and two types of targets stimuli were used. The context was either coherent or incoherent with various durations, and it was presented either before a congruent

"ba" AV target – serving as a control – or before an incongruent "McGurk" target combining an audio "ba" with a visual "ga" (Figure 1-14). The subject's task was to monitor online the perception of either "ba" or "da" stimuli. According to Nahorna *et al.* (2012), the coherent context (Figure 1-14, top) should enable the listener to trust the coherence between the audio and visual components and hence fuse them in the perception of the McGurk target, which should result in a large proportion of "da" responses. Conversely, the incoherent context (Figure 1-14, bottom) should decrease the subject's confidence that the auditory and visual streams are part of a coherent source and hence reduce the role of the visual input within phonetic decision. In consequence, it should decrease the amount of McGurk responses and hence increase the proportion of "da" responses in McGurk targets.

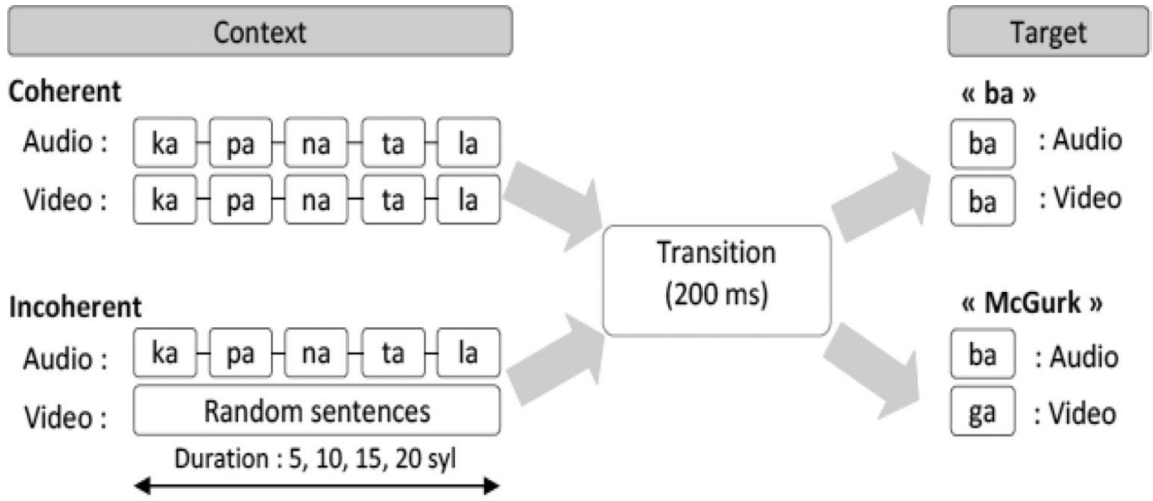

Figure 1-14 Experimental paradigm for assessing the binding/unbinding effect. Taken from (Nahorna *et al.*, 2012).

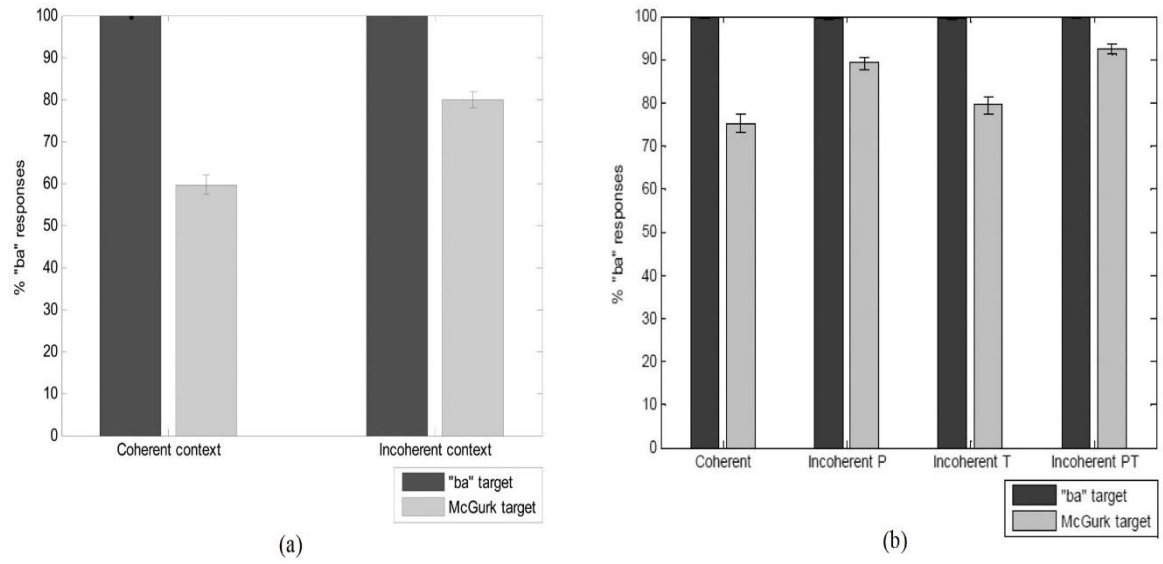

Figure 1-15 Experimental results of Nahorna *et al.* (2012). a) Percentage of "ba" responses for "ba" and "McGurk" stimuli in the coherent vs. incoherent contexts, b) Percentage of "ba" responses for "ba" and "McGurk" stimuli in the coherent (C) vs. phonetically incoherent (P), temporally incoherent (T), and phonetically and temporally incoherent (PT) contexts. Taken from (Nahorna *et al.*, 2012).

The results of the first series of experiments showed that incoherent contexts such as acoustic syllables dubbed on video sentences (Figure 1-15a) or phonetic or temporal modifications (Figure 1-15b) of the acoustic content of a regular sequence of AV syllables, produced a significant amount of reduction in the McGurk effect. This was obtained for rather short context durations less than 4s. Altogether, these data confirm that McGurk fusion depends on the previous AV context, and were considered by the authors as providing evidence for the proposed "AV binding stage" hypothesis, compatible with the two-stage architecture for AV speech processing. They also appear consistent with the experiments on AV detection suggesting that the coherence of the auditory and visual inputs is computed early enough to enhance auditory processing, resulting in the AV speech detection advantage.

These robust data on AV binding/unbinding stimulated Nahorna *et al.* (2015) to design additional experiments to search for conditions that could reset the system and put it back in its default mode in which the McGurk effect would recover from unbinding. This was termed as a "rebinding' process". The context set before the McGurk target now consisted of a first

portion of incoherent context followed by variable durations of a "reset" stimulus, which was either acoustic silence dubbed on a fixed image, or coherent AV material (Figure 1-16).

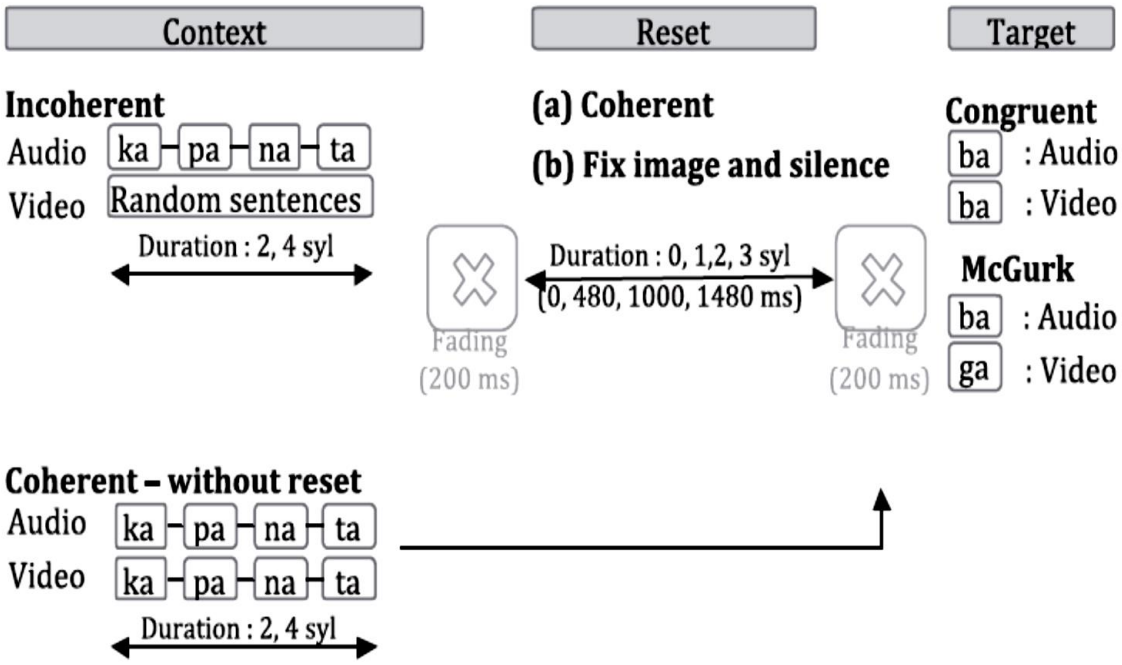

Figure 1-16 Experimental paradigms for assessing the unbinding and rebinding effects. Taken from (Nahorna *et al.*, 2015).

The results showed that the "silence + fixed image" reset did not provide any rebinding (reset did not influence the McGurk effect) (Figure 1-17). On the contrary, the coherent reset did produce rebinding, that is a significant increase in the McGurk effect, coming back to its "default" state for a coherence period of three syllables.

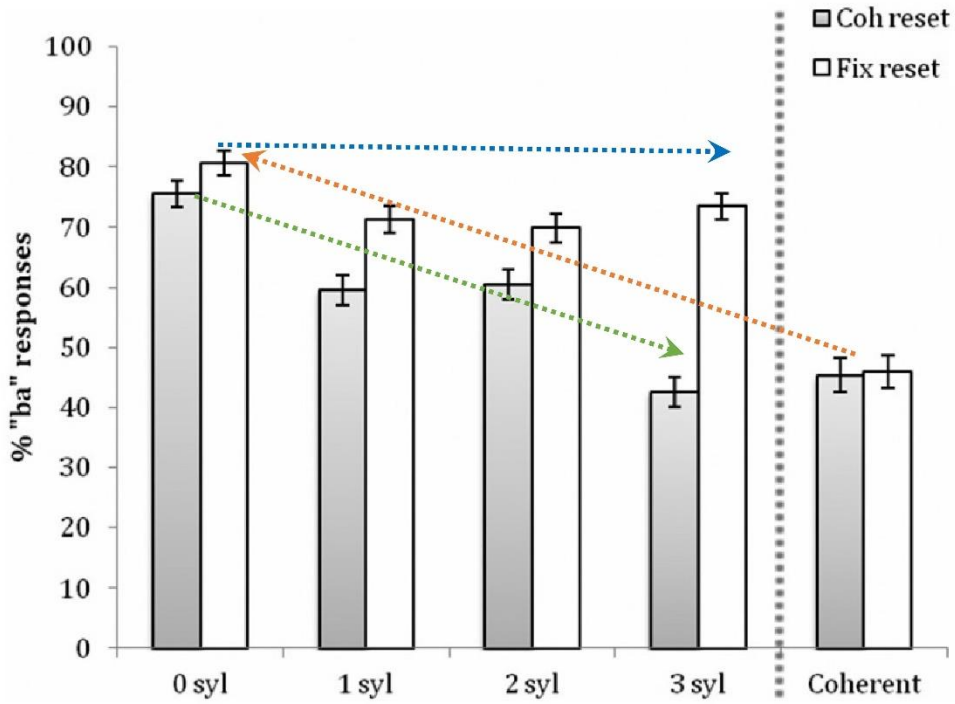

Figure 1-17 Experimental results of Nahorna *et al.* (2015). Percentage of "ba" responses for the McGurk targets with coherent context and with incoherent context for the two reset types and the four reset durations. The orange arrow shows unbinding increase in "ba" responses from Coherent to Incoherent context without reset. The green arrow shows rebinding with coherent reset (decrease in "ba" responses that is increase in McGurk "da" responses from 0 to 3 syllables of coherence in the reset). The blue arrow shows that a fixed reset of any duration between 0 and 3 syllables produce essentially no effect. Adapted from (Nahorna *et al.*, 2015).

1.6 Objectives and Plan

Altogether, the experimental data are in good agreement with the two-stage architecture in which a first binding stage assessing the coherence between sound and face would control the output of the fusion process and hence modify the nature of the percept. The "unbinding" mechanism would result in a smaller role of vision in the decision process. The various experiments in Nahorna *et al.* (2012, 2015) provide a number of specifications of the qualitative and quantitative conditions of unbinding and rebinding. However, the two-stage architecture should be further evaluated and developed in various dimensions such as introducing noise, considering multiple sources, assessing neurophysiological correlates and testing in different

populations. These are the objectives of the experiments described in the present work, aiming at further characterizing the "AVSSA process" within the two-stage model in order to increase our knowledge of this essential process in speech perception.

The experiments are organized into three parts:

1. Behavioral characterization of the AV binding mechanism and its implications in the processing of speech-in-noise as well as in competing sources. The goal here is to determine whether the incoherent AV context that causes unbinding would also modulate the benefit of vision in noisy conditions and competing sources.

2. Neurophysiological characterization of the binding mechanism. The goal is to search for neurophysiological correlates of the binding/unbinding process by using an electrophysiological tool (EEG).

3. Studies in specific populations, like aging adults. The precise aim is to report possible changes in the binding mechanism from younger to older adults. More generally, the question is to know how binding might depend on subjects, in relation to age, culture, developmental history, sensory or cognitive deficits, etc.

These studies will be described in four specific chapters corresponding to four sets of experiments. Since they all involve some stable specifications of paradigms and stimuli, a preliminary chapter will present these general principles. The document will be concluded by a discussion attempting to synthesize the main findings of this work inside a possible improved architecture for AV speech perception, and some perspectives will be proposed for future works.

Chapter 2

2. General Principles-Methods & Materials

The present chapter is dedicated to describe the general principles that were implemented for stimuli preparation, participant's selection, methods, and other details on stimuli preparation. The objective of this chapter is to provide information that is relevant for all experiments in the following chapters.

2.1 Participants Information

The participants were native French speakers (although no standard tests were used to measure first or, possibly, second language proficiency), without any reported history of hearing disorders and with normal or corrected-to-normal vision. They were either normal hearing adults (18 to 55 years) for the majority of experiments or older adults (60 to 75 years) in a specific set of experiments. Screening audiometry was performed on older adults to exclude participants with a peripheral hearing loss from the experiments. Written informed consent was obtained from each participant and all procedures were approved by the Grenoble Ethics Board (CERNI). In addition to the informed consent, the participants were also asked to fill a form with questions about name, age, sex, handedness, native language, vision and hearing abilities.

2.2 AV Material

The general objective of the experiments is to test the effect of context on congruent "ba" or incongruent "McGurk" targets. To achieve this objective, it is required to modulate the coherence and incoherence in the context and to construct good McGurk stimuli for the tar-

gets. We utilized the material that was prepared for the initial AV binding experiments by (Nahorna *et al.*, 2012).

The stimuli for all experiments were prepared from two sets of audiovisual material, a "syllables" material and a "sentences" material (see Figure 2-1), produced by a French male speaker with lips painted in blue to allow precise video analysis of lip movements (Lallouache, 1990). The recordings were carried out in a soundproof room at GIPSA-Lab. The "syllables" and "sentences" material both included 60 AV stimuli of various durations, always ending with the syllables "ba", "da" or "ga". The stimuli in the "syllables" material consisted of 5, 10, 15 or 20 successive French syllables randomly selected within the set "pa", "ta", "va", "fa", "za", "sa", "ka", "ra", "la", "ja", "cha", "ma", "na" – before the final "ba", "da" or "ga". The speaker produced the syllables with a short temporal gap between two consecutive syllables enabling easy cuts for stimuli preparation. The stimuli in the "sentences" material consisted of sequences of sentences freely uttered by the speaker during the recording session, with a total duration of 4, 7, 10, and 13 seconds (typically the same duration as for the 5, 10, 15 and 20 syllables respectively in the "syllables" material) before the speaker uttered the final "ba", "da" or "ga".

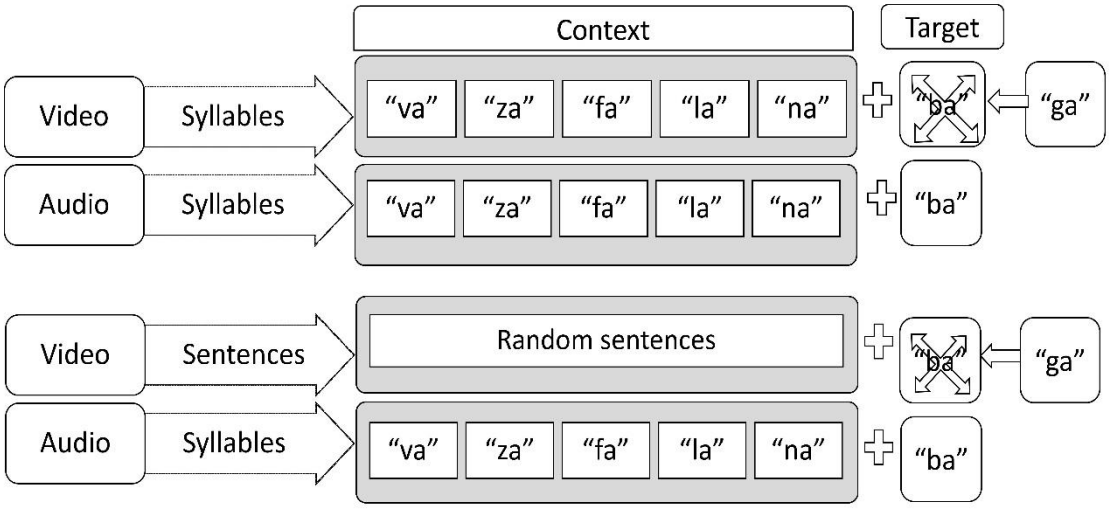

Figure 2-1 Stimuli preparation for both contexts and targets.

These two materials were used to prepare either coherent contexts made of coherent excerpts from the "syllables" material, or incoherent contexts dubbing sounds from the "syllables" material with video coming from the "sentences" material. The syllables that were recorded at the end of each AV sequence were extracted and utilized to construct the target stimuli. This will be presented in more detail in the next section.

2.3 EXPERIMENTAL PARADIGM

Basically, the general experimental paradigm comprised two types of contexts respectively "coherent" and "incoherent", and two types of targets respectively "congruent" and "incongruent" (Figure 2.2).

2.3.1 Contexts

The coherent context was made of 2 or 4 AV syllables extracted from the "syllables" material. The incoherent context was prepared by dubbing a sequence of 2 or 4 acoustic syllables extracted from the "syllables" material (same syllables that were used in preparing the coherent context) on a video stream extracted from the "sentences" material with the adequate duration. The durations of 2 or 4 syllables have been shown by (Nahorna *et al.*, 2015) to be sufficient to produce maximal effects of the incoherent context compared with the coherent one that is a maximal decrease of the McGurk effect. Indeed, longer incoherent contexts produce the same decrease compared with coherent context. Sound and video files were automatically extracted from the AV material with desired length using Matlab (Mathworks, Natick, MA, USA).

2.3.2 Targets

The targets comprised voiced plosives for behavioral experiments. Voiceless plosive were used in the targets in the electrophysiological experiment, and their construction will be discussed in the corresponding chapter. Otherwise, the target was either a congruent AV "ba" syllable or an incongruent McGurk stimulus with an audio "ba" mounted on a video "ga".

The McGurk stimuli were prepared from an audio occurrence of the "ba" syllable produced at the end of the "syllables" material (see Figure 2-1) and from the sequence of images of an occurrence of a "ga" syllable produced at the end of the "syllables" material. The audio "ba" and video "ga" were synchronized by using the precise temporal localization of the acoustic bursts of the original "ba" and "ga" stimuli. It was expected that the McGurk stimuli should be perceived as "da" (McGurk and MacDonald, 1976) while congruent "ba" stimuli should be unambiguously perceived as "ba". The McGurk targets were the main interest in the present study while the congruent "ba" targets only served as controls. We utilized the same AV targets associated with either coherent or incoherent contexts.

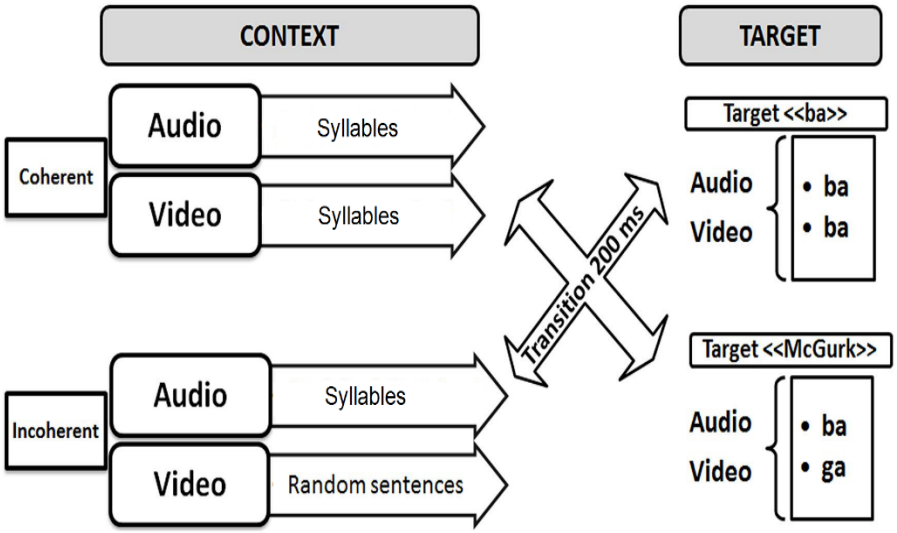

Figure 2-2 Experimental paradigm.

2.4 Construction of the AV Stimuli

The McGurk effect largely depends on the nature of the AV input such as intensity of the auditory signal (Colin *et al.*, 2002a), auditory noise (Sekiyama and Tohkura, 1991; Fixmer and Hawkins, 1998), visual noise (Fixmer and Hawkins, 1998), and it is characterized by large inter-subject variability (Schwartz, 2010; Basu Mallick *et al.*, 2015). Therefore, it is crucial that we carefully control these variables in the comparison between coherent and in-

coherent context. This why the same McGurk stimuli were used in both contexts and the same subjects were systematically compared with both contexts.

2.4.1 Preparation of the auditory stimuli

Stereo soundtracks were digitized in Adobe Audition at 44.1 kHz with 16-bit resolution. For each auditory target, the acoustic onset, burst and acoustic offset were detected for both "ba" and "ga" audio files. Detection was done using the Praat software (Boersma and Weenink, 2013). All the auditory stimuli were filtered to remove the DC (direct current) component in the signal and normalized to keep the same mean energy for all "contexts" and "targets" stimuli throughout the experiment.

2.4.2 Preparation of the video stimuli

Videos were edited in Adobe Premiere Pro into a 720/576 pixels movie with a digitization rate of 25 frames/s (1frame = 40 ms). To construct various combinations of context and target from the AV materials, we need to join different sequences of images from the "syllables" and "sentences" material. This could create abrupt breaks and thus continuity could be lost. To ensure continuity, a 200 ms transition stimulus (5 images) was inserted with a progressive linear shift from face to black from images 1 to 3, and a progressive linear shift from black to face from images 3 to 5 (see Figure 2-3). This transition stimulus provided a small cue for the arrival of the target stimulus.

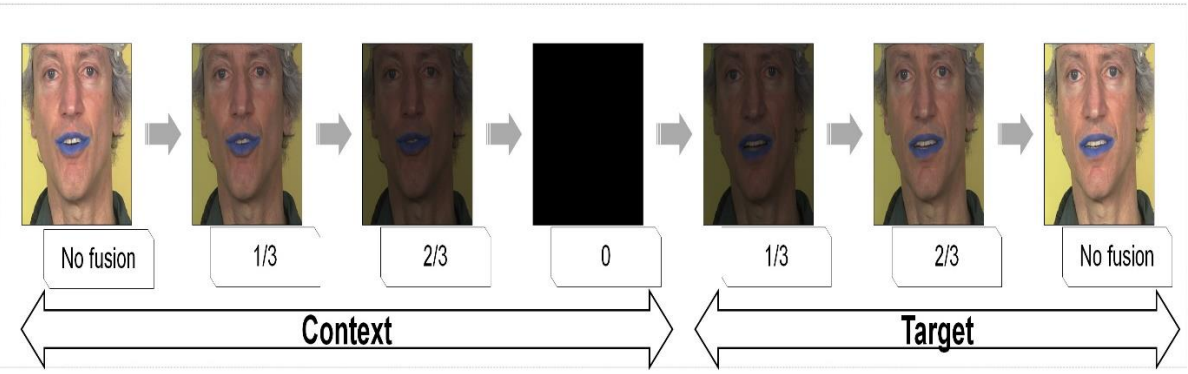

Figure 2-3 Illustration of image fusion using black image.

2.4.3 Final AV film preparation

Stimuli were mixed randomly to produce films containing all possible stimuli in a given experiment. Since the number of syllables in the context varied between 2 and 4, the arrival of the target remained largely unpredictable – despite the small temporal cue provided by the 200-ms transition stimulus - thus participants needed to stay always focused and attentive to detect the targets. Since the "ba" targets were only used as controls, we maintained a proportion of ¼ "ba" targets and ¾ "McGurk" targets.

We inserted an 840-ms inter-stimulus silent interval between the end of one target and the beginning of the next target. The video component of this silent interval was made of the repetition of the last image of the previous stimulus. Such a short inter-stimulus interval was selected to put the subjects in a real monitoring task where there was large uncertainty about the temporal arrival of possible targets, to decrease as much as possible post-decision biases on target detection.

2.5 PROCEDURE

All experiments were carried out in a soundproof booth, which was located in the Speech and Cognition Department in GIPSA-Lab. Stimulus presentation was coordinated with the Presentation® software (Neurobehavioral Systems Inc., Albany, CA). Apart from the EEG experiment that will be presented in the dedicated EEG experiment section, the participant's task was to monitor for the arrival of target stimuli "ba" or "da" within the displayed films, by pressing as soon as possible the appropriate key (two-alternative-forced-choice identification task). This is different from classical speech recognition tests where participants know when the target stimuli will be presented.

Participants were instructed to look constantly at the screen and, each time a "ba" or a "da" was perceived, to press the corresponding button immediately. The distance of the participant to the screen at about 50 cm from the screen and the intensity of the audio stimulus

were kept fixed. The films were presented on a computer monitor with high-fidelity headphones set at a comfortable fixed level or presented through speakers in the case of EEG experiment. Trial sessions were provided before each block to enable participants to familiarize with stimuli and task. In the case of various blocks within a given experiment, the order of the blocks was counterbalanced across participants, and the response button was also interchanged between subjects.

2.6 PROCESSING OF RESPONSES

2.6.1 Detection of responses

The expectation in this monitoring task was that for each congruent "ba" target the participants should detect a "ba", while for each incongruent "McGurk" target they should detect either a "ba" or a "da". Since the context material contained no "ba", "da" or "ga" in the audio stream, we expected that no target should be detected during the context periods. However, such an online monitoring task may lead to either wrong detections – that is the detection of "ba" or "da" during the context – or failure of target detection. Therefore, the first step in the analysis process was to define a protocol for detecting responses to target stimuli.

For this aim, we capitalized on the process defined by (Nahorna, 2013) in her Ph.D. and described in Nahorna *et al.* (2012; 2015). The analysis was based on the evaluation of the response time relative to the acoustic onset of target syllables – defined as the plosive burst onset. The absolute response time is provided by the Presentation® software (Neurobehavioral Systems Inc., Albany, CA), in absolute values in reference to the beginning of the film. For each detection, we first calculated the difference between response time and the acoustic onset of the target syllable: this is what will be called "response time" in the following.

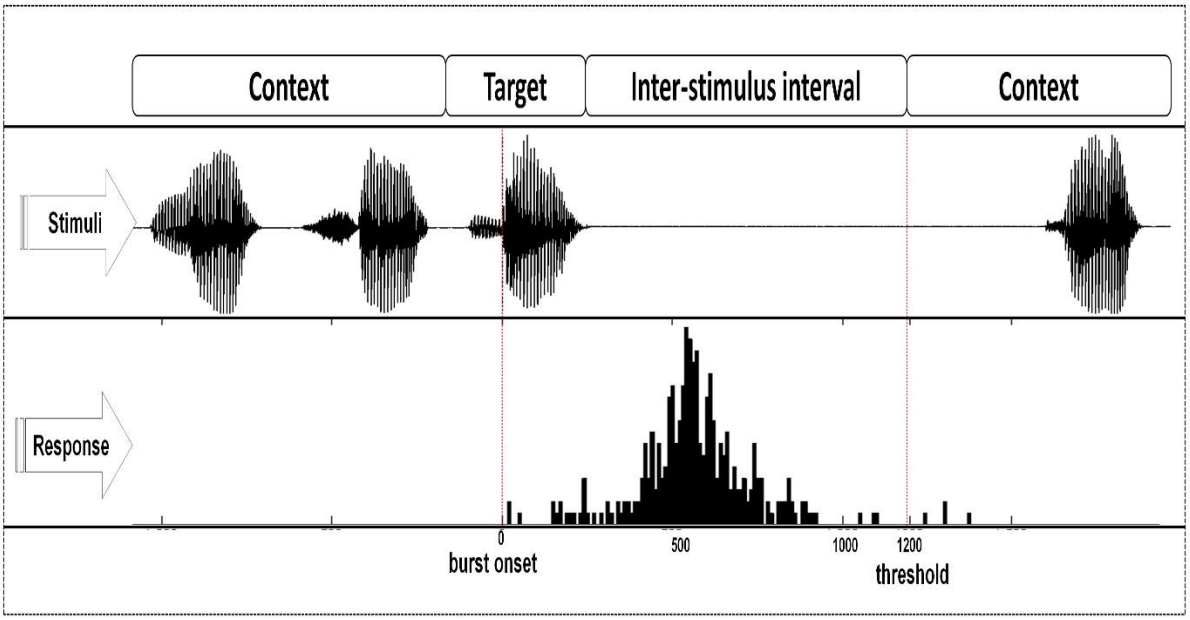

Figure 2-4 Example of analysis of response time within the [200-1200ms] time window. The histogram of response times for one subject is shown as an example here.

Any response provided with a response time larger than 1200 ms, or smaller than 200 ms was considered as a false detection and discarded from the analysis. The value of 1200 ms has been proposed by Nahorna (2013) from the analysis of response time histograms (see Figure 2-4), showing that it enabled to accept most responses while discarding spurious responses that could actually be due to the beginning of the next context period (remember that the inter-stimulus interval was short, namely 840 ms). We will systematically report the number of missed targets, and show that indeed most targets are detected by the participants in all experiments. In the rare cases of double responses within the acceptable [200-1200] window, we accepted the first response together with its corresponding response time if both responses were the same, and rejected the response in case of two different responses. All the possible outcomes are described in Figure 2.5.

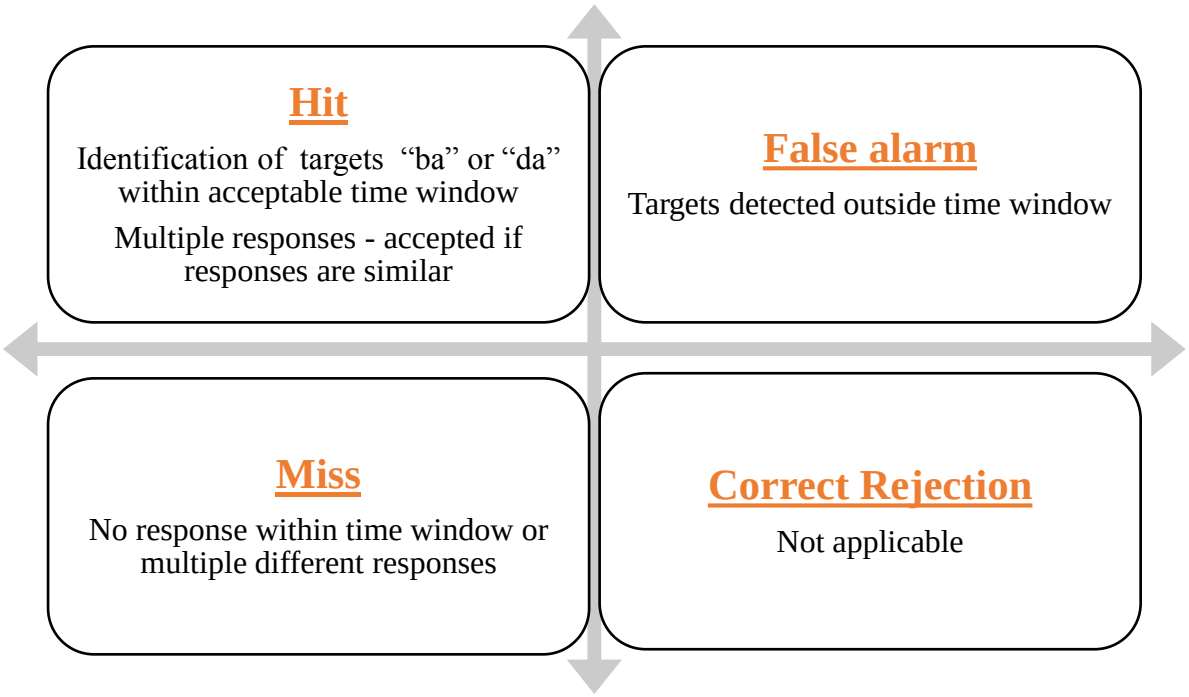

Figure 2-5 Classification of responses.

2.6.2 Analysis of responses

The total number of "ba" and "da" hit responses was calculated for each condition of context and target and for each participant. Then the percentage of "ba" responses – that is the ratio "total number of ba responses" divided by "total number of ba or da responses" – was taken as the score of responses by this participant in this context for further statistical analyses presented in the next section. The number of "no responses" and "multiple different responses" within the acceptable time window was also systematically computed.

2.6.3 Analysis of response time

As said previously, response time was defined as the time separating the plosive burst at the onset of the target stimulus and the response (within the 1200 ms cut-off) measured with the Presentation® software (Neurobehavioral Systems Inc., Albany, CA). For each condition of target and context and for each participant, the mean response time was estimated by averaging the response times for all stimuli in the corresponding condition.

2.7 STATISTICAL ANALYSIS

The suitable statistical analysis was performed on both response scores ("ba/ (ba+da)" scores) and response times (mean response times) using the SPSS Statistics 17 © IBM software. The response scores to the "ba" targets were systematically close to 100%, and not considered in the analysis since these targets only served as a control stimulus. To ensure quasi-Gaussian distribution of the variables, the response scores were processed with arcsine square root transformation [asin (sqrt)] transform, and the mean response times were logarithmically transformed. Then analyses of variance (ANOVAs) were performed on both transformed response scores and transformed response times, applying a Greenhouse – Geisser correction in case of violation of the sphericity assumption. *Post-hoc* analyses with Bonferroni correction were done when appropriate and were reported at the [($p < 0.05$) level].

2.8 CONCLUSIONS

Overall, the present chapter provided general principles and procedures, which are similar across all the experiments. Of course, the stimuli will be modified as per the requirements for each experiment and specific modifications of paradigm or processing will be discussed in detail in each particular chapter. Globally, care was taken to (1) ensure the control of target and context material – with the same set of targets for the different contexts compared in each experiment, (2) increase the unpredictability of time arrival of the targets to decrease as much as possible decision biases in the monitoring procedure, while (3) maintaining the naturalness of audio and visual stimuli by minimizing distortions through various signal and image processing techniques. We will now describe in detail the methods and results for each of our planned experiments.

Chapter 3

3. Effect of Context, Rebinding and Noise on AV Speech Fusion[1]

3.1 Background and Hypothesis

The major output of the experimental work by Nahorna *et al.*, (2012; 2015) is the demonstration that context may modulate the McGurk effect. This was interpreted by the authors as an "unbinding/rebinding" mechanism in the framework of a tentative AVSSA process. However, all the experiments done so far have involved a single acoustic source and a single visual source within context. Of course, the incoherent context material actually corresponds to two differing sources, one syllabic source presented in the auditory modality and one sentence source presented in the visual modality. However, there is no competition of sources in individual modalities.

The objective in the first part of this thesis is to go towards more realistic situations in which there is a competition of sources inside the auditory modality – apart from possible incoherence between modalities. In a first step, we will consider acoustic noise added to the acoustic source. However, the acoustic noise will be presented only in the context part. Therefore, we will exploit the "unbinding/rebinding" paradigm by Nahorna *et al.* (2015, Experiment 2) presented in Section 1.5.5, though with an important variant, that is the addition of acoustic noise in the context before the McGurk target (see Figure 3-1).

[1] This is an extended version of a paper submitted to the Journal of the Acoustical Society of America.

The first condition without noise will enable to replicate the findings about unbinding and rebinding in the original study (Nahorna *et al.*, 2015). These results, presented in Figure 1-17, are recalled in Figure 3-1: while a coherent context makes the McGurk effect stable, an incoherent context decreases the McGurk effect, but a coherent reset stimulus presented between the incoherent context and the target produces rebinding, that is increases the McGurk effect back to its original level before unbinding.

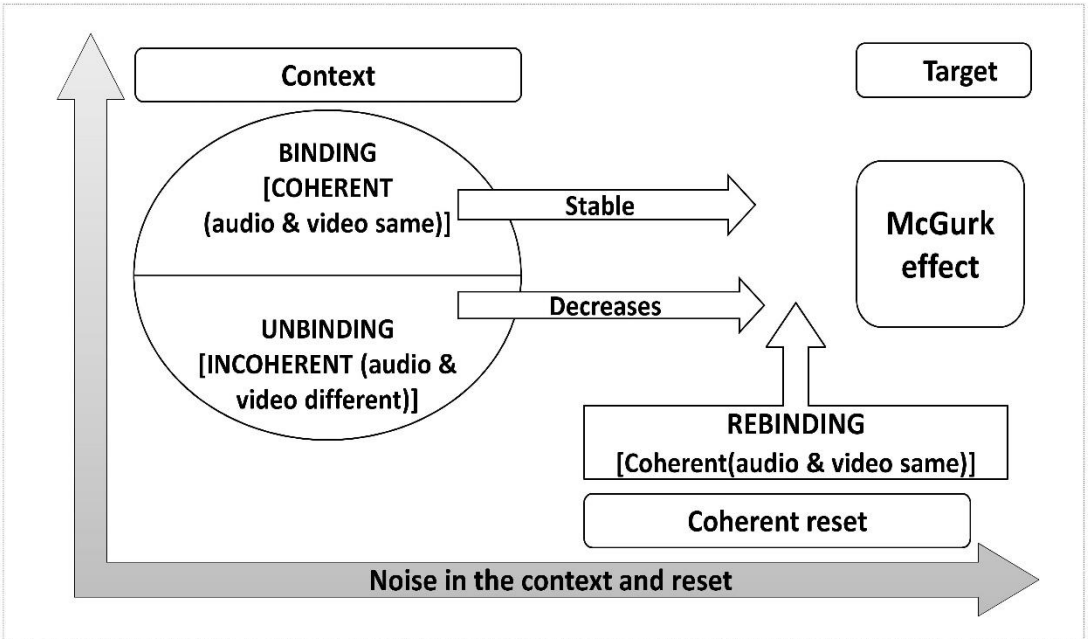

Figure 3-1 Experimental paradigm for displaying unbinding or rebinding mechanisms.

In the second condition, there will be acoustic noise all around the context and reset periods, though not during the target. The first question asked in this experiment is to know how coherence computations at hand in the binding/unbinding/rebinding process (see Figure 1-17) will work in this case. Indeed, it could be envisioned that noise will partly blur AV correlations and hence globally decrease the role of context in all its aspects, with less unbinding and less rebinding – that is, less differences between contexts in terms of McGurk effect when the target is presented. More generally, the first objective of this experiment was to replicate part of the Nahorna *et al.* (2015)'s experiment (with just the coherent reset and not

the fixed reset condition, see Figure 1-16) while assessing how acoustic noise modifies the computation of AV coherence and hence the magnitude of unbinding/rebinding processes.

There was, however a second objective with more direct potential theoretical consequences, which we will explain now.

The importance of visual cues in the perception of speech-in-noise was discussed in an earlier section in detail (see Section 1.2). Concerning the McGurk effect, we saw that it appears to increase when the acoustic component is noisy and decrease when the McGurk stimulus is presented with visual noise (Sekiyama and Tohkura, 1991; Sekiyama, 1994; Fixmer and Hawkins, 1998; Kim and Davis, 2011). These outcomes could receive two different interpretations.

In the first interpretation, within the framework of the FLMP developed by Massaro (1998) (see Section 1.3.2), AV fusion is obtained by a multiplicative fusion process between the unisensory evidence for each possible decision in a given AV speech perception task. The fusion process is hence conceived as automatic, just dependent on unisensory percepts, and supposedly optimal in the sense that the less ambiguous a sensory percept, the larger its weight in the fusion process. FLMP provides good simulations of the McGurk effect (Massaro, 1998). For FLMP, any changes in the final percept by the addition of noise would be due to the increasing ambiguity of the noisy component, which would automatically decrease its role in the fusion process.

In the second interpretation, the subjects would control the weight of the auditory and visual modalities in the fusion process as a function of noise present in the environment. According to this assumption, fusion would depend not only on the phonetic information contained in each sensory input, but also on a cognitive mechanism by which subjects would control fusion depending on the conditions of communication (Fixmer and Hawkins, 1998). This can be captured by the so-called WFLMP presented in Section 1.3.4.

If the first assumption were true, then AV fusion would only depend on the unisensory stimuli and not on any cognitive mechanism by which the listener would adjust the weights of each modality in the fusion process in relation with noise or any other contextual factor. However, in the case of the second interpretation the modulation of the fusion mechanism would depend on the reliability of the auditory and visual channels. The addition of noise inside the channel would change the reliability of the channel and hence lower its weight significantly in fusion. These two interpretations are difficult to disentangle in available McGurk data, since there is possibly a confounding bias in the way FLMP is tuned to these data (see Schwartz, 2006).

However, the present experimental paradigm could provide an answer and enable to discriminate between the two previous interpretations. Indeed, since there will be no noise in the target, if fusion depends only on unisensory percepts as suggested by FLMP, then the McGurk effect should not change from one condition to the other since the target remains the same. However, if the subjects are able to estimate the amount of noise during the context period and hence control the weight of the auditory and visual modalities accordingly in the fusion process, then application of acoustic noise in the context part should lead them increase the visual weight. This would result in an increase of the McGurk effect.

In summary, we aim to test in this first experiment (1) if acoustic noise will globally decrease the unbinding/rebinding processes associated with context, and (2) if acoustic noise will globally increase the role of the visual input and hence the McGurk effect. The first question will be tested by looking at possible interactions between context coherence and noise in response scores. The second question will be tested by looking at a possible increase of the McGurk effect independently on context coherence.

3.2 METHODS AND MATERIALS

3.2.1 Participants

Thirty-one participants (22 women and 9 men; 30 right-handed and 1 left-handed; mean age=31.7 years; SD=11.7 years) took part in this experiment. Other details on participants and selection criteria were already presented in Chapter 2 (see Section 2.1)

3.2.2 Stimuli

3.2.2.1 *Preparation of the context, reset and target parts*

The stimuli used in the present experiment were similar to those of the 2nd experiment in (Nahorna *et al.*, 2015). Stimuli began with a "context" and ended with a "target". The target was either a congruent AV "ba" syllable or an incongruent McGurk stimulus with an audio "ba" mounted on a video "ga". The congruent "ba" targets only served as controls. The context could be either incoherent (Figure 3-2, top) or coherent (Figure 3-2, bottom), with a 2- or 4-syllable duration. In case of incoherent context, a "reset" was introduced between the context and the target. The construction of "context" and "target" stimulus were described in Chapter 2 (Sections 2.2 & 2.3).

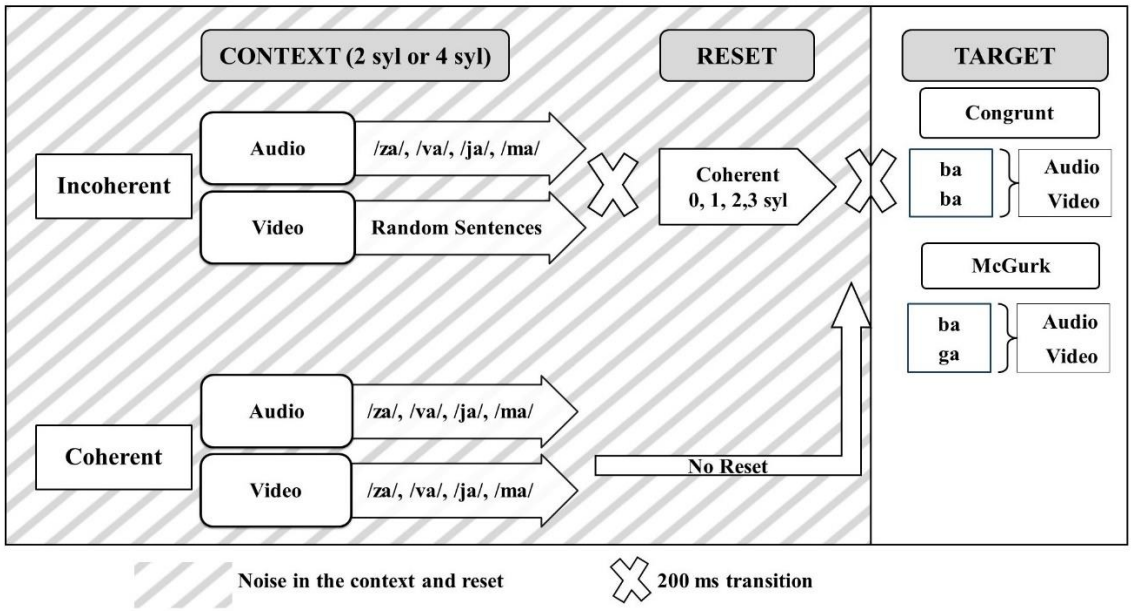

Figure 3-2 Description of the AV material.

The reset stimulus, which was always presented after the incoherent context, consisted of 0, 1, 2 or 3 coherent audiovisual syllables extracted from the "syllables" material (Section 2.2). The "0" syllable reset was nothing but pure incoherent context where there was no reset material presented. To ensure visual continuity between context and reset, a 200 ms transition without sound was inserted according to the procedure described in Section 2.4.2 (Figure 2-.2), though with an image fusion process without black image, that is by a linear transition between the last three images of the context and the first two images of the reset.

3.2.2.2 *Addition of noise on the context and reset parts*

The target stimuli were always presented without acoustic noise in all conditions. In one condition however, acoustic noise was added to the context and reset periods of the stimuli (see Figure 3-2, where shaded regions represent noise on context and reset stimuli, and Figure 3-3 which displays the acoustic waveforms with the context part either clear or mixed with noise, and the target without noise). We used Gaussian white noise at 0 dB SNR which was generated using Matlab (Mathworks, Natick, MA, USA). SNR values were computed on the portions of the speech input removing all silent portions between syllables.

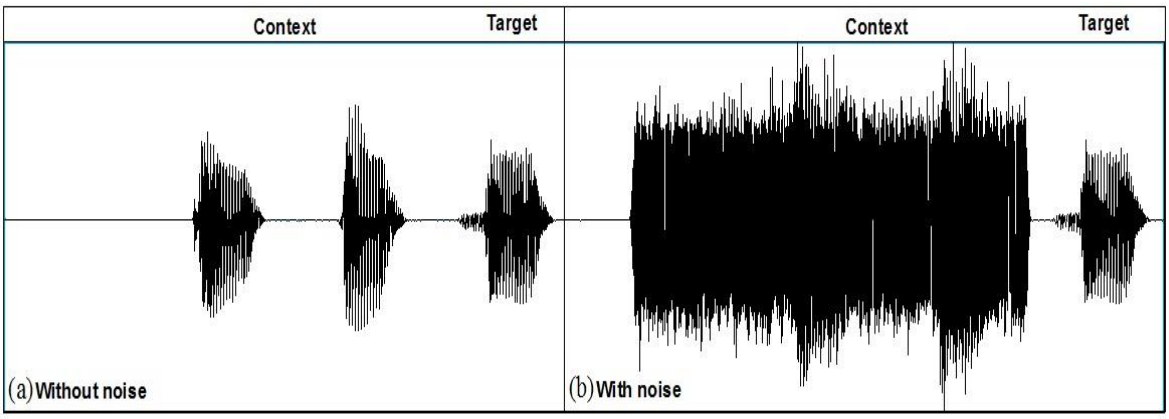

Figure 3-3 Preparation of Audio material a) Without noise b) With noise.

3.2.3 Procedure

Stimuli presentation and experimental procedure were already explained in Section 2.5. The whole experiment consisted in two blocks, one without acoustic noise and the other one

with acoustic noise. As explained in Chapter 2, McGurk targets were presented three times more than congruent "ba" targets, which served as controls. For each (context+reset) condition (2 context durations; coherent context + incoherent context with 4 possible reset durations; 2 noise conditions; hence altogether 20 conditions) there were 4 occurrences of a "ba" target and 12 occurrences of a McGurk target. Hence there were 320 sequences in total, spread over 2 blocks of 10 min each, one for each noise condition (see Table 3-1). All stimuli were randomized and we prepared five different films with five different orders in each block. The five different films were randomly distributed among the subjects. The order of the two blocks ("silent" and "noise") was counterbalanced between participants, and the response button was also interchanged between subjects.

	2-syl context duration					**4-syl context duration**				
		Incoherent context with reset of					Incoherent context with reset of			
Targets	Coherent context	0 syl	1 syl	2 syl	3 syl	Coherent context	0 syl	1 syl	2 syl	3 syl
"Ba"	4	4	4	4	4	4	4	4	4	4
"McGurk"	12	12	12	12	12	12	12	12	12	12

Table 3-1 Number of stimuli presented for each condition in each block (without noise or with noise).

3.2.4 Processing of responses and statistical analyses

As described in Section 2.6, responses were detected within a [200-1200] ms window after the plosive acoustic burst in the target, and the response scores provided by the proportion of "ba/ (ba+da)" responses together with the mean response time were calculated for each condition and each participant. ANOVAs were performed on both response scores processed with an asin (sqrt) transform) and logarithm values of response times.

3.3 RESULTS

3.3.1 Individual data and No response data

Participants with more than 90% "ba" scores in the "coherent condition" for McGurk targets (without noise) were considered as subjects with a poor level of audiovisual fusion (no or very small amount of AV binding) and were hence excluded from the statistical analysis. Overall, 10 participants were excluded from further analysis and the remaining 21 participants' data were subjected to statistical analysis (see Figure 3-4).

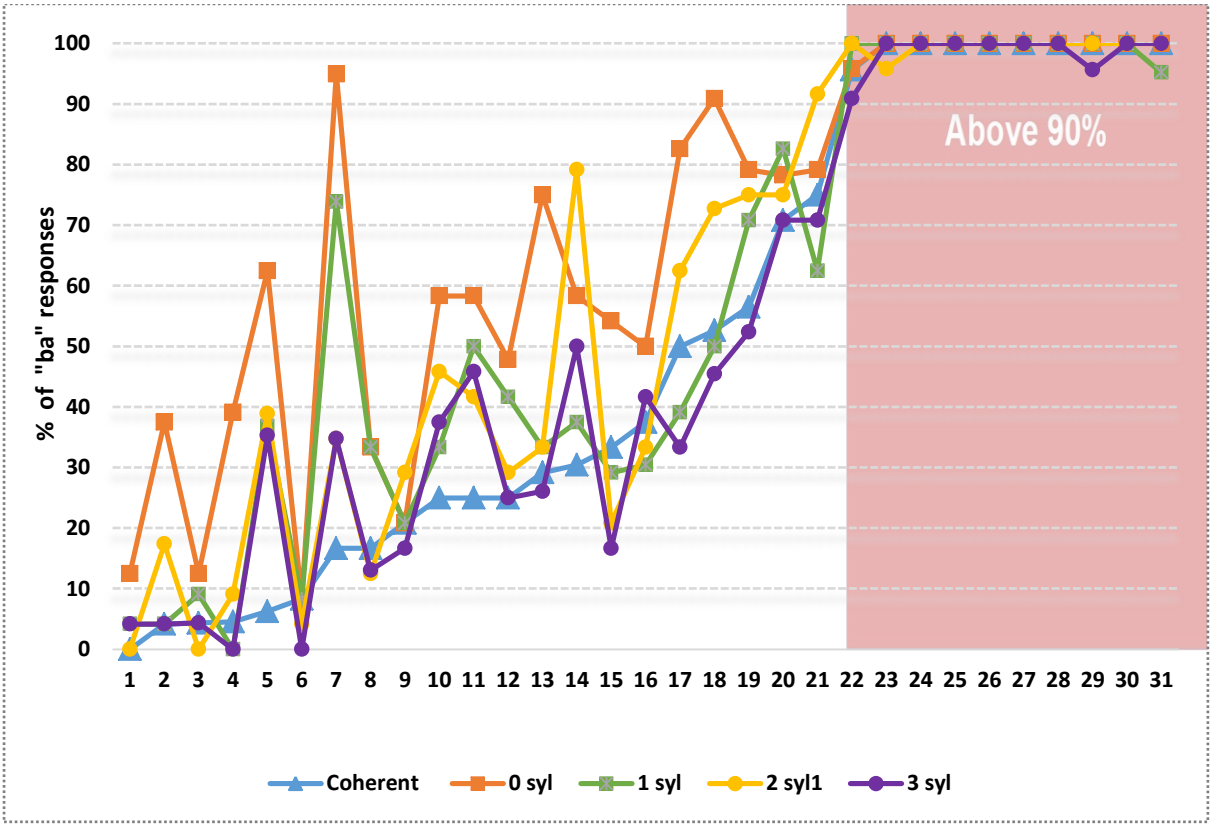

Figure 3-4 Individual "ba" scores for McGurk targets, in the "coherent" and "incoherent" contexts (with 0, 1, 2 & 3 syllable reset duration) in the "without noise" condition. The subjects are ordered by increasing score in the "coherent" condition.

More details about the participant's responses for each condition can be found in Appendix I. Overall, there was only a small amount of missed targets with 6.3 % of the cases with either "no response" or "multiple different responses" within the acceptable temporal window, for the whole experiment in 31 subjects. The "without noise condition" led to slightly

lesser errors (3.9%) compared with the “noise condition” (8.8%). More details can be found in Appendix 1 and on Figure 3-5.

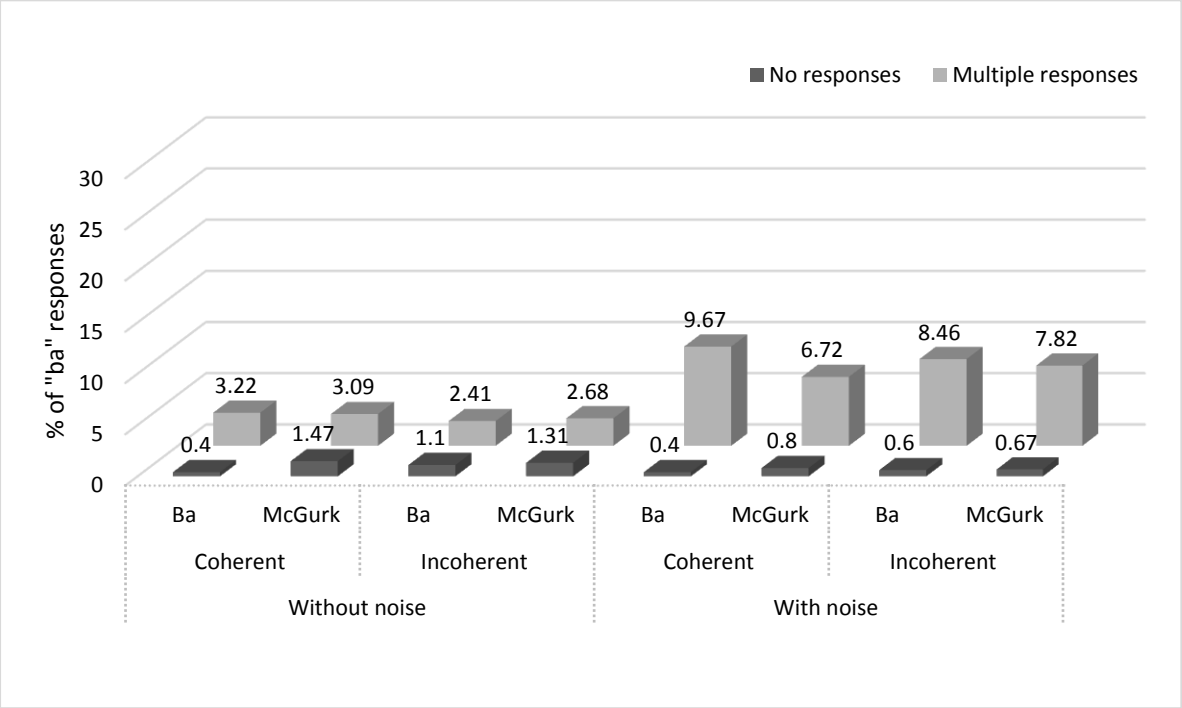

Figure 3-5 Mean number of missed targets. Averaged over the 31 subjects and overall coherent vs. incoherent conditions, for the two noise levels and the two types of targets.

3.3.2 Analysis of the proportion of “ba” responses

As expected, the percentage of “ba” responses for all “ba” targets was close to 100% in all conditions. Therefore, hereafter, only McGurk targets will be considered in the statistical analysis (Figure 3.6). Three factors, context/reset type (coherent vs. incoherent with 4 reset durations, hence 5 possibilities altogether), context duration (two vs. four syllables) and noise (with noise vs. without noise) were analyzed using repeated-measures ANOVA. The Green-house-Geisser correction was applied in the case of violation of the sphericity assumption. *Post-hoc* analyses were used with Bonferroni corrections, and only differences significant after Bonferroni correction were reported ($p<0.05$).

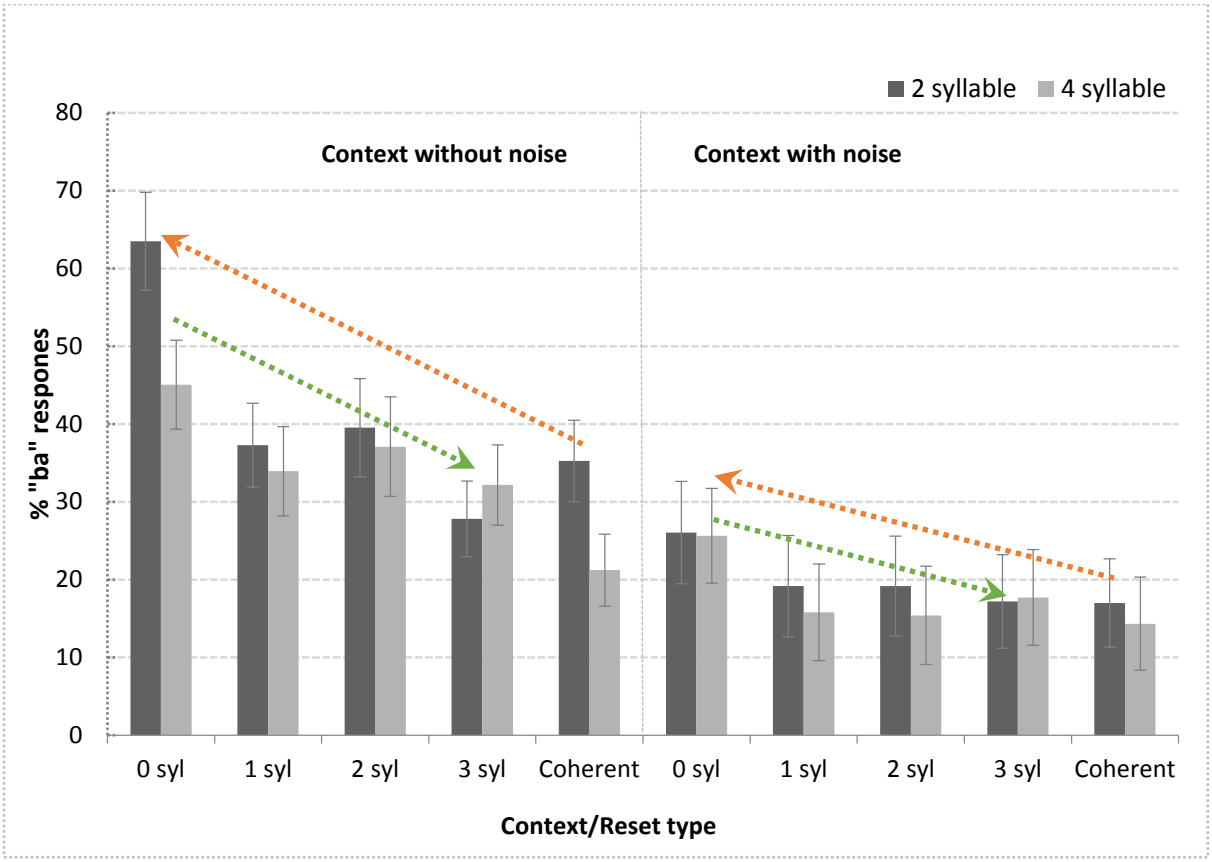

Figure 3-6 Proportion of "ba" responses for "McGurk" targets, without noise (left) or with noise (right) for incoherent context with four reset durations (0syl, 1syl, 1syl or 3syl), compared with coherent context, and for both context durations (2 or 4 syllables). Standard errors are displayed for all conditions. Unbinding (orange) and rebinding (green) are displayed by colored arrows.

The effect of context duration [F (1, 20) =13.55, p<0.005], context/reset type [F (4, 80) =18.59, p<0.001] and noise [F (1, 20) =15.28, p<0.005] were significant. Interactions between context/reset type and context duration [F (4, 80) =3.18, p<0.05], between noise and context duration [F (1, 20) =5.73, p<0.05], between noise and context/reset type [F (4, 80) =4.75, p<0.005] together with overall interaction between all the variables [F (4, 80) =4.85, p<0.05] were also significant. The statistical main effects with all significant effects and interaction effects are summarized in Table 3-2. *Post-hoc* results are displayed in Table 3-3.

Source	d.f=F	Sig.
Noise (with noise vs. without noise)	(1, 20)=15.28	.001
Context duration (2 syl vs. 4 syl)	(1. 20)=13.55	.001
Context/Reset nature (Coherent, 0, 1, 2 & 3 syl reset duration)	(4, 80)=18.59	.000
Noise * Context duration	(1, 20)=5.73	.027
Noise * Context/Reset nature	(4, 80)=4.75	.002
Context duration * Context/Reset nature	(4, 80)=3.18	.018
Noise*Context duration * Context/Reset nature	(4, 80)=4.85	.001

Table 3-2 Detailed results of the three-way repeated-measures ANOVA for response scores for the McGurk target.

This lets emerge the following outcomes.

1) *Replication of "unbinding" and "rebinding".* Globally, the proportion of "ba" responses increases (hence the McGurk effect decreases) from the coherent to the incoherent-without-reset (0 syl reset) condition: this is unbinding. Conversely, the proportion of "ba" responses decreases (hence the McGurk effect increases) in the incoherent context when reset duration increases from 0 syllable to 3 syllables: this is rebinding. Considering the various interactions that are all significant, the amount of unbinding and rebinding depends on noise and context duration. Without noise, the amount of unbinding between the coherent context and the incoherent context without reset amounts to around 25%. It is smaller with noise (around 10% in both context duration). Then complete rebinding (that is, the McGurk effect with incoherent context plus reset comes back to its level for coherent context) does not occur before 3-syllable reset duration in the worst case (without noise, with 2-syllable context duration)

while it can be complete sooner (with one- or two-syllable reset duration in the 2-syllable context duration without noise, or for both context durations with noise).

2) *Replication of the effect of context duration (two vs. four syllables).* As in Nahorna *et al.* (2015), there is a trend that the proportion of "ba" score increases for the smallest context duration (2 syllables). However, the effect appears to depend on context/reset type and noise. *Post-hoc* analyses show that the effect of context duration is present only without noise and for the smallest global duration of context+reset that is for the coherent context (14% difference between scores for the two context durations) or the incoherent context without reset (18% difference).

3) *Evidence that the McGurk effect is modulated by acoustic noise in the context.* Globally, noise decreases "ba" scores (increases the McGurk effect) for all conditions. The effect is large since the addition of noise decreased roughly by half the percentage of "ba" responses in all conditions of context and reset. Indeed, without noise, this percentage increases from about 25% in the coherent or totally rebound 3-syl reset conditions to about 50% in the unbound 0-syl reset condition. With noise, this percentage increases from about 13% in the coherent or totally rebound 3-syl reset conditions to about 25% in the unbound 0-syl reset condition. The consequence is that all statistically significant interaction effects with noise appear as basically ceiling effects, in which the effects of context/reset type and context duration are decreased in the "noise" condition in respect to the "no noise" condition.

Tested Effect	**Tested Variable**	**Post-Hoc Results**
Context duration		2 syl > 4 syl**
Context/Reset nature		0 syl > 1, 2, 3 syl & coherent context** 1, 2, 3 syl & coherent context (n.s.)
Noise		Without noise > With noise**
Context Duration*Noise	2 syl	Without noise > With noise**

	4 syl	Without noise > With noise**
	Without noise	2 syl > 4 syl**
Context Duration * Context/Reset nature	0 syl	2 syl > 4 syl**
	Coherent context	2 syl > 4 syl**
	2 syl	0 syl > 1, 2, 3 syl & coherent context **
	4 syl	0 syl > 1, 3 syl & coherent context *
Noise*Context/Reset nature	Without noise	0 syl > 1, 2, 3 syl & coherent context**
	With noise	0 syl > 1, 3 syl & coherent context**
	0, 1, 2, 3 syl & Coherent context	Without noise > With noise**
Context/Reset nature *Noise*Context Duration		
Between Noise	2 syl	0, 2 syl & coherent context (Without noise > With noise)** 1 & 3 syl (Without noise > With noise)*
	4 syl	0, 1, 2 & 3 syl (Without noise > With noise)**
Between context duration	Without noise	0 & coherent context (2 syl > 4 syl)**
	With noise	2 syl (2 syl > 4 syl)*
Between Context/Reset nature	Without noise	2 syl (0 syl>1, 2, 3 syl & coherent context)** 4 syl (0 syl > 1 syl)*
	With noise	2 & 4syl (0 syl >1, 2, 3 syl & coherent context) n.s.

Table 3-3 *Post-hoc* analysis for response scores for the McGurk target (**=p<0.001, *=p<0.05, n.s= not significant).

3.3.3 Analysis of response time

Response times are displayed on Figure 3.7, averaged over participants and the two context durations. The data were analyzed in a four-way repeated-measures ANOVA with factors target ("ba" vs. McGurk), context/reset type (coherent vs. incoherent with 4 reset durations, hence 5 possibilities altogether), context duration (two vs. four syllables) and noise (with noise vs. without noise). The ANOVA shows an effect of target [F (1, 20) =18.77,

p<0.001], noise [F (1, 20) =102.44, p<0.001], context/reset type [F (4, 80) =5.36, p<0.005], and context duration [F (1, 20) =10.73, p<0.005], but no interaction between any variables (see Table 3-4).

A first finding is that the responses were quicker for all "ba" targets compared to "McGurk" targets (65 ms average difference). Importantly, the lack of interaction between the target and all other variables shows that the effect of AV incongruence in the McGurk target produces the same amount of delay compared with a congruent "ba" target, whatever the noise, context/reset type and context duration. This is compatible with a general finding in all the previous experiments by Nahorna *et al.* (2012; 2015). The effects of context/reset type and context duration are also in line with previous findings in Nahorna *et al.* (2015), with larger response times for shorter contexts (that is, 2-syllable context duration or context without reset). On average, the 2-syllable context duration led to larger response times than the 4-syllable context duration by 29 ms, and the context without reset had larger response times than the context with 3-syllable reset by 25 ms.

Surprisingly, the response was quicker for both targets with noise compared to without noise, with a large difference equal to 143 ms in average. This might seem surprising, but the interpretation is straightforward. Indeed, since noise stops soon after the context, it provides a clear temporal cue for participants regarding arrival of the target stimuli, which results in quicker responses in the "noise" condition.

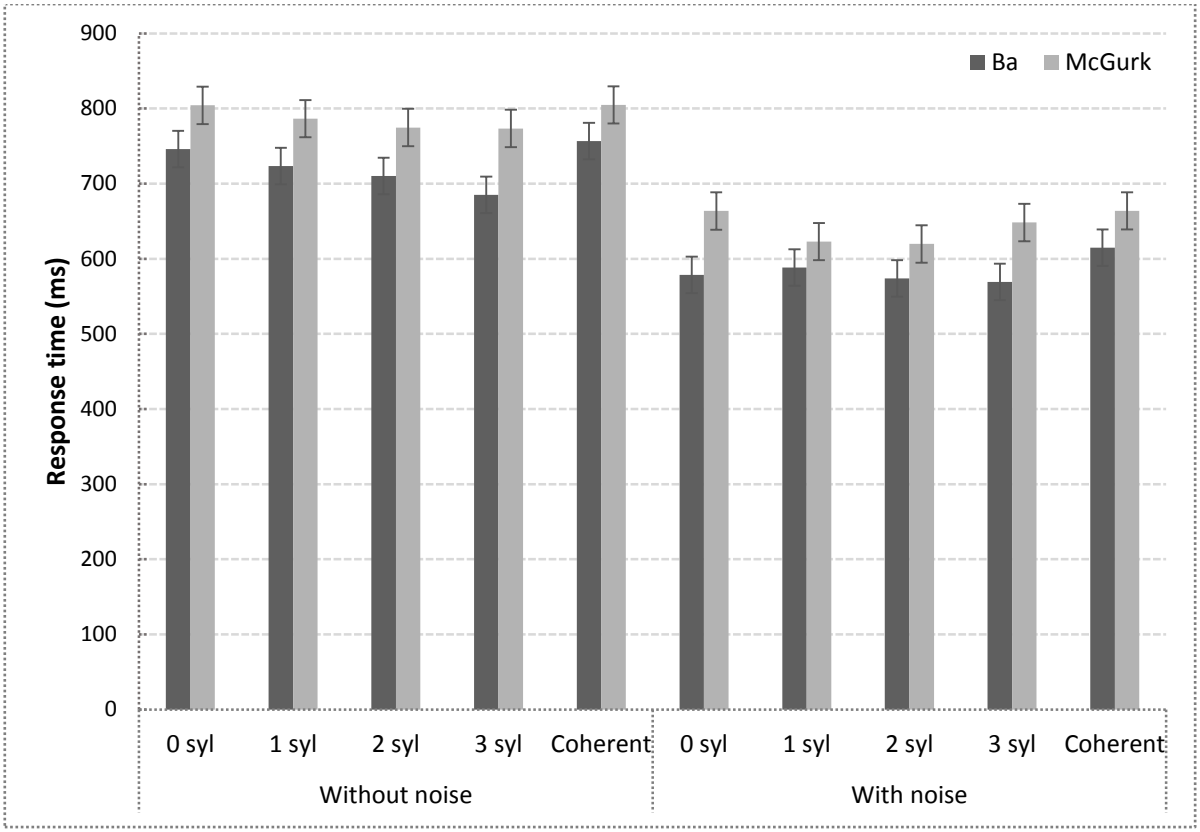

Figure 3-7 Mean response times for "McGurk" and "Ba" targets without noise (left) or with noise (right) for incoherent context with four reset durations (0syl, 1syl, 1syl and 3syl), compared with coherent context. Values are averaged over the two context durations (2 and 4 syllables). Standard errors are displayed for all conditions.

Source	d.f=F	Sig.
Noise (with noise vs. without noise)	(1, 20)=102.44	.000
Context Duration (2 syl vs. 4 syl)	(1, 20)=10.73	.004
Context/Reset Nature (coherent, 0, 1, 2 & 3 syl reset durations)	(4, 80)=5.36	.001
Targets ("Ba" vs. "McGurk"	(1, 20)=18.77	.000

Table 3-4 Detailed results of the four-way repeated-measures ANOVA for response times.

3.4 DISCUSSION

The present results first provide a confirmation about the unbinding/rebinding process: without noise, we obtain a set of experimental results similar to the ones obtained by (Nahorna *et al.*, 2015) and displayed in Figure 1-17. The quantitative differences between the results with a coherent reset in Figure 1-17 and the condition without noise in Figure 3-6 (while the paradigm is exactly the same) come both from classical differences associated with inter-individual variability in the McGurk effect (Schwartz, 2010) and from a difference in the analysis, since all subjects were incorporated in (Nahorna *et al.*, 2015) while only subjects with a certain amount of McGurk effect are incorporated in the present study (see Section 3.3.1).

The results with noise present a first interest: extend the binding paradigm to scenes composed of a mixture of sources and display the same kind of global behavior. Importantly, it appears that in the noisy condition, the role of context decreases in terms of absolute variation of the McGurk effect (compare the dynamics of the unbinding and rebinding effects between the left and right parts of Figure 3-6). This could be due, as expected in Section 3.1, to a decrease in the envelope modulations of the acoustic component of the target, because of noise, and likely to result in a reduction in the AV coherence between lip dynamics and envelope modulations. However, the fact that noise produces an increase in the McGurk effect globally, that we will comment later, also results in possible ceiling effects that could as well explain the decrease in modulations of the McGurk effect with context.

Now we can come back to what is a major result of the present experiment: the global decrease of the percentage of "ba" responses (hence the global increase in fusion rate) associated with acoustic noise added on the context. The result is clear: adding acoustic noise *before* a McGurk target though *not on the target itself* dramatically increases the McGurk effect. Noise systematically decreased the number of auditory "ba" responses by half in all

conditions of context coherence, context duration and reset duration. The fact that this happens while the target stays unchanged strongly supports the hypothesis that the effect occurs at the level of the fusion process.

In the framework of FLMP, it could be argued that the effect, in fact, occurs at the level of the intelligibility of the target components. More precisely, it is difficult to control for the fact that the intelligibility of the auditory component could be modified by the surrounding noise, thus automatically decreasing its role in the multiplicative process. However, this is quite unlikely, for two reasons. Firstly, auditory masking could not explain modification in intelligibility. Indeed, it is known that forward masking effects decrease to zero after 200 ms at most (Moore, 2004). Hence, the 200-ms transition component between context/reset and target ensures that noise in the context/reset cannot decrease the audibility of the acoustic component of the target stimulus.

A second argument comes from the analysis of response times. Indeed, it appears that McGurk targets are processed more slowly than congruent "ba" targets, which is not surprising, but also that the difference in response time is independent of context, reset and noise. It confirms our previous studies (Nahorna *et al.*, 2012; 2015) together with the interpretation proposed in these studies, that the increase in response times for McGurk stimuli is at least partly due to the detection of local AV incoherence, independently on the decision process. The fact that the difference in response times is the same with and without noise confirms that the intelligibility of the auditory component is the same in both conditions.

This result adds to a number of previous studies showing that audiovisual fusion is not entirely automatic, but rather depends on subjects (Schwartz, 2010), language (Sekiyama and Tohkura, 1991), attention (Tiippana *et al.*, 2004; Alsius *et al.*, 2005) and context coherence (Nahorna *et al.*, 2012; 2015) (see Section 1.3.3). It suggests that human listeners are able to

constantly evaluate the level of noise and the conditions of communication, and to monitor the audiovisual fusion process accordingly.

It has been proposed that AV fusion and more generally intersensory fusion would be an optimal process driven by a maximum-likelihood integration mechanism (Massaro, 1998; Ernst and Banks, 2002). The present data indicate that this process could actually be driven by other factors than the stimuli themselves. This could be inserted inside maximum-likelihood computation by adding a prior related to the evaluation of the ambient noise in each sensory stream, or by other priors expressing the confidence a subject has in the value of each sensory information in the integration process. This will be further elaborated in the general discussion (Chapter 7).

Chapter 4

4. AV INTEGRATION WITH COMPETING SOURCES IN THE FRAMEWORK OF AVSSA[2]

4.1 BACKGROUND AND HYPOTHESIS

At the present stage of this Ph.D. work, the situation is the following. Thanks to the previous works by Nahorna *et al.* (2012; 2015), we have reasons to believe that the AV process comprises, at least, two stages, one constantly evaluating AV coherence, and the other one performing AV fusion and decision, and that the output of the first stage modulates the output of the second stage. Modulation is related to the unbinding/rebinding process, by which the subject would decrease/increase her/his confidence that the audio and video sources are coherent, and accordingly decrease/increase the visual weight at the fusion stage.

Our results in the previous chapter showed that subjects also constantly evaluate the reliability of the sensory channels (related to the amount of noise) and that the output of this reliability evaluation also intervenes in AV fusion: the less reliable a sensory channel, the smaller its weight in AV fusion.

In Chapter 1, we have attempted to incorporate the two-stage model inside a theoretical framework that we termed as AVSSA– extending to AV scenes made of various interacting speakers the concepts developed by Bregman and others about ASA. We have suggested that

[2] This is an extended version of a book chapter
Ganesh AC, Berthommier F, and Schwartz J-L (2016). Audio Visual integration with competing sources in the framework of Audio Visual Speech Scene Analysis in Advances in Experimental Medicine and Technology: Physiology, Psychoacoustics and Cognition in Normal and Impaired Hearing, (Springer, New York).

the AV box in the first stage of the proposed model could enable to compute an AV primitive crucial for organizing the AV speech scene.

In the present chapter, we aim to further explore the possibility that a scene analysis process would take place in the course of AV fusion. For this aim, we intend to present a context made of a mixture of sources. In the incoherent context explored by Nahorna *et al.* (2012; 2015), there were implicitly two sources since the audio and video components were incoherent, but there was only one single audio source and one single video source. In Chapter 3, we began to play with two audio sources, but one of the sources was stationary noise, which is a rather specific case of source mixture. We will now present a mixture of two audio sources, one of them being coherent with the video input. Therefore, we expect that the coherence box will now serve two roles: 1) compute partial correlations, which could enable the system to select the audio source coherent with the video input, and 2) assess the binding state modulating AV fusion.

For this aim, we decided to mix two audio sources which have very different properties over time, and which are hence likely to lead to very different correlations with their corresponding video counterpart: a syllable stream and a sentence stream (see Figure 4-1).

Indeed, syllables correspond to stronger AV modulations in time and hence stronger AV coherence than a sentence, as it will be confirmed later. Therefore, the association between the visual input and the corresponding auditory input should be stronger for syllables than for sentences. Hence, the coherence of the AV context would be stronger for syllables, and it would lead to a larger visual weight and more McGurk effect than with the visual sentences.

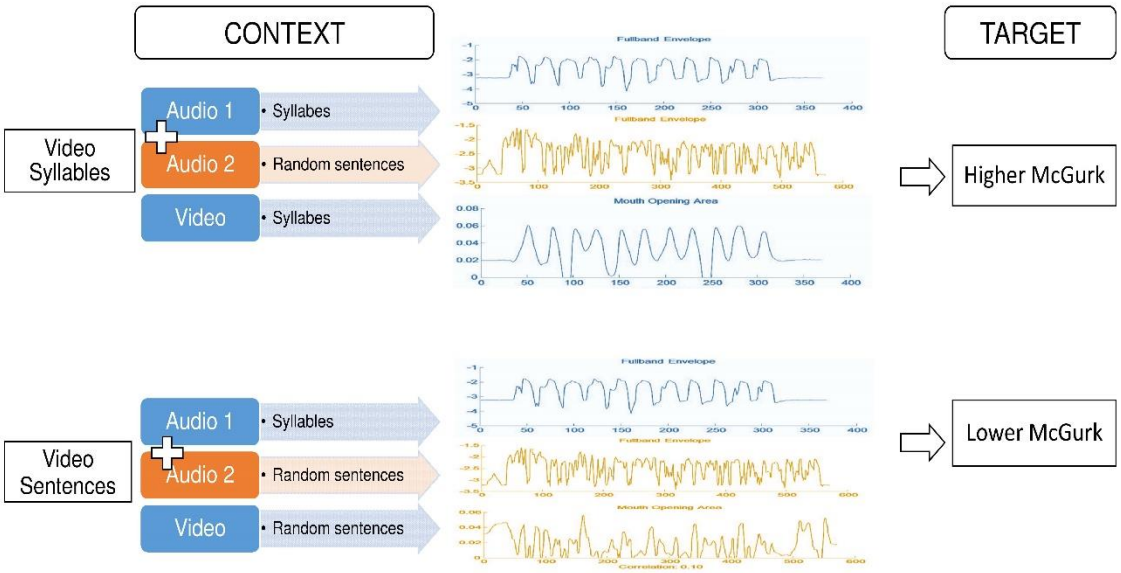

Figure 4-1 Experimental paradigm.

Therefore the first objective of the present set of experiments was to explore the way a context made of a mixture of sources would modify the McGurk effect, and to test the possibility that with a mixture of audio sources with different AV coherence properties, the McGurk effect would indeed differ whether the video component of the context would be coherent with one or the other audio source.

We also expect that an additional streaming mechanism based on rhythm could enhance the difference between the two contexts. Indeed, in the case of an audio mixture presented with video syllables, the extracted AV syllabic stream should be more easily associated with the McGurk syllabic targets inside a single stream which is likely to increase fusion, while video sentences would promote AV sentences less clearly able to be fused in a single stream with the McGurk target.

A second objective of the present chapter was to explore the potential role of attentional mechanisms in the scene analysis process. We reviewed in Chapter 1 various studies displaying how attention could intervene in AV fusion. Some of the proposals concern a global attentional control of fusion related to cognitive load (e.g. Alsius *et al.*, 2005, 2007). Others

deal with specific attentional biases on a single sensory channel (e.g. vision in Tiippana *et al.*, 2004).

Our goal here is to go down to the level of a single source. Previous studies by Andersen *et al.* (2009) or Alsius and Soto-Faraco (2011) explore the way auditory or visual spatial attention intervene in processing mixtures of auditory and visual speech sources (faces and voices). Here, considering that our experimental paradigm involves two competing AV sources, a "sentence" and a "syllable" one, we intend to assess whether attending to one or the other AV source could modify binding and the McGurk effect. For this aim, in a second experiment, we attempted to manipulate the participant's attentional state towards one single AV source and to measure the influence of attention at the level of the binding process rather than at the decision level. Therefore, we instructed participants to focus their attention either on syllables or on sentences in both contexts ("Video syllables" & "Video sentences")

In this second experiment, our assumption was that the attentional load put on a given coherent AV source would reinforce binding and hence increase the McGurk effect. We particularly expected an effect on "Video sentences" supposed to have a rather low binding efficiency and hence to result in low McGurk scores. In this case, we expected that focusing attention on sentences could significantly enhance binding and increase the McGurk effect. On the contrary, "Video syllables" with their intrinsic good AV coherence would probably benefit less from the attentional process.

In summary, the experiments in this chapter were conducted in two parts, Experiment A and Experiment B. Within Experiment A, there was no specific instruction given to participants, and we measured the role of context type (displayed in Figure 4-1) without an explicit attentional focus on any component. We expected a larger McGurk effect with AV syllables. In Experiment B, specific instructions were given to put attention either on syllables or on sentences, and we expected a global increase of the McGurk effect when attention

was oriented towards a coherent AV source (syllables or sentences), though possibly with a larger effect for sentences.

4.2 METHOD AND MATERIALS

4.2.1 Participants

Twenty-nine French participants without hearing or vision problems (22 women and 7 men; 27 right-handed and 2 left-handed; mean age= 29.2 years; SD=10. 4 years) took part in these experiments. Other details on participants and selection criteria were already presented in Chapter 2 (see Section 2.1).

4.2.2 Stimuli

The context and target material came from the same AV material as in the previous experiments. The whole experiment consisted of two types of contexts followed by a target. The target was either a congruent AV "ba" syllable ("ba-target" in the following), serving as a control, or an incongruent McGurk stimulus with an audio "ba" mounted on a video "ga" ("McGurk target" in the following). In the present experiment, the important change in the stimulus was that there were two audio components in the context instead of one as in the previous experiments by Nahorna *et al.* (2012; 2015).

There were two types of contexts i.e. "Video syllables" (Figure 4-2, top) and "Video sentences" (Figure 4-2, bottom). In both contexts, the set of audio stimuli was the same. It consisted of a sequence of 2 or 4 syllables (A-syl-2 or A-syl-4) randomly extracted from the AV "syllables" material mixed with random excerpts of the AV "sentences" material with the adequate duration (A-sent-2 or A-sent-4). The video component consisted in the video stream corresponding either to the syllable source A-syl-2 or A-syl-4 ("Video syllables" context) or to the sentence source A-sent-2 or A-sent-4 ("Video sentences" context). The 2- vs. 4-syllable duration was selected from earlier experiments by Nahorna *et al.* (2015), showing that the effect of incoherent context was maximal (maximal reduction of the McGurk effect)

for short 2-syllable contexts and slightly less for longer 4-syllable contexts. Therefore, in the "Video syllables" contexts, there was an AV "syllables" source competing with an audio "sentences" source, while in the "Video sentences" context, there was an AV "sentences" source competing with an audio "syllables" source (Figure 4-2).

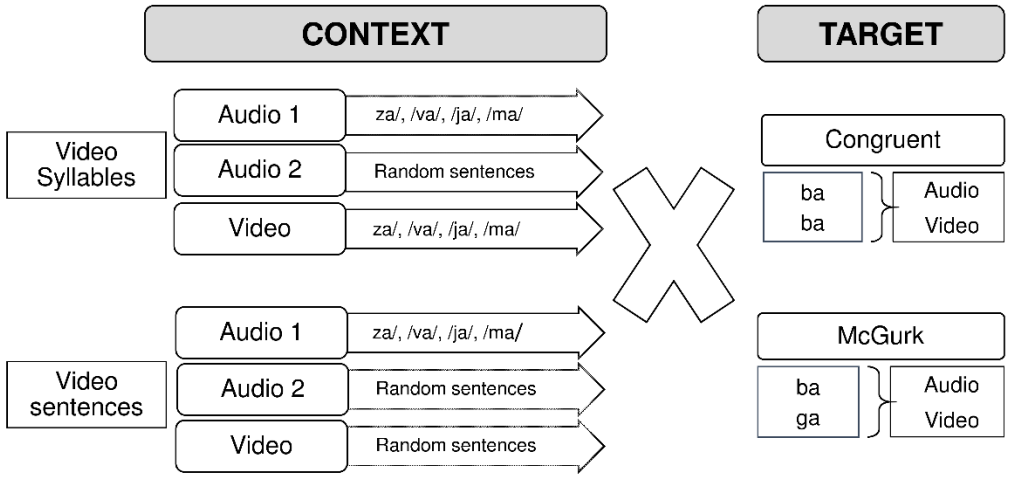

Figure 4-2 Description of the AV material.

The mixture of the two audio signals was carried out using Matlab (Mathworks, Natick, MA, USA), and it was based on the summation of the two auditory stimuli normalized for equal root mean square (RMS) value (for illustration see Figure 4-3). The mixture was then normalized to the same RMS amplitude for both "context" and "target" to ensure stable loudness throughout the experiment. A 200 ms fading transition stimulus (five images) was implemented between context and target to ensure continuity between images using image fusion process without black image. It consisted in a linear interpolation between the last three images in the context and the first two images in the target (more details on image fusion in Section 2.5).

There were altogether 120 stimuli with four times more "McGurk" than "Ba" targets (serving as controls) and with the same number of occurrences of the V-syl-2, V-syl-4, V-sent-2 and V-sent-4 contexts (6 occurrences each for "Ba" targets, 24 occurrences each for McGurk targets). The 120 stimuli were presented in a random order and concatenated into a

single 7-minutes film. The films were presented on a computer monitor with high-fidelity headphones set at a comfortable fixed level.

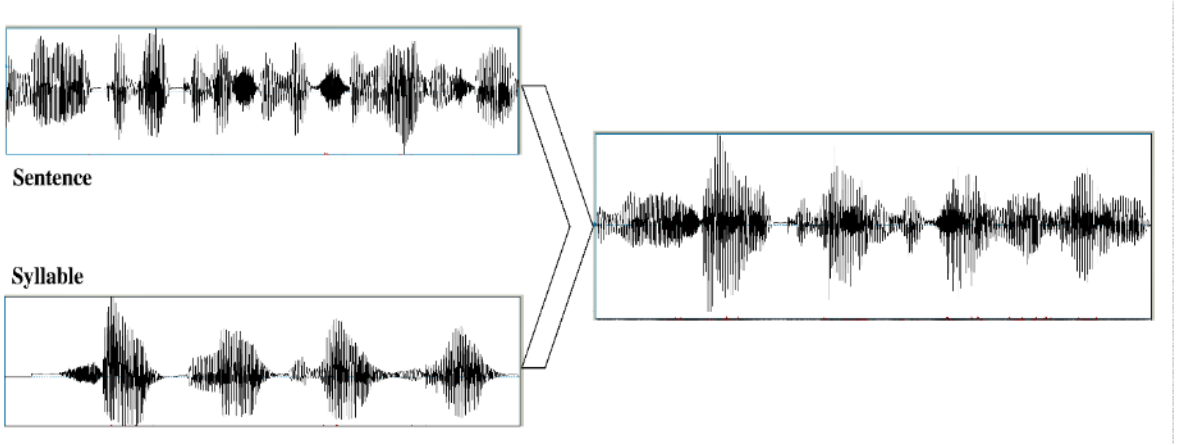

Figure 4-3 Illustration of a mixed auditory signal (syllables + sentences).

4.2.3 Procedure

The study included two consecutive experiments, Experiment A followed by Experiment B (always in this order). In Experiment A, the participants were involved in a monitoring paradigm in which they were asked to constantly look at the screen and monitor for possible “ba” or “da” targets by pressing an appropriate key, as in our previous experiments. In Experiment B the monitoring “ba” vs. “da” task remained the same (with a different order of the 120 stimuli in the film), but in addition, specific instructions were given to participants, to direct their attention either towards the syllables (“Attention syllables”) or towards the sentences (“Attention sentences”). The order of the “Attention syllables” and “Attention sentences” conditions was counterbalanced across the participants.

To increase the efficiency of the attentional demand and to control it to a certain extent, participants were informed that they would be questioned on the content of either the “syllables” or the “sentences” material at the end of the experiment. The questions were of the type “did you perceive the syllable ‘ja’ or ‘va’?” in the “Attention syllables” task, or “did you perceive the word ‘triangle’ or ‘line’?” in the “Attention sentences” task. Most of the partici-

pants were indeed able to recall specific syllables or words. The whole recall task was hence kept as simple as possible, attempting to focus the participants' attention on one or the other source without involving a real dual task likely to have decreased overall the amount of McGurk fusion, according to Alsius *et al.* (2005, 2007).

4.2.4 Processing of response

As described in Section 2.6, responses were detected within a [200-1200] ms time window after the plosive acoustic burst in the target. Then, for each participant and each condition of context and target (and attention in Experiment B), a global score of "ba" responses was calculated as the percentage of "ba" responses divided by the sum of "ba" and "da" responses to the target, and a mean response time was calculated as the average of response times for all the responses to the target.

4.3 Results

4.3.1 Individual data

As expected, the global score (percentage of "ba" responses relative to "ba" + "da" responses) for all control "ba" targets was close to 100 % in all conditions in both experiments. Therefore, from now on we will concentrate on McGurk targets. Individual responses to McGurk targets in the two types of context conditions and averaged over the two context durations in Experiment A are displayed for the 29 participants on Figure 4-4.

The participant rejection criterion implemented for the two experiments in the present study was different from the experiment in Chapter 3. Indeed, in Chapter 3, we used a criterion related to the coherent context condition, which enabled us to keep subjects with a sufficient level of AV fusion for further statistical analysis and to exclude subjects with almost no McGurk effect. However, the present experiment did not involve a condition with coherent context. Therefore, in the present study, we calculated in Experiment A the mean percentage of "ba" scores for McGurk targets over both conditions (i.e. Video syllables and Video sen-

tences) for each participant. The participants with a mean score larger than 95% or less than 5 % were discarded, considering that these subjects provided either too strong or too low McGurk effects to enable binding modulations to be displayed. This resulted in discarding 8 out of 29 participants (see Figure 4-4). All further analyses for both Experiment A and B will hence concern only the 21 remaining subjects.

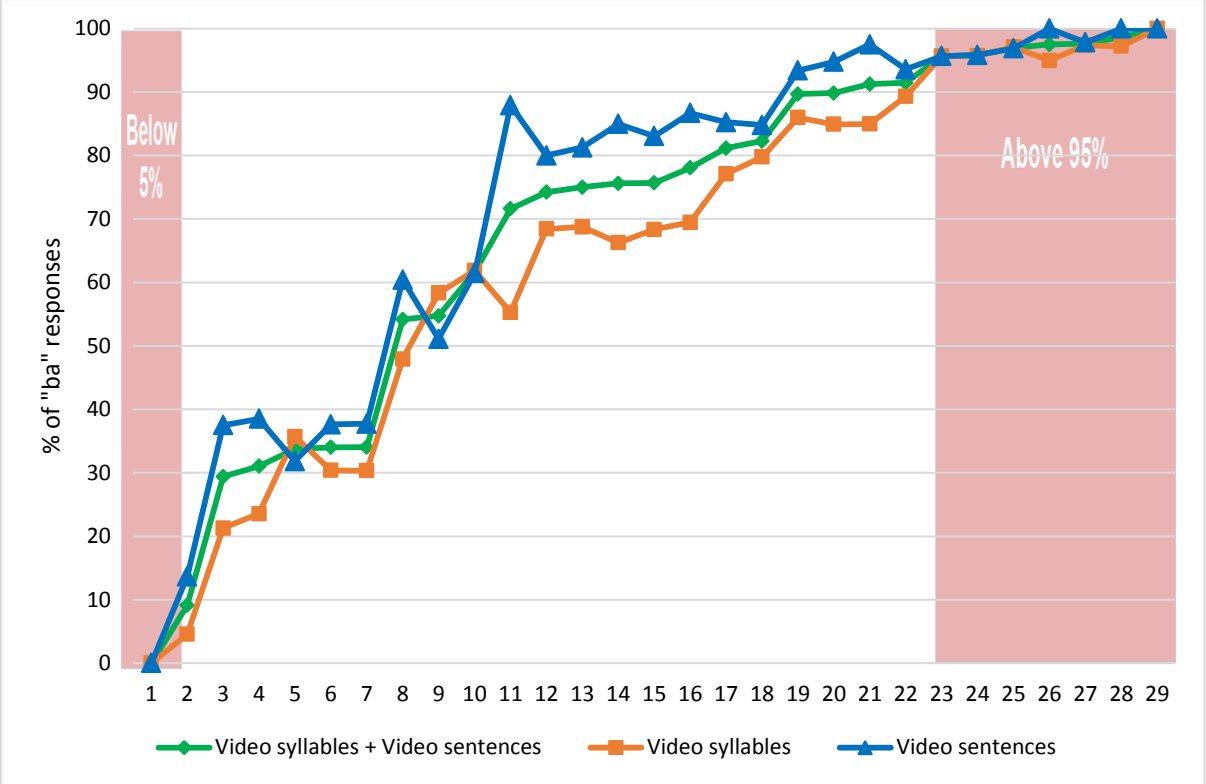

Figure 4-4 Individual mean "ba" scores for McGurk targets for both contexts and averaged over both contexts. The subjects are ordered by increasing score in the average over both contexts (green line).

More details about individual participants' responses for each condition can be found in the confusion matrix in Appendix I. Overall, in 5.3% of the cases there was either "no response" or "multiple responses" (i.e. different responses within the selected time window) in 29 subjects. The details about these different cases can be found in the confusion matrix and in Figure 4-5.

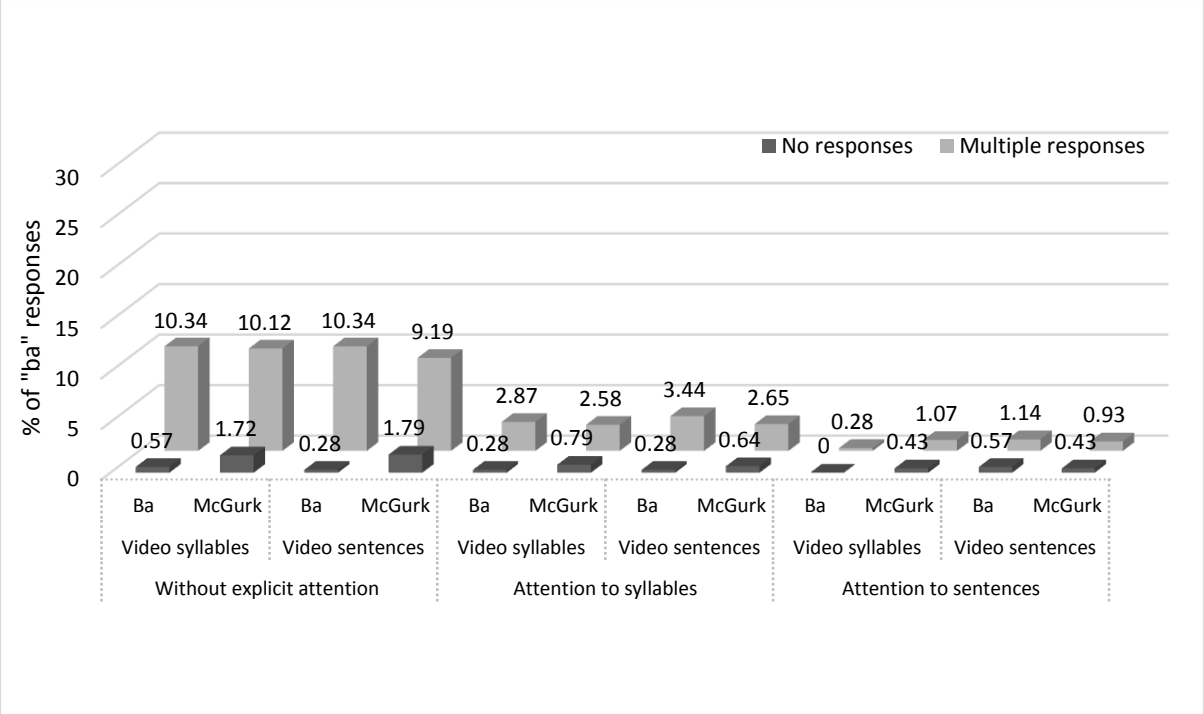

Figure 4-5 Mean number of missed targets. Averaged over 29 subjects for "no response" (no response/total responses) and multiple responses (multiple responses/total responses).

4.3.2 Experiment A - Without explicit attention focus

4.3.2.1 *Analysis of the proportion of "ba" responses*

Percentages of "ba" responses to McGurk targets in Experiment A (without explicit attentional focus) are displayed on Figure 4-6. A two-factor repeated-measures ANOVA with context type ("Video syllables" vs. "Video sentences") and context duration (2- vs. 4-syllables) as the independent variables was administered on these percentages (applying Greenhouse-Geisser correction when applicable). The effect of context type is significant [F (1, 20) =34. 65, p<0.001], with a higher McGurk effect (10 % less "ba" responses) with the "Video syllables" context. This is in line with our prediction that AV coherence is higher in the "Video syllables" condition, leading to a higher binding level, a larger visual weight and hence a larger number of McGurk fusion ("da" responses). Context duration displayed no significant effect on "ba" scores, either in isolation or in interaction with context type.

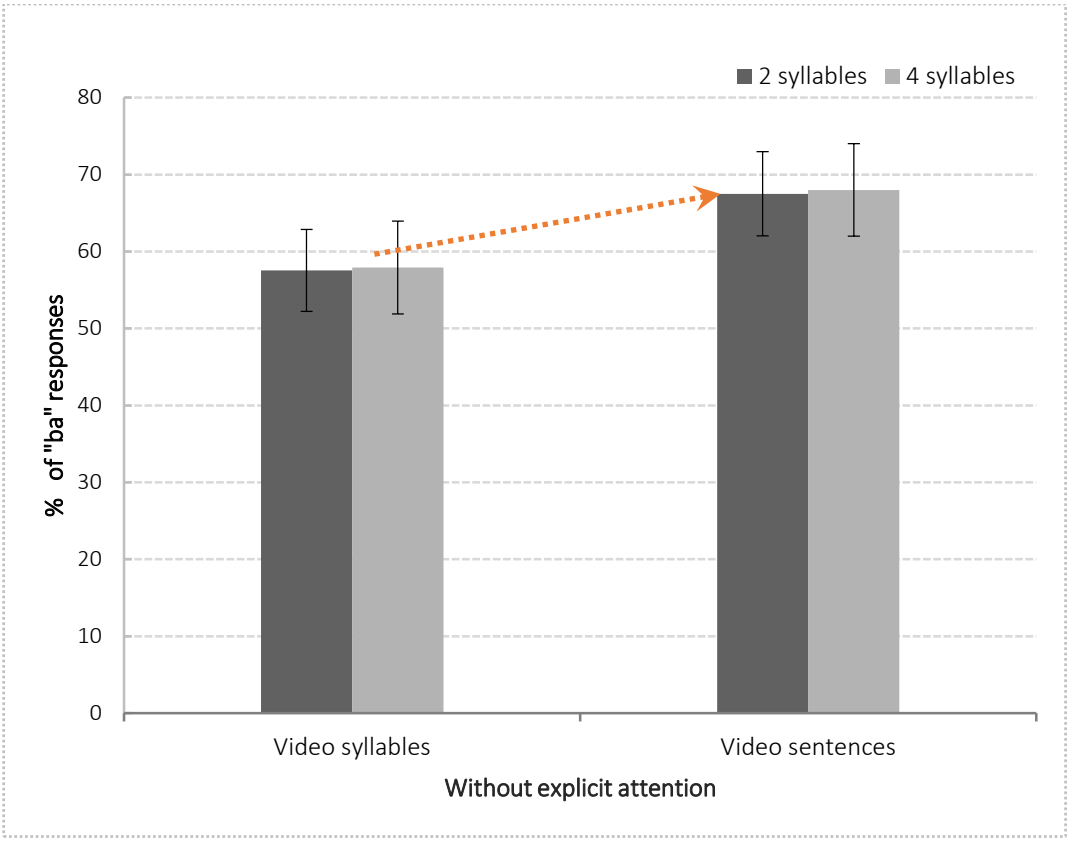

Figure 4-6 The percentage of "ba" responses (relative to the total number of "ba" or "da" responses) for "McGurk" targets, in the "Video syllables" vs. "Video sentences" contexts in Experiment A. The orange arrow displays the significant effect of context type. Standard errors are displayed for all conditions.

4.3.2.2 *Analysis of response time*

Mean response times for Experiment A are displayed in Figure 4-7. The results are consistent with the previous findings (Nahorna *et al.*, 2012) in which response times were larger for McGurk targets, independently on context (see green arrows in Figure 4-7). The processing of "ba" responses was indeed quicker compared to McGurk responses and 2-syllables context duration led to longer response times compared to 4-syllables context duration. A three-way repeated-measures ANOVA on target, context type and context duration in Experiment A displays an effect of target (70ms quicker response for "ba" targets, F (1, 20) =15.42, p<0.005), context duration (44ms quicker response for 4-syllables context duration, F (1, 20) =7.62, p<0.05) and no effect of context nor any interaction effect.

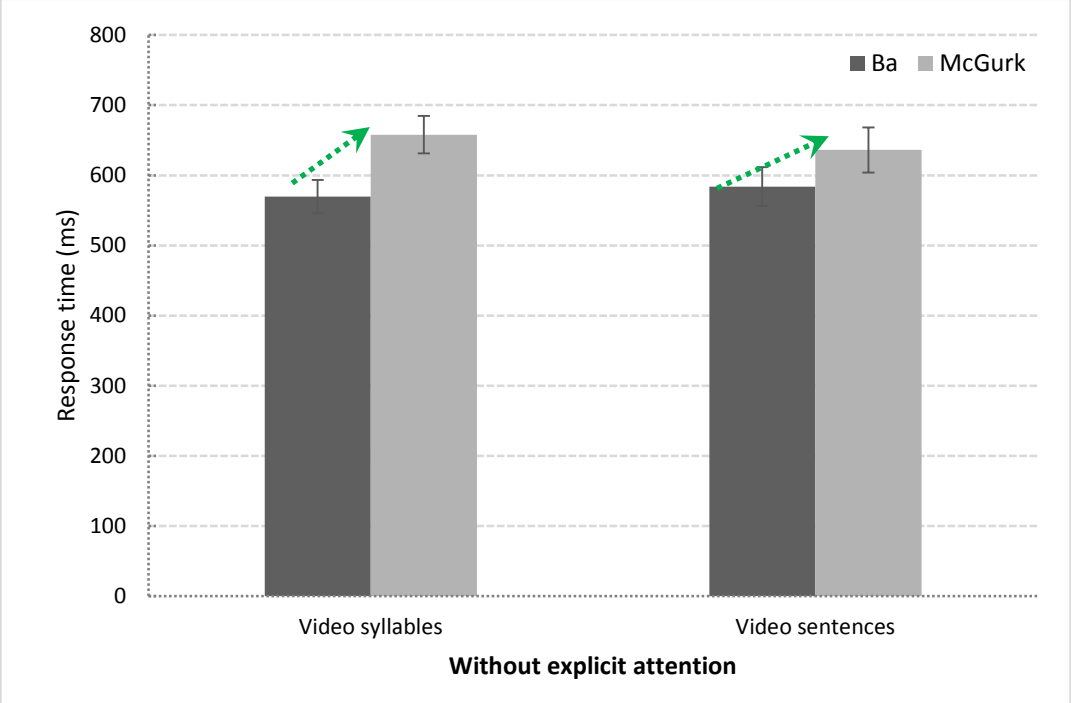

Figure 4-7 Mean response times for "McGurk" and "Ba" targets in Experiment A. Values are averaged over the two context durations (2 and 4 syllables). Standard errors are displayed for all conditions.

4.3.3 Experiment B - On the interaction between context type and attention focus

4.3.3.1 *Analysis of the proportion of "ba" responses*

Percentages of "ba" responses to McGurk targets in Experiment B (involving explicit attention towards one or the other source) are displayed on Figure 4-8. A repeated-measures ANOVA was administered on these percentages with three factors, context type ("Video syllables" vs. "Video sentences"), context duration (2- vs 4-syllables) and attention ("Attention syllables" vs. "Attention sentences"), applying Greenhouse-Geisser correction when applicable. The effect of context type [F (1, 20) =11. 91, p<0.001] is significant (orange arrow), and as in Experiment A "Video syllables" produce more McGurk fusion than "Video sentences". Contrary to Experiment A, the effect of context duration [F (1, 20) =33. 86, p<0.001] is also significant, with more "ba" responses and hence less fusion with the 2-syllables duration relative to the longer 4-syllable duration see green arrows in the Figure 4-2). There is no interaction between context type and context duration.

The attention factor alone is not significant, but its interaction with context type is significant (red and violet arrows) [F (1, 20) =11.07, p<0.005]. *Post-hoc* analyses with Bonferroni corrections show that while there is no significant difference between the two attention conditions for the "Video syllables" context type (violet arrow), there is a difference for the "Video sentences" condition, with a lower "ba" percentage (a higher McGurk effect) in the "Attention sentence" condition (red arrow). Interestingly, *post-hoc* analysis shows that while the "ba" percentage is significantly higher for the "Video sentences" than for the "Video syllables" condition when attention is put on syllables, there is no more significant difference when attention is put on sentences (see Table 4-2).

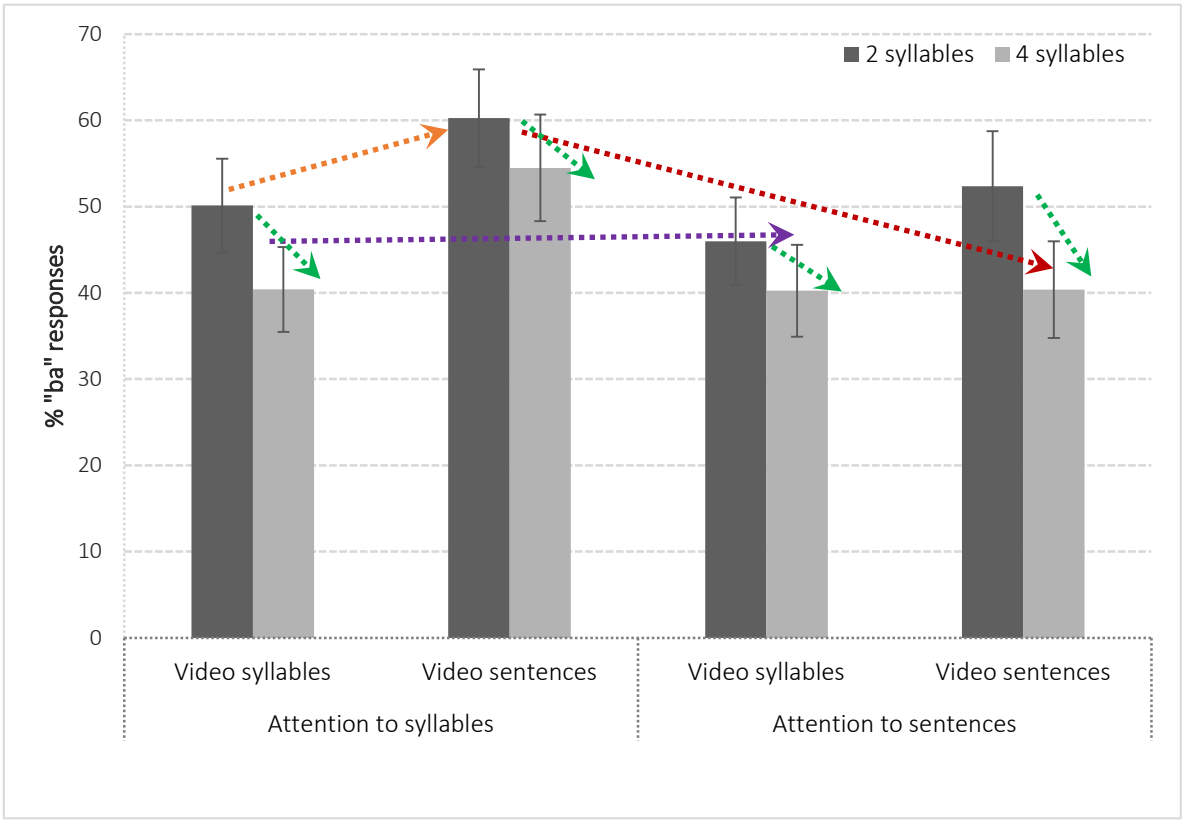

Figure 4-8 The percentage of "ba" responses (relative to the total number of "ba" or "da" responses) for "McGurk" targets, in the "Video syllables" vs. "Video sentences" contexts in Experiment B. The effects of context type, and attention are displayed by colored arrows (see text). Standard errors are displayed for all conditions.

Source	d.f=F	Sig.
Context type (Video syllables vs. Video sentences)	(1,20) =11.91	.003
Context duration (2 syllables vs. 4 syllables)	(1,20) =33.86	.000
Attention*Context	(1,20) =11.07	.003
Attention*Context*Context duration	(1,20) =6.51	.019

Table 4-1 Detailed results of the three-way repeated-measures ANOVA for response scores for the McGurk target.

Finally, the three-way interaction between context type, context duration and attention is significant [F (1, 20) =6. 51, p<0.05], with a larger difference between durations from the "Video syllables" to the "Video sentences" condition in the "Attention sentences" than in the "Attention syllables" condition.

Tested Effect	**Tested Variable**	**Post-Hoc Results**
Context		Video sentences < Video syllables*
Context duration		4 syl < 2 syl**
Context*Attention	Video sentences	Attention to sentences < Attention to syllables *
	Attention to syllables	Video syllables < Video sentences **
Context*Attention*Context duration		
Between Attention	Video sentences	4 syl (Attention to sentences <Attention to syllables)*
Between Context duration	Attention to syllables	Video syllables (4 syl < 4 syl)** Video sentences (4 syl <4 syl)*
	Attention to sentences	Video sentences (4syl < 2 syl)**

Between Context	Attention to syllables	2 syl (Video syllables < Video sentences)* 4 syl (Video syllables < Video sentences)**
	Attention to sentenc-es	2 syl (Video sentences < Video yllables)*.

Table 4-2 Post-hoc analysis for response scores for the McGurk target in Experiment B (**=p<0.001, *=p<0.05, n.s= not significant).

4.3.3.2 *Analysis of response time*

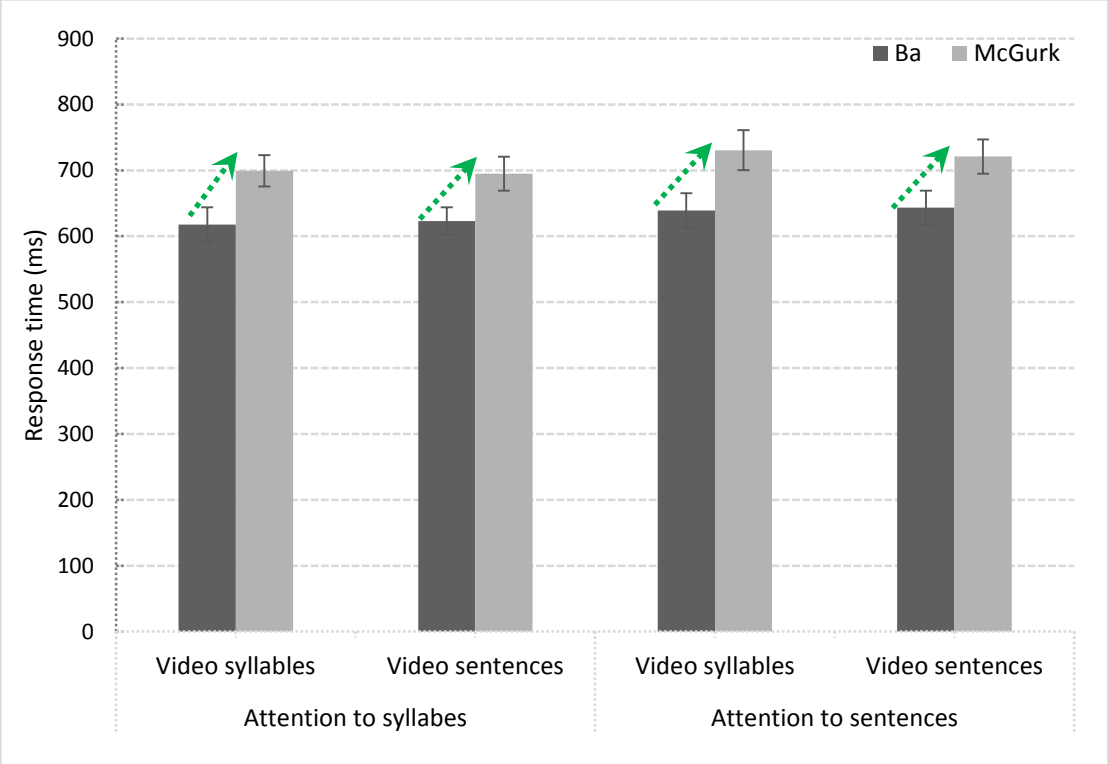

Figure 4-9 Mean response time for all conditions – averaged over both context durations – in Experiment B. Standard errors are displayed for all conditions.

Mean response times for Experiment B are displayed in Figure 4-9. A four-way repeated-measures ANOVA on context type, attention, context duration and target in Experiment B displays once again an effect of target (80ms quicker response for "ba" targets, see green arrows in Figure 4-9), F (1, 20) =27.61, p<0.005), context duration (28 ms quicker response for 4 syllables context duration, F (1, 20) =5.31, p<0.005), and no other significant effect of other factors, alone or in interaction. The results are consistent with the previous

findings (Nahorna *et al.*, 2012) and similar to Experiment A in which response times were larger for McGurk targets, independently on context, and larger for 2-syllable contexts.

4.4 DISCUSSION

The two experiments in the present study confirm once more that context matters in setting the amount of AV fusion, in agreement with the hypotheses about AV binding and the two-stage model introduced by Nahorna *et al.* (2012; 2015). However, it extends these findings in two directions. Firstly it considers for the first time two competing sources in the AV context; secondly, it introduces attentional mechanisms in the process. This sheds important light on the relationship between the two-stage model and AVSSA. Let us analyze the results of the two experiments one after the other.

Experiment A showed that the "Video syllables" context leads to a higher amount of binding and fusion. This can be related to three possible interpretations: (1) global binding/unbinding; (2) syllable/sentence streaming with a higher intrinsic AV coherence for syllables; (3) syllable/sentence streaming with the target embedded in the syllable stream. We will detail each of these three interpretations.

In the first one, it can be assumed that the difference between the two contexts is a direct consequence of the different amounts of AV correlation in the two contexts. Indeed, because of the higher salience and AV coherence in syllables than in sentences, the global AV correlation in the "Video syllables" context is larger than in the "Video sentences" context. On Figure 4-10 we display the envelope variations of the audio mixture of "sentences" and "syllables" together with the variations in time of the mouth opening area for either the "Video syllables" or the "Video sentences". Notice that the mouth opening area can be easily computed thanks to the blue makeup applied on the video (Lallouache, 1990). The AV correlation amounts to 0.21 for the "Video sentences" context, and to 0.47 for the "Video sylla-

bles" context. Therefore, the difference of correlations provides a possible explanation for the difference in fusion, according to the two-stage model introduced in Chapter 1.

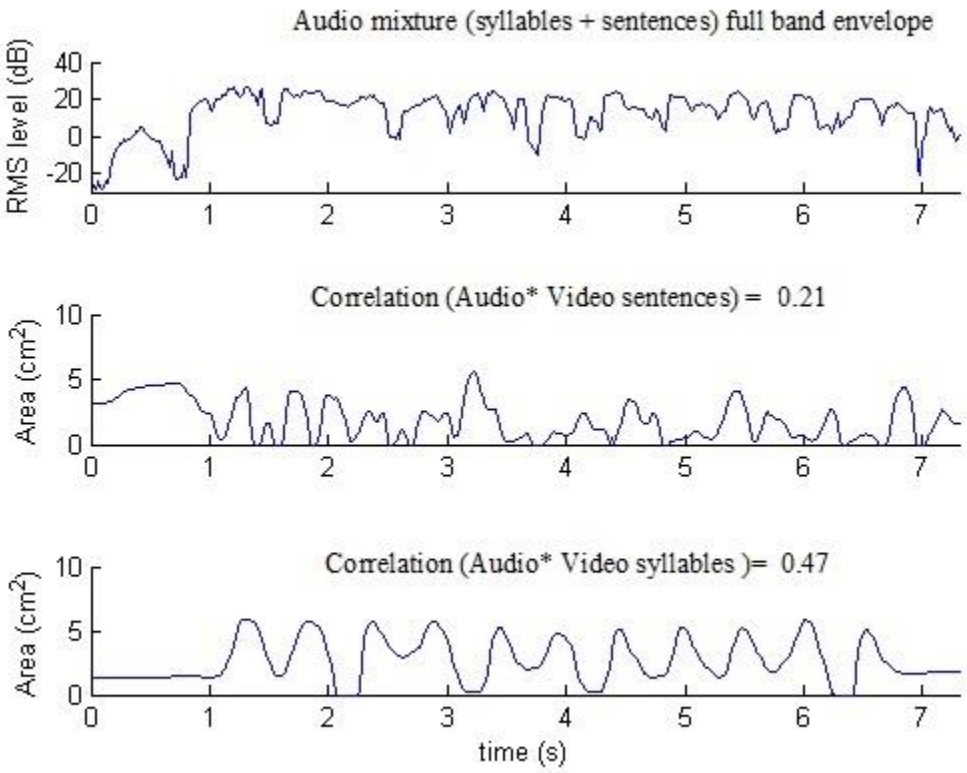

Figure 4-10 Correlation analysis between audio mixture (characterized by the full band envelope) and video stimulus (characterized by the mouth opening area) for video syllables or sentences.

In the second interpretation, there would first be an AVSSA process enabling to separate the two audio sources and associate one source, either the syllables or the sentences, with the video input. Then the effect of context type (larger McGurk effect in the "Video syllables" context) would be due to the differences in AV correlations for syllables and sentences. Indeed, the syllables are regular and salient and lead to high coherence between the audio and video sources, whereas, for sentences, the correlation between sound and image is much fuzzier and leads to less coherence compared to syllables. It is confirmed by a correlation analysis between audio (full band envelope) and video (mouth opening area) material for syllables and

sentences, which provides respective correlation values of 0.63 for “Video Syllables” and 0.10 for “Video Sentences” (Figure 4-11).

Finally, in a third interpretation, there would still exist the first stage of scene analysis in which the adequate audio component would be grouped with the video one, and then the increased level of fusion for the “Video syllables” context would be due to the natural coherence between the syllabic target and the syllable context source. Since the targets are AV syllables, they would be better embedded in the AV syllables in the “Video syllables” context than within the AV sentences in the “Video sentences” context.

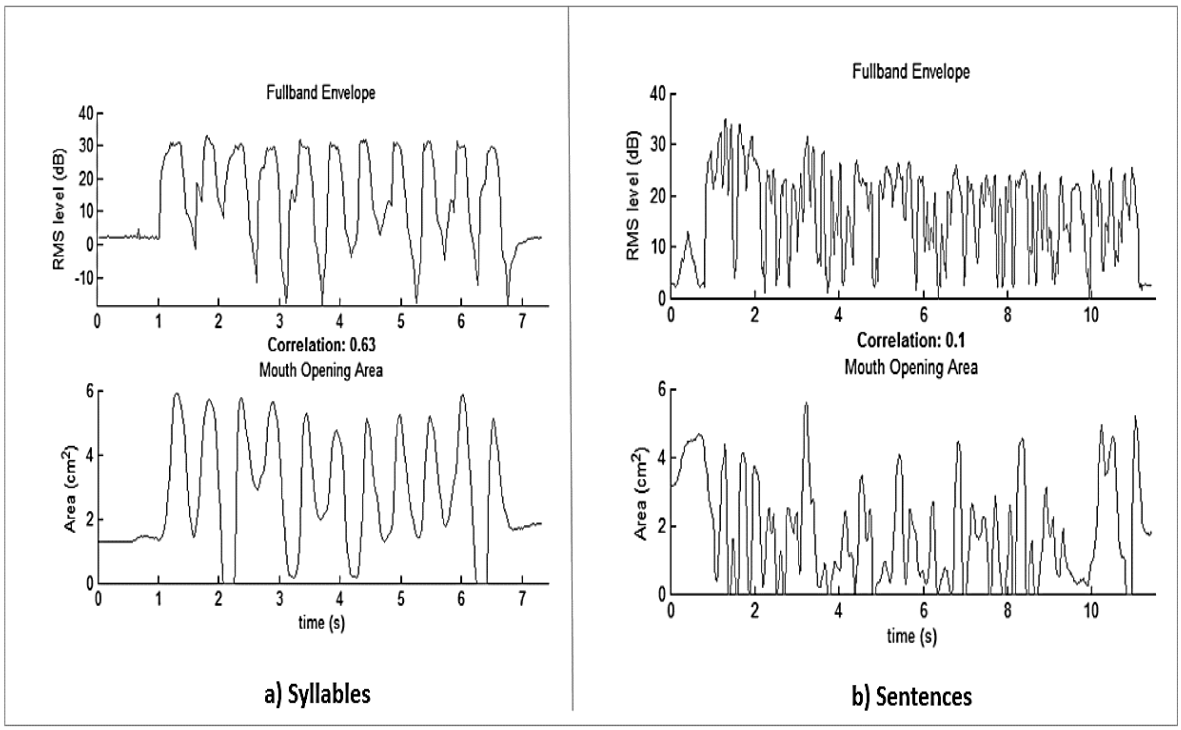

Figure 4-11 Correlation analysis between audio and video stimulus. Variations in time of the audio full band envelope (top row) and the video mouth opening area (bottom row) for syllables (A, left) and sentences (B, right). Notice that the fluctuations in time of the audio and video information are much more coherent between the audio and the video streams for syllables than for sentences.

Experiment B provides experimental data that enable to shed some light on these three interpretations. First of all, they provide attention effects on binding and fusion different from previous experiments. As explained previously in the introduction of this chapter and Chapter

1, attentional processes have been shown to intervene in AV fusion, either at a global level in relation to cognitive load (Alsius *et al.,* 2005; 2007) or at the level of a given modality as in. Tiippana *et al.* (2004). The study by Andersen *et al.* (2009) enables to go a step further and show how attention towards a given source in a particular modality modifies the AV percept. However, here attention is oriented towards a particular AV source rather than a particular auditory or visual source. The fact that attention on a particular AV source modifies fusion suggests that AV speech scene analysis occurs and that its output modulates the fusion process as proposed in the two-stage model. This is rather compatible with the second assumption proposed for Experiment A. Indeed, if fusion modulation were based on global AV coherence (first assumption), attention could not penetrate this global computation process. Also, at the output of the scene analysis process, if the continuity between the syllable context and the syllable target was playing a key role in the difference of fusion (third assumption), attention towards sentences would have no reason to increase fusion.

Therefore the couple of experiments A and B rather suggests that there is an AV scene analysis process, providing more coherent context and hence larger fusion for video syllables, and that attention may enable to increase the perceived coherence of the attended AV source and hence increase fusion when attention is oriented towards the intrinsically less coherent AV sentences.

The results are hence in line with our primary hypothesis and show that attention plays a role only for “Video sentences” but not for “Video syllables”. We suggest that the AV binding could be pre-attentive in “Video syllables” because of their strong, salient AV co-modulations making them pop-out as strong bottom-up AV primitives. A number of previous studies have shown that multisensory interactions may occur in a bottom-up way, whenever there is strong salience between modalities likely to automatically draw attention (Driver, 1996; Van der Burg *et al.,* 2008; 2009). For example, Van der Burg *et al.* (2008) display a

decrement in the search time for a visual object when it is presented with a simple auditory pip. Their interpretation is based on a pop-out mechanism in which the auditory pip, temporally matched with the visual object, would increase its salience without voluntary control of attention. Alsius and Soto-Faraco (2011) found that attentional intervention was needed in detecting temporally correlated AV speech in the case of visual distractors, but it was not required among auditory distractors. In our experiments, the competing sources were auditory, hence, stimulus-driven bottom-up AV integration mechanisms could occur, particularly in the case of the salient AV coherence of the syllables stream.

In contrast, attention appeared to play a role for "Video sentences", in which the AV coherence was relatively low. This suggests that the attentional focus could enhance AV binding. Hence, in this case, top-down schemas seem to play a role in integration.

Overall, our results are in line with the global architecture for multisensory integration proposed by Talsma *et al.* (2010) introducing bidirectional interplay between attention and multisensory processing. However, the present study is rather exploratory. It requires a number of experimental developments and controls, to assess how these potential "bottom-up" and "top-down" processes could depend on the salience of mixed sources (for example the relative intensities of the two sources), the nature of their informational content, the temporal regularity of the syllable stream, etc.

Altogether, the AVSSA process, in which the coherence between auditory and visual features would be evaluated in a complex scene, seems to provide a central mechanism in order to associate the adequate components inside a coherent AV speech source properly. It would result in both source extraction and fusion modulation. The two experiments in this study provide confirmation and development to the view that AV fusion in speech perception includes the first stage of AV speech scene analysis. Their theoretical consequences will be further analyzed in the general discussion.

Chapter 5

5. A POSSIBLE NEUROPHYSIOLOGICAL CORRELATE OF AV BINDING AND UNBINDING[3]

5.1 BACKGROUND AND HYPOTHESIS

The neurophysiological correlates of AV integration were already extensively discussed in Section 1.4.2. To summarize, the bimodal presentation of audio and visual signals resulted in temporal facilitation of the N1/P2 component of the auditory ERPs (Van Wassenhove *et al.*, 2005; Baart *et al.*, 2014; Knowland *et al.*, 2014) and amplitude reduction of the N1/P2 complex (Klucharev *et al.*, 2003; Van Wassenhove *et al.*, 2005; Pilling, 2009; Baart *et al.*, 2014; Knowland *et al.*, 2014) compared to auditory alone condition. The interpretation was generally termed as "predictive mechanisms" (Van Wassenhove *et al.*, 2005), according to which the visual input, arriving ahead of sound, would enable to predict part of its content and hence modulate the auditory ERP in amplitude and latency. Importantly, some literature suggests that the modulation of auditory ERP components by visual speech is different for N1 (possibly based on a non-speech specific anticipation mechanism) and P2 (speech specific and depending on phonetic content) (Stekelenburg and Vroomen, 2007; Vroomen and Stekelenburg, 2010).

The influence of the visual input on N1/P2 can be modulated under certain circumstances, for example, introducing temporal AV asynchrony (Pilling, 2009) or increasing attention load by imposing a dual task paradigm (Alsius *et al.*, 2014). However, to our knowledge,

[3] This is slightly modified version of a paper published in Frontiers in Psychology.
Ganesh AC, Berthommier F, Vilain C, Sato M and Schwartz J-L (2014) A possible neurophysiological correlate of audiovisual binding and unbinding in speech perception. *Front. Psychol.* **5**:1340.

none of the previous electrophysiological studies have reported the role of context in the AV integration. Capitalizing on the previous results obtained by Nahorna *et al.* (2015) and also by electrophysiological studies on AV interactions, we aimed at determining a possible neuro-physiological marker of the AV binding/unbinding process in the cortical auditory speech pathways. Therefore, in the present experiment we will search for a neurophysiological correlate of early binding/unbinding in AV interactions, by adding either a coherent or an incoherent AV context before an auditory, congruent AV or incongruent AV speech target and measuring the effect of context on amplitude and latency of the N1/P2 component of the ERP response to the target.

The basic assumption of the present study is that with coherent context we should replicate the results of previous EEG studies on auditory N1/P2 responses (decrease in amplitude and latency in the AV vs. A condition) (Klucharev *et al.*, 2003; Besle *et al.*, 2004; Van Wassenhove *et al.*, 2005; Stekelenburg and Vroomen, 2007; Pilling, 2009; Vroomen and Stekelenburg, 2010; Stekelenburg and Vroomen, 2012; Baart *et al.*, 2014; Knowland *et al.*, 2014; Treille *et al.*, 2014a; b) (see Figure 5-1 top). However, an incoherent context should lead to unbinding (as robustly displayed by behavioral data in Nahorna *et al.* 2012; 2015), with the consequence that the visual influence on the auditory stimulus should decrease. Hence, the N1/P2 latency and amplitude in the AV condition should increase (reaching a value close to their value in the A condition) in the incoherent context compared with the coherent context (see Figure 5-1 bottom).

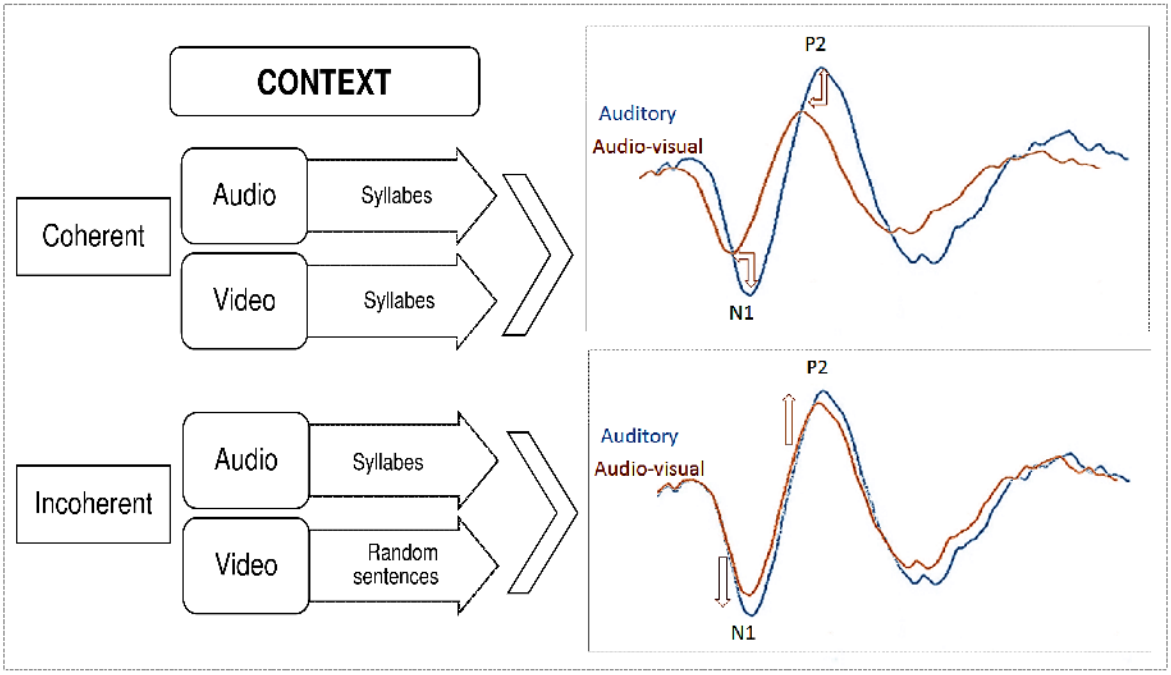

Figure 5-1 Experimental paradigm for the EEG experiment.

5.2 Methods and Materials

5.2.1 Participants

Nineteen healthy volunteers (17 women and 2 men, all right-handed, mean age = 30 years, SD = 13.1 years) participated in the experiment. Other details on participants and selection criteria were already discussed in Section 2.1.

5.2.2 Stimuli

As in our previous experiments, the AV stimuli were made of an initial part called "context" followed by a second part called "target." Contrary to the behavioral experiments in Chapters 3 and 4, the "targets" in the present experiment were voiceless plosives ("pa" & "ta") instead of voiced plosives "ba" and "da". This choice was done to avoid the prevoicing component in voiced plosives, which would drastically reduce the N1/P2 response to the plosive release. The target was either a pure audio stimulus ("pa" or "ta" dubbed with a fixed face image with the same duration), or a congruent AV stimulus ("pa" or "ta") or an incongruent "McGurk" stimulus (audio "pa" dubbed on a video "ka").

The AV context was either coherent or incoherent (Figure 5-2). Coherent contexts consisted of regular sequences of coherent AV syllables randomly selected from the recorded AV "syllables" material. These syllables were carefully extracted from the set of possible /Ca/ syllables in French, where C is a consonant not contained in the /p t k b d g/ set, so that target syllables /pa, ta, ka/ or their perceptually voiced counterparts /ba, da, ga/ did not appear in the context. In the incoherent context material, as in previous experiments, the auditory content was exactly the same as in the coherent context, but the visual content was replaced by excerpts of the video "sentences" material and matched in duration. The context duration of both coherent and incoherent context was always four syllables.

The context and target were separated by a 1 s period of silence associated with a fixed black image. Importantly, such a period of silence and fixed image has been shown by Nahorna *et al.* (2015) to maintain the unbinding effect (see Figure 1-17). Therefore silence should enable to let the auditory system recover from the context period to generate a normal value of N1/P2, while freezing the unbinding state and possibly removing the effect of the video input on the ERP components.

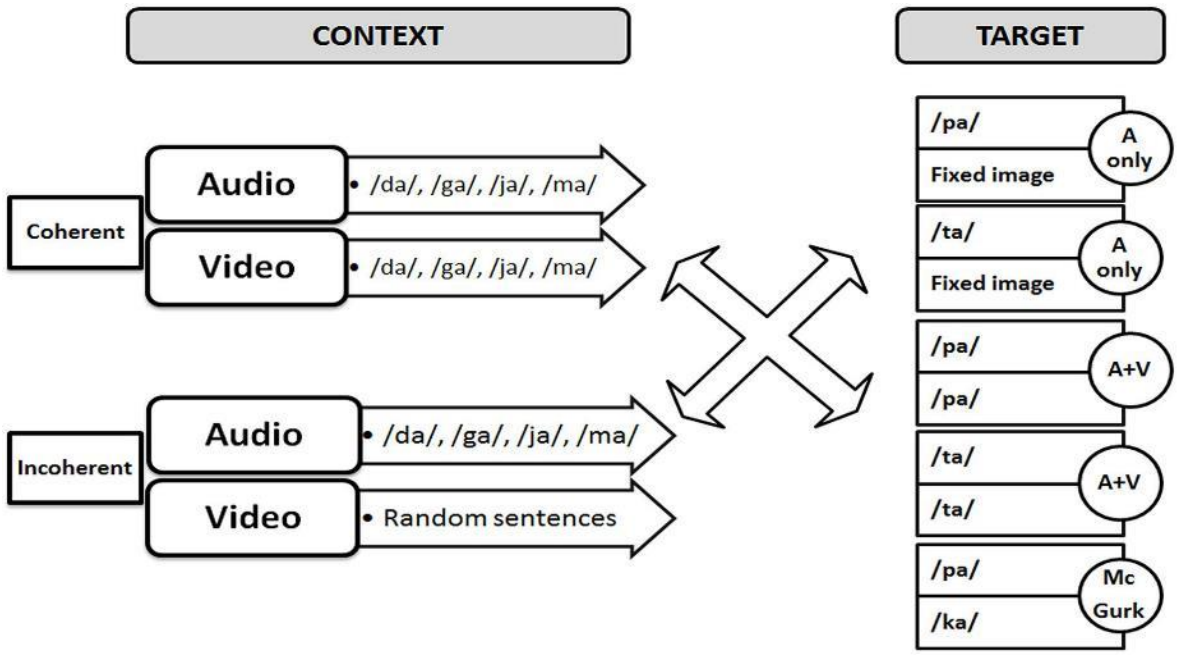

Figure 5-2 AV material used in the EEG experiment.

The duration of each trial was 5280 ms, in which the context AV movie, lasting 2000 ms, was followed by silence for 1000 ms, then by the target with a duration of 1080 ms (see Figure 5-3). Visual continuity between the end of the context stimulus and silence and between silence and the onset of the target stimulus was obtained by a 120-ms transition stimulus without black image. In the auditory-only conditions, the auditory targets were presented with a static image of the speaker's face. The difference between the visual and auditory onsets for /pa/ and /ta/ were respectively 287 and 206 ms.

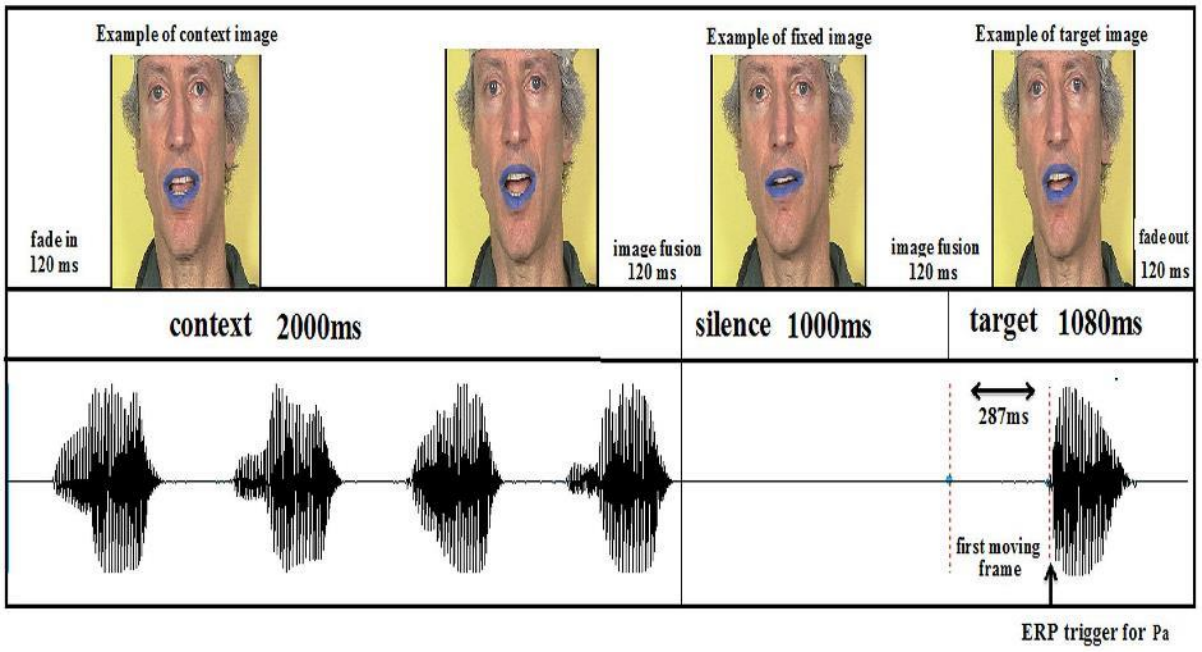

Figure 5-3 Experimental sequence.

5.2.3 Procedure

The subject's task was to categorize the stimuli as "pa" or "ta," by pressing the appropriate key (two-alternative-forced-choice identification task). Stimulus presentation was coordinated with the Presentation software (Neurobehavioral Systems). In order to avoid possible interference between speech identification and motor response induced by key pressing, participants were told to produce their responses a short delay after the stimulus end when a question mark symbol appeared on the screen (320 ms after the end of the stimulus). Therefore, because of the specific requirement of the ERP paradigm, the recording of responses in

the present experiment differed from the online monitoring task used in the previous experiments. There were six conditions, with three targets (audio-only, A vs. AV congruent, AVC vs. AV incongruent, AVI) and two contexts (coherent vs. incoherent), and altogether 100 repetitions per condition (with 50 “pa” and 50 “ta” in the audio-only or AV congruent targets, and 100 McGurk stimuli) (see Figure 5-2). This provided 600 occurrences, presented in a random order inside five experimental blocks altogether. Overall, the experiment lasted more than one hour, including subject preparation, explanations and pauses between blocks. This unfortunately removed the possibility to add a specific visual-only condition, since it would have added two targets – visual congruent and visual incongruent – and hence almost doubled the experiment duration. We will discuss later what the consequences of this specific choice could be in the processing and interpretation of EEG data.

5.2.4 EEG Parameters

EEG data were continuously recorded from 64 scalp electrodes (Electro-Cap International, Inc., according to the International 10–20 system) using the Biosemi Active Two AD-box EEG system operating at a 256 Hz sampling rate. Two additional electrodes served as reference [common mode sense (CMS) active electrode] and ground [driven right leg (DRL) passive electrode]. One other external reference electrode was put at the top of the nose. Electrooculogram measures of the horizontal (HEOG) and vertical (VEOG) eye movements were recorded using electrodes at the outer canthus of each eye as well as above and below the right eye. Before the experiment, the impedance of all electrodes was adjusted to get low offset voltages and stable DC.

5.2.5 Analyses

All EEG data were processed using the EEGLAB toolbox (Delorme and Makeig, 2004) implemented in Matlab (Mathworks, Natick, MA, USA). EEG data were first re-referenced offline to the nose recording and band-pass filtered using a two-way least-squares FIR filter-

ing (2–20 Hz). Data were then segmented into epochs of 600 ms including a 100 ms pre-stimulus baseline, from –100 to 0 ms referred to the acoustic burst onset of the target syllable, individually determined for each stimulus from prior acoustical analyses. Epochs with an amplitude change exceeding ±100 μV at any channel (including HEOG and VEOG channels) were rejected (<5%).

As previously noted, because of time limitations a visual-alone condition was not incorporated in the study, while it is generally included in EEG studies on AV perception. However, to attempt to rule out the possibility that visual responses from the occipital areas could blur and contaminate auditory evoked responses in fronto-central electrodes, we performed various topography analyses using EEGLAB to define the spatial distributions and dynamics of the activity on the scalp surface. Fp1, Fz, F2, P10, P9, and Iz electrodes were not included in this analysis because of noisy electrodes or dysfunction of electrodes for at least one participant. We studied the spatial distribution in two steps. Firstly, we plotted the scalp maps for all six conditions (context × modality) to confirm that the maximal N1/P2 auditory evoked potentials were indeed localized around fronto-central sites on the scalp. The aim of the second step was to evaluate the presence and amount of possible contamination in the auditory fronto-central electrodes by the visual responses in corresponding cortical areas dedicated to the processing of visual information. To do so, we calculated scalp maps between conditions in the N1/P2 time period.

Since the first part of the topographic analysis confirmed that maximal N1/P2 auditory evoked potentials indeed occurred over fronto-central sites on the scalp [see Figure 5-4; see also Scherg and Von Cramon (1986); Naatanen and Picton (1987)], and in line with previous EEG studies on AV speech perception and auditory evoked potentials [e.g. (Van Wassenhove *et al.*, 2005; Stekelenburg and Vroomen, 2007; Pilling, 2009; Vroomen and Stekelenburg, 2010; Treille *et al.*, 2014a; b)], an ERP analysis was then conducted on six representative left,

middle, and right fronto-central electrodes (F3, Fz, F4, C3, Cz, C4) in which AV speech integration has been previously shown to occur (note that Fz was replaced by the average of F1 and F2 responses for two participants because of a dysfunction of electrodes). For each participant, the peak latencies of auditory N1 and P2 evoked responses were first manually determined on the EEG waveform averaged over all six electrodes for each context and modality. Two temporal windows were then defined on these peaks ±30 ms in order to individually calculate N1 and P2 amplitude and latency for all modalities, context and electrodes. Peak detection was done automatically.

For P2 amplitude and latency it has to be noticed that the N1-to-P2 latency could reach small values as low as 75 ms, with double P2 peaks for many subjects. This is not unclassical: double peaks in the P2 time period have actually been found in a number of studies in both adults, children, elderly and also in impaired populations (Ponton *et al.*, 1996; Hyde, 1997; Ceponiene *et al.*, 2008; Bertoli *et al.*, 2011). Since the classical range for P2 is 150–250 ms and since the first P2 peak was close to this range, the analysis was focused on the first P2 peak for further analyses.

Notice that we also tested another baseline earlier on in the silence portion between context and target that is from –500 to –400 ms to the acoustic target syllable onset, and we checked that this did not change the results presented later, in any crucial way, either in whole graphs or statistical analysis.

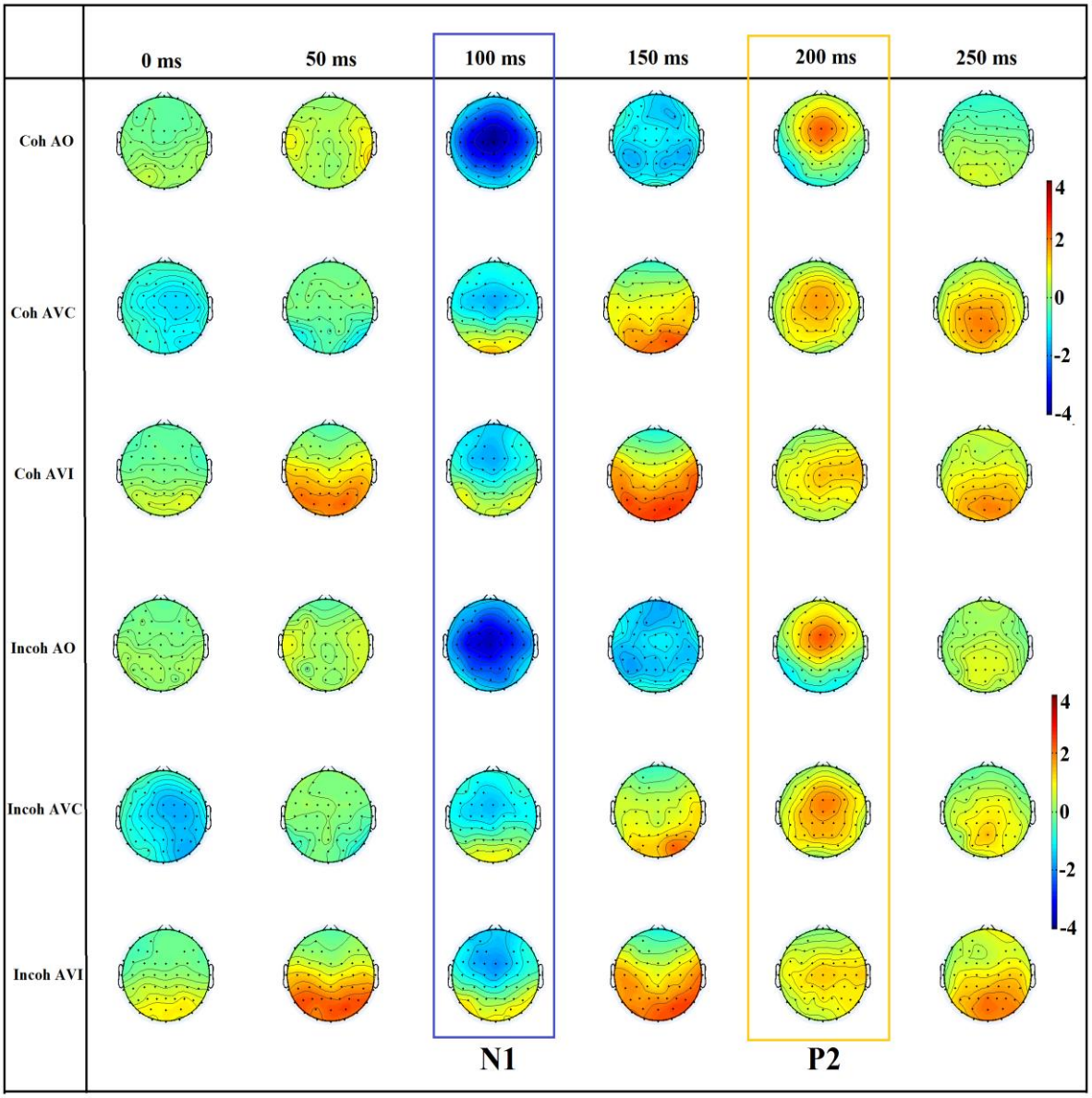

Figure 5-4 The scalp topography of N1 and P2 for the six conditions (Coh AO, Coh AVC, Coh AVI, Incoh AO, Incoh AVC, Incoh AVI) in time steps of 50 ms. The range of the voltage maps is from –4 to 4 μv.

Repeated-measure ANOVAs were performed on N1 and P2 amplitude and latency with context (coherent vs. incoherent) and modality (A vs. AVC vs. AVI) as within-subjects variables. *Post-hoc* analyses with Bonferroni correction were done when appropriate, and are reported at the $p < 0.05$ level.

Concerning behavioral data, the proportion of responses coherent with the auditory input was individually determined for each participant, each syllable, and each modality. A repeated-measures ANOVA was performed on this proportion with context (coherent vs.

incoherent) and modality (A vs. AVC vs. AVI) as within-subjects variables. *Post-hoc* analyses with Bonferroni correction were done when appropriate, and are reported at the $p < 0.05$ level.

5.3 RESULTS

5.3.1 Behavioral analysis

On Figure 5-5, we display the behavioral scores, presented as percentage of responses coherent with the auditory input. The scores were close to 100% in the A and AV conditions. They were lower in the AVI conditions since the visual input changes the percept and produces some McGurk effect. The main effect of modality of presentation was significant [$F(2, 36) = 6.14$, $p < 0.05$], with more correct responses in A and AVC than in AVI modalities (as shown by *post-hoc* analyses; on average, A: 98.2%, AV: 98.3%, and AVI: 77.7%). There was no significant effect of context or interaction. Contrary to our previous studies (Nahorna *et al.*, 2012; 2015), the amount of McGurk effect is hence very small and independent of context. This is likely due to the specific procedure associated with EEG experiments in which the number of different stimuli is quite low (only five different target stimuli altogether) with highly predictable targets.

Of course, contrary to the previous experiments, we did not discard subjects with a low-level of McGurk effect, since the effect of context on congruent targets (AV condition) was also of major interest here.

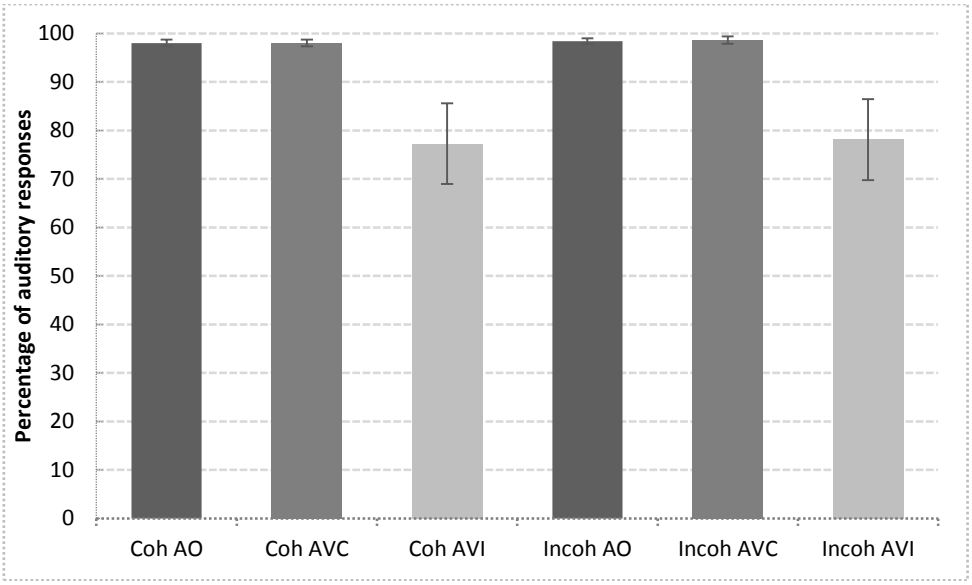

Figure 5-5 Mean percentage of auditory responses in each modality and context presentation in the behavioral experiment. Standard errors are displayed for all conditions.

5.3.2 EEG Analyses

5.3.2.1 *N1 amplitude and latency*

In the following analysis, N1 amplitudes were reported in absolute values, hence reduced amplitude means a reduction in absolute value and an increase in real (negative) values. The repeated-measures ANOVA on N1 amplitude displayed no significant effect of context, but a significant effect of modality [F (2,36) = 13.29, $p < 0.001$], with a reduced N1 amplitude observed for the AVC and AVI modalities as compared to the A modality (Figure 5-6 & 5-7a). The *post-hoc* analysis shows that the amplitudes in both AVC (–2.00 μV) and AVI (–1.64 μV) were indeed smaller compared to A (–3.62 μV) irrespective of context. The interaction between context and modality was not significant.

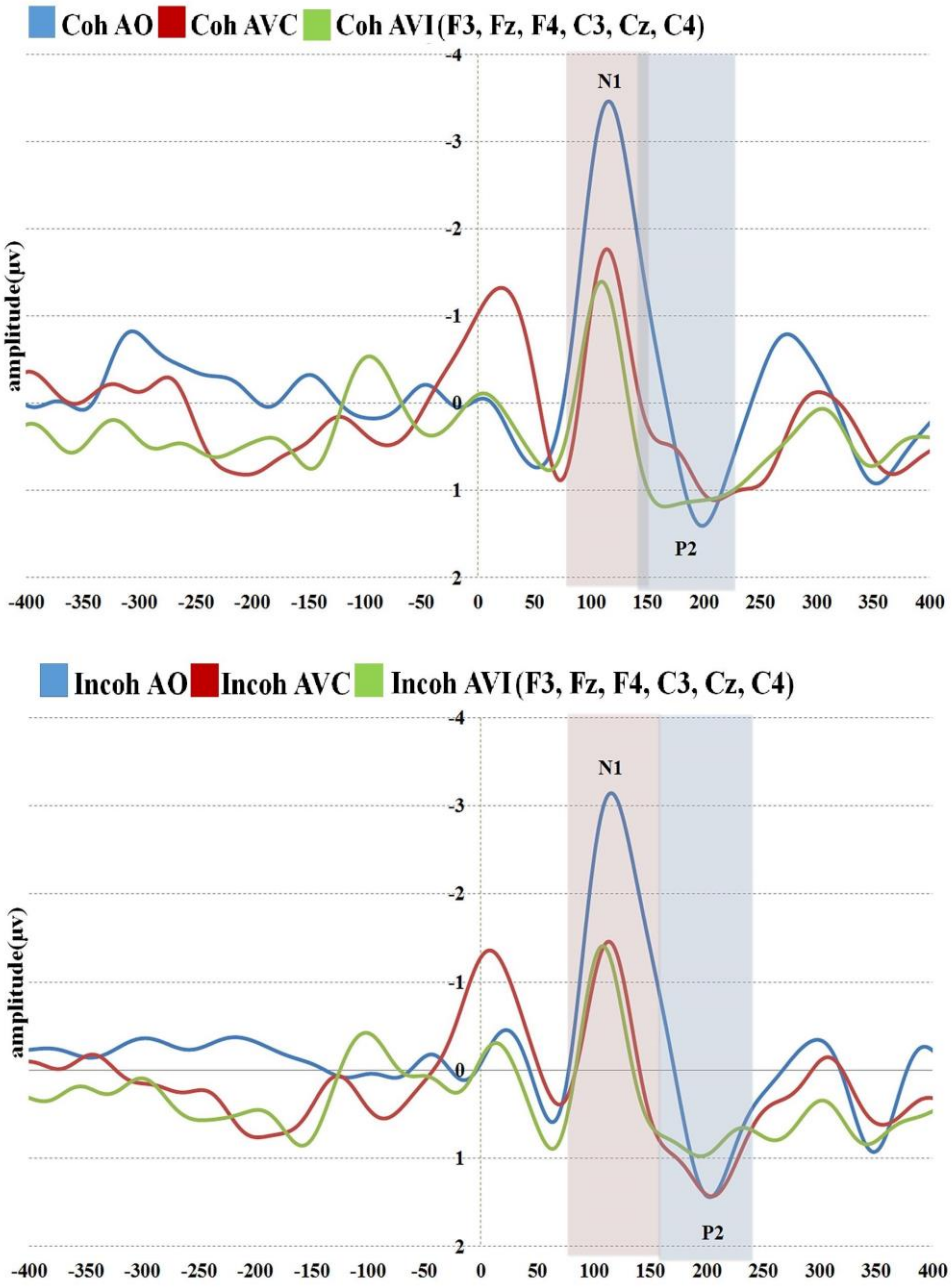

Figure 5-6 Grand-average of auditory evoked potentials for the six electrodes (frontal and central) for coherent (top) and incoherent (bottom) context and in the three conditions (AO, AVC, and AVI).

The repeated-measures ANOVA on N1 latency displayed no significant effect of context (Figure 5-6 & 5-7b). The modality effect was close to significance [F (2,36) = 3.20, p = 0.07], with a shorter latency in the AVI (109 ms) compared to the A (115 ms) and AVC (115 ms) conditions. The interaction between context and modality was not significant.

In brief, the results about N1 amplitude are similar to the previously mentioned EEG studies on AV speech perception, with a visually induced amplitude reduction for both

congruent (AVC) and incongruent (AVI) stimuli irrespective of context. Regarding N1 latency, the difference between auditory and AV modalities is smaller than in few previous EEG studies, and consequently not significant.

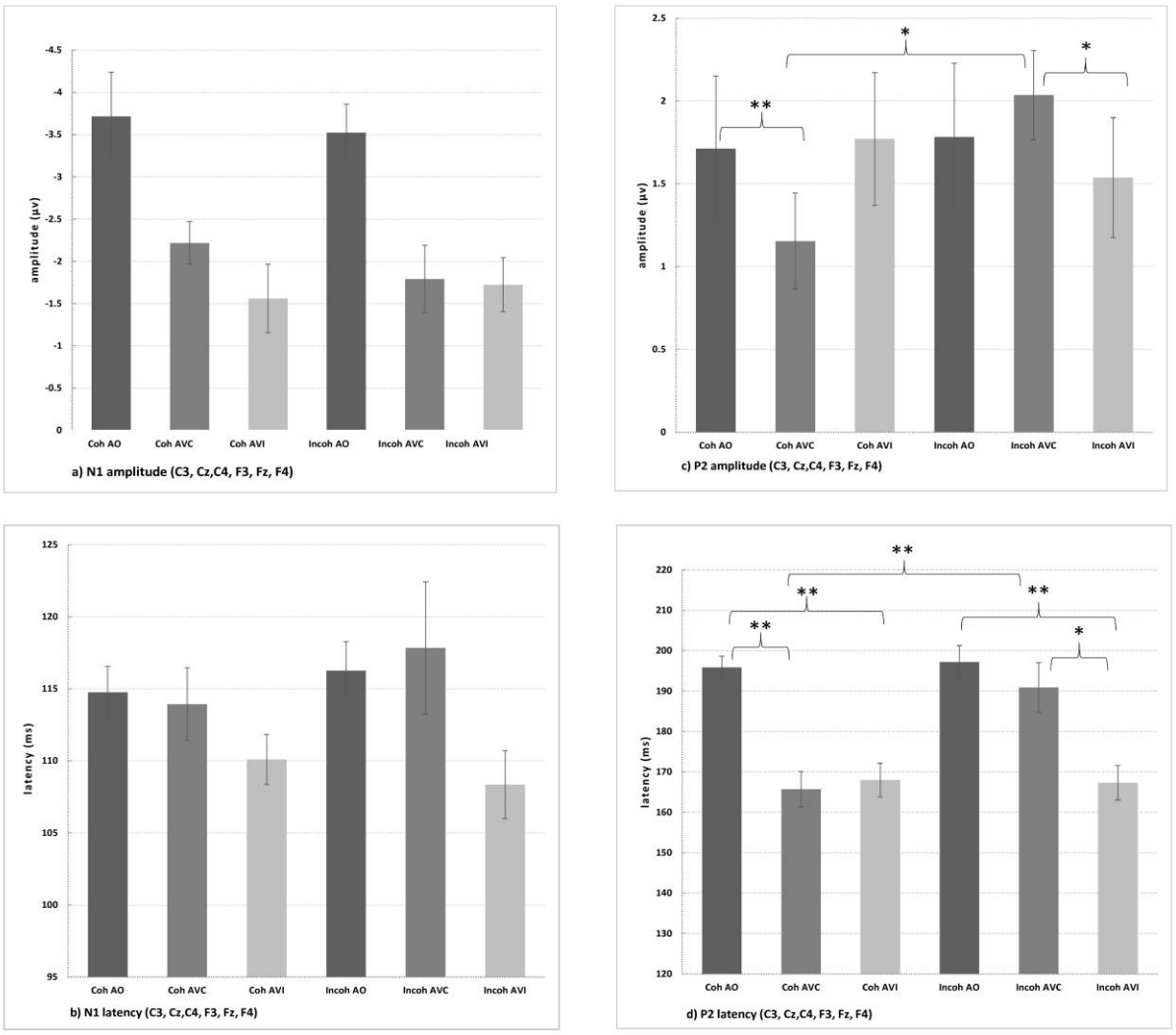

Figure 5-7 Mean N1/P2 amplitude and latency in the three conditions. (a) N1 amplitude, (b) N1 latency, (c) P2 amplitude and (d) P2 latency averaged over the six electrodes in the three conditions (AO, AVC, and AVI) and the two contexts (coherent and incoherent). Error bars represent standard errors of the mean. Significant differences in interaction effects, *p = 0.05; **p = 0.005.

5.3.2.2 *P2 amplitude and latency*

There was no significant effect of context or modality in P2 amplitude, but the interaction between context and modality was significant [F (2, 36) = 3.51, $p < 0.05$], which is in line with our hypothesis (Figure 5-6 & 5-7c). To further examine the interaction effect

between context and modality in P2 amplitude, pairwise comparisons were done using Bonferroni corrections to test the effect of context separately for each modality. The *post-hoc* analysis within modality provided a significant difference between Coherent and Incoherent AVC conditions ($p = 0.01$), showing that Coherent AVC (1.15 μV) has smaller amplitude compared to Incoherent AVC (2.03 μV). The context provided no other significant differences either in the AVI or in the A modality.

Concerning P2 latency (Figure 5-7d), there was a significant effect of context [F (1,18) = 5.63, $p < 0.05$], the latency in the Coherent context (176 ms) being smaller than in the Incoherent context (185 ms). There was also a significant effect of modality [F (2,36) = 23.35, $p < 0.001$], P2 occurring earlier in the AVC (178 ms) and AVI (167 ms) modalities compared to AO (196 ms). As in the case of P2 amplitude, there was a significant interaction effect between context and modality [F (2,36) = 8.07, $p < 0.005$]. The *post-hoc* analysis provided a significant difference between Coherent and Incoherent AVC conditions ($p = 0.002$), showing that P2 in the Coherent AVC condition occurred earlier (165 ms) than in the Incoherent AVC condition (190 ms). The context provided no other significant differences either in the AVI or in the A modality.

Therefore, contrary to the data for N1, we observed significant effects of context on P2. These effects concern both amplitude and latency. They are focused on the AVC condition with rather large values (25 ms increase in latency and 0.88 μV increase in amplitude from Coherent to Incoherent context in the AVC condition). They result in removing the latency difference between AVC and A, in line with our expectations. However, there appears to be no effect of context in the AVI condition, neither for amplitude nor for latency.

5.3.2.3 *Scalp topographies and the potential role of contamination from visual areas*

To assess potential contamination of the previous responses by visually driven responses from the visual cortex, we analyzed scalp topographies in the N1-P2 time periods in various

conditions. Firstly we assessed whether visual areas could intervene in the visual modulation of N1 and P2 responses in the congruent and incongruent configurations, independently on context, by comparing the AO condition (Figure 5-8A) with either the AVC (Figure 5-8B) or the AVI (Figure 5-8C) condition (averaging responses over context, that is combining Coherent AVC and Incoherent AVC in Figure 5-8B and Coherent AVI and Incoherent AVI in Figure 5-8C).

In the N1 time period (100–150 ms) it appears that the negative peak value was more prominent in central than in occipital electrodes (Figure 5-8A), but the decrease in N1 amplitude in central electrodes in both AVC and AVI conditions, associated with a negative amplitude in central electrodes in both AO-AVC and AO-AVI maps (Figures 5-8B, C) was accompanied by an even larger negative amplitude in occipital electrodes. This is due to a positive peak in AV conditions corresponding to the arrival of the visual response in this region. Therefore, a possible contamination of the visual influence on N1 response due to occipital activity cannot be discarded at this stage.

In the P2 time period (175–225 ms), once again the positive peak was more prominent in central than in occipital electrodes (Figure 5-8A). The AO-AVC and AO-AVI scalp maps (Figures 5-8B, C) displayed positive values in central electrodes, corresponding to a decrease in P2 amplitude from AO to both AV conditions. Contrary to what happened for N1, the situation in occipital electrodes was here completely reversed: there were indeed negative values of AO-AVC and AO-AVI differences in the occipital region. Therefore, the possible contamination of visual effects on P2 by visual responses is much less likely than for N1.

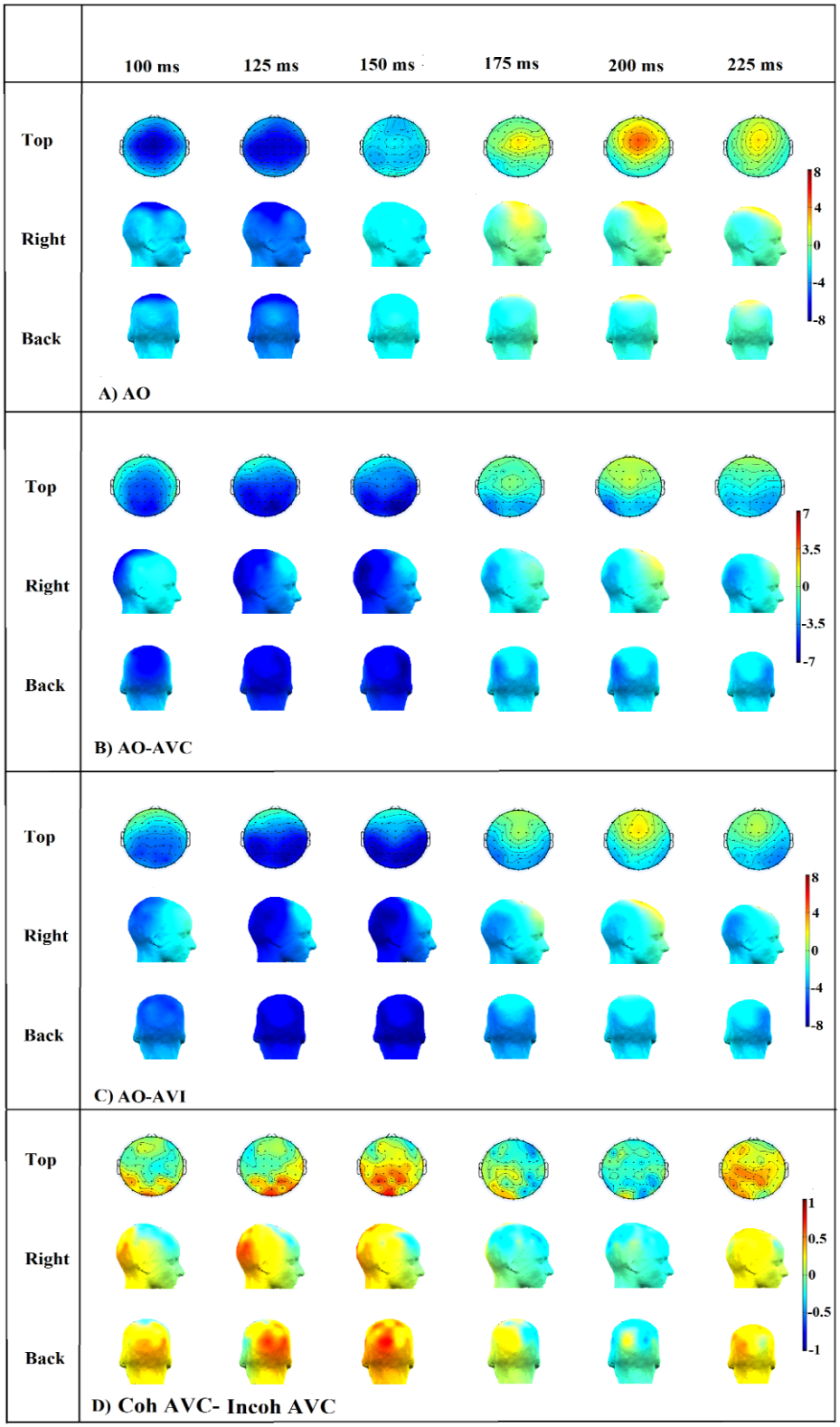

Figure 5-8 Topographical distributions of the Grand-average ERPs for the AO (A), AO-AVC (B), AO-AVI (C) and Coh AVC-Incoh AVC (D) different waves in time steps of 25 ms. The range of the voltage maps varies between maps but is always expressed in µv.

Finally, to directly assess possible contaminations on the major effect of interest that is the difference between incoherent and coherent contexts in the AVC condition, we computed scalp topographies for the difference between Coherent AVC and Incoherent AVC conditions (see Figure 5-8D). The differences were rather small all over these maps, and the topography differences were globally relatively noisy and make difficult any clear-cut conclusion from these topographies.

Altogether, the results in the coherent context condition seem partially consistent with previous findings of EEG studies, if we assume that the Coherent context provides a condition similar to previous studies with no context. Visual speech in the congruent AVC and incongruent AVI conditions is associated to both a significant decrease in amplitude for N1 and in latency for P2. Importantly we found a significant effect of context in the AVC condition for both amplitude and latency in P2, in line with our prediction. However, scalp topographies raise a number of questions and doubts on the possibility to unambiguously interpret these data, in the absence of a visual-only condition. We will now discuss these results in relation with both previous EEG studies on AV speech perception and with our own assumptions on AV binding.

5.4 DISCUSSION

Before discussing these findings, it is necessary to consider one important potential limitation of the present findings. Testing cross-modal interactions usually involve determining whether the observed response in the bimodal condition differs from the sum of those observed in the unimodal conditions (e.g., AV ≠ A + V). In the present study, as previously noted, the visual-alone condition was not obtained because of time limitation. Although direct comparison between AV and auditory conditions performed in previous EEG studies on AV speech integration have provided fully coherent results with other studies

using an additive model (see Pilling, 2009; Treille *et al.*, 2014a,b; Van Wassenhove *et al.*, 2005), this limitation is important, and will lead to a specific component of our discussion.

5.4.1 Comparison of the Coherent context conditions with previous EEG studies

A preliminary objective of the study was to replicate the results of previous EEG studies on N1/P2 in coherent context (Klucharev *et al.*, 2003; Besle *et al.*, 2004; Van Wassenhove *et al.*, 2005; Stekelenburg and Vroomen, 2007; Pilling, 2009; Stekelenburg and Vroomen, 2012; Baart *et al.*, 2014; Knowland *et al.*, 2014; Treille *et al.*, 2014a; b). Concerning AV congruent stimuli AVC, our data are partially in line with previous studies. For the N1 component, we obtained an amplitude reduction in AVC compared to AO, as in previous studies (Figure 5-7A), though this amplitude reduction was not accompanied by a latency reduction (Figure 5-7B), contrary to previous studies. In the P2 component, the decrease in amplitude and latency (Figure 5-7C, D) from AO to AVC is also in line with previous studies (Van Wassenhove *et al.*, 2005; Stekelenburg and Vroomen, 2007; Pilling, 2009; Vroomen and Stekelenburg, 2010; Knowland *et al.*, 2014). Concerning AV incongruent ("McGurk") stimuli AVI, there was an amplitude reduction compared to the AO condition for N1 (Figure 5-7A) and the two peaks also occurred earlier than in the AO condition, not significantly in N1 (Figure 5-7B) but significantly in P2 (Figure 5-7C). Here, the output of previous studies is more contrasted. As a matter of fact, the N1 amplitude and latency values for incongruent stimuli are not available in the Van Wassenhove *et al.* (2005) study, whereas in the studies by Stekelenburg and Vroomen (2007) and Baart *et al.* (2014) there is no difference between incongruent and congruent conditions on both amplitude and latency. However, the results for P2 are not consistent with the previous studies that compared congruent and incongruent stimuli, e.g., in the study by Stekelenburg and Vroomen (2007) there is an effect of incongruent stimuli on amplitude but no effect on latency whereas in the study by Van Wassenhove *et al.* (2005) there is no amplitude effect but a latency effect. On the contrary, the recent study

by Knowland *et al.* (2014) is in line with the present findings in the incongruent condition for N1 and P2 amplitude, even though the stimulus for incongruency differs from the present study. Of course, some of these differences could also be due to various methodological differences in the analyses, including in the present case the specific choice to systematically keep the first peak in the P2 region in the case of double peaks responses, which occur for many subjects (see analyses).

5.4.2 Comparison of the coherent and incoherent context conditions

The primary objective of the study was to test the possible role of an incoherent context supposed to lead to unbinding as robustly displayed by behavioral data in Nahorna *et al.* (2012; 2015) and hence decrease the effects of the visual input on N1/P2 latency and amplitude.

We obtained no effect of context, either alone or in interaction with modality, for both N1 amplitude and latency (Figure 5-7). However, we obtained a significant effect of context for P2, alone for latency, and in interaction with modality for both latency and amplitude. *Post-hoc* tests showed that these effects could be due to a suppression of the decrease in amplitude and latency from AO to AVC when the context is incoherent (Figure 5-7).

The fact that there is an effect of context on P2 but not on N1 is coherent with the view that these components could reflect different processing stages, AV effects on N1 possibly being not speech specific and only driven by visual anticipation independently on AV phonetic congruence, while P2 would be speech specific, content dependent and modulated by AV coherence (Stekelenburg and Vroomen, 2007; Baart *et al.*, 2014). In summary, the visual modality would produce a decrease in N1 amplitude and possibly latency because of visual anticipation, independently on target congruence and context coherence. A congruent visual input (AVC) would lead to a decrease in P2 amplitude and latency in the coherent

context because of visual predictability and AV speech specific binding. Incoherent context would suppress this effect because of unbinding due to incoherence.

As for AVI stimuli, there was no context effect, both in behavioral and EEG results. Actually, it appears that there is almost no AV integration in the present study for incongruent McGurk stimuli (as shown by behavioral data), which likely explains the lack of a role of context on EEG for these stimuli. The discrepancy in behavioral data with previous experiments by Nahorna *et al.* (2012; 2015) likely comes from differences in the nature and number of stimuli. The studies by Nahorna *et al.* (2012; 2015) involved voiced stimuli "ba," "da," and "ga" whereas in the present study the EEG requirement to avoid prevoicing forced us to select unvoiced stimuli "pa," "ta," and "ka." More importantly, the previous studies were based on a larger level of unpredictability, the subjects did not know when the targets would happen in the films, and the coherent and incoherent contexts were systematically mixed. In the present study, because of the constraints of the EEG paradigm, there was no temporal uncertainty of the time when the target occurred, and the AV material was highly restricted, with only ten different stimuli altogether (five different targets and two different contexts). A perspective would hence be to use more variable stimuli in a further experiment.

The difference between AO and AVI conditions in P2 latency and amplitude could be related to the fact that the subjects detect an AV incongruence. Indeed, behavioral data in Nahorna *et al.* (2012; 2015) consistently display an increase in response times for McGurk stimuli compared with congruent stimuli, independently of context, and the authors interpreted this as suggesting that subjects detected the local incongruence independently on binding *per se*, while binding would modulate the final decision. In summary, AVI would produce (i) decrease in N1 amplitude and possibly latency because of visual anticipation; (ii) decrease of P2 amplitude and latency because of incongruence detection; (iii) but no

integration *per se*, as displayed by behavioral data, and hence no modulation by context and binding/unbinding mechanisms.

5.4.3 Possible contamination by visual areas

A crucial limitation of the present work is the lack of a visual-only condition. We consider that this was a necessary evil in such a preliminary study since it was the only way to be able to assess both congruent and incongruent targets in coherent vs. incoherent contexts. However, this might have resulted in possible contamination effects from visual regions that we will discuss now.

Firstly, contamination could be due to visual context. This is, however, rather unlikely considering that the different contexts finish 1000 ms before the target. We systematically compared results obtained with two baseline conditions, one far from the end of the context (–100 to 0 ms) and the other one closer (–500 to –400 ms). It appeared that this baseline change did not change the current results in any crucial way, either in whole graphs or statistical analysis, which suggests that the fluctuations in ERP responses before the apparition of the auditory stimulus at 0 ms do not intervene much in the further analysis of AV interactions on N1 and P2.

It is more likely that contamination effects could be due to visual responses to the visual component of the target. This appears particularly likely in the N1 time period, where scalp maps in the AO-AVC and AO-AVI conditions (Figure 5-8) display larger negative values in occipital areas than in central electrodes. Therefore, it cannot be ruled out that (some unknown) part of the visual modulation of the auditory response could be due to propagation of visual responses from the occipital region.

In the P2 time period, this is much less likely, considering that the pattern of responses is now completely inverse between central and occipital electrodes, with a decrease of P2 amplitude from AO to AVC or AVI in the first ones, and an increase in the second ones.

However, the pattern of scalp difference between Coherent and Incoherent AVC conditions is complex and fuzzy, and the amplitude differences between conditions are small. Therefore, we cannot discard the possibility that the modulation of P2 response in the incoherent compared with coherent context is due to propagation of the visual activity – though we must remind that in these two conditions, the visual response actually corresponds to exactly the same visual input, which makes the "visual propagation" hypothesis more unlikely.

Altogether our interpretation of the observed results is that (1) the pattern of EEG responses we obtained in the N1/P2 time periods is compatible with classical visual effects on the auditory response in this pattern of time, and with a possible modulation of these effects by AV context, in line with our assumptions on AV binding; (2) however, the lack of a visual-only condition impedes to firmly discard other interpretations considering contamination from visual regions due to responses to the visual component of the stimulus; and (3) this suggests that more experiments using the same kind of paradigm with AV context, incorporating visual-only conditions to enable better control of the visual effects are needed to assess the possibility to exhibit electrophysiological correlates of the binding/unbinding mechanism in the human brain.

To conclude, we displayed a new paradigm for ERP AV studies based on the role of context. We presented data about modulation of the auditory response in the N1/P2 time periods due to the visual input, both in the target and context portions of the stimulus. We proposed a possible interpretation of the modulations of the N1 and P2 components, associated to (1) a classical visual modulation generally associated with predictive mechanisms (see e.g., Van Wassenhove *et al.*, 2005) and (2) possible modifications of this effect due to incoherent context, in the framework of the two-stage "binding and fusion" model proposed by Nahorna *et al.* (2012). However, we also discussed in detail a concurrent

interpretation only based on the contamination by visual responses in the visual regions, due to the impossibility in the present study to incorporate a visual-only condition.

The search for electrophysiological correlates of attentional processes possibly modifying AV interactions is an important challenge for research on AV speech perception (see e.g., the recent study by Alsius *et al.* (2014), measuring the effect of attentional load on AV speech perception using N1 and P2 responses as cues just as in the present study). We suggest that binding associated with context should be integrated into general descriptions of AV modulations of the N1 and P2 components of auditory ERP responses to speech stimuli, in relation with general and speech specific effects and the role of attention. We will come back to this in the general discussion in Chapter 7.

Chapter 6

6. Dynamics of AV Binding in Older Adults

6.1 Background and Hypothesis

Age is an important factor to consider in terms of an individual's ability to listen and communicate because as adults age, their sensory, perceptual and cognitive function decline (Baltes and Lindenberger, 1997; Pichora-Fuller and Singh, 2006). Presbycusis (age-related hearing loss) is one of the common disorders seen in older adults, which can affect the ability to understand speech, especially in noisy situations. Beside age-related hearing loss, there could appear a decline in auditory processing skills in which most normal hearing older adults perform more poorly than younger adults, particularly in adverse listening conditions (CHABA, 1988). In terms of day-to-day listening, many older adults indicate that listening in noisy situations is a challenging and often exhausting experience. In addition to hearing, several studies have shown that older individuals with normal or corrected vision also exhibited reduced lip-reading skills (Shoop and Binnie, 1979; Dancer *et al.*, 1994; Cienkowski and Carney, 2002; Sommers *et al.*, 2005; Feld and Sommers, 2009). In spite of a general deficit in the unisensory modalities, the literature suggests that older adults could actually exhibit *greater* multisensory integration when compared with younger adults (see Mozolic *et al.*, 2012 for review). Various studies which used McGurk stimuli to assess AV fusion have indeed shown that with aging the McGurk effect increases (Thompson, 1995; Behne *et al.*, 2007; Setti *et al.*, 2013), whereas some highly controlled studies reported non-significant differences between young and older adults in AV speech perception (Cienkowski and Carney, 2002; Sommers *et al.*, 2005). However, a recent behavioral study by Sekiyama *et al.* (2014) found that the visual influence was greater in older adults compared with younger

ones not only with equal SNRs but also with SNRs calibrated to equalize unisensory performance, which seems to confirm that older adults do exhibit more dependency on visual information. Elements of this debate between two contradictive views were already discussed in detail in an earlier Section (1.2.3).

The mechanism underlying such a potential increased multisensory integration in older adults is not yet clear. The literature suggests various possible reasons such as a decline in cognitive skills not specific to multisensory integration, inverse effectiveness associated with sensory deficits, the temporal window for integration that changes with aging and failure of top-down modulation on sensory processing in older adults. Yet, there is a lack of strong evidence to support either one of these explanations individually (see Mozolic *et al.*, 2012 for review). Our objective in the present chapter was to estimate AV binding and its dynamics in the older population, capitalizing on the experimental paradigms developed by Nahorna *et al.* (2012; 2015) and in the present doctoral work.

Our expectations at the beginning of this work were not completely firm. Our first objective was to test whether the same kind of binding/unbinding/rebinding processes would be displayed on seniors. On this basis, we considered it likely that, considering the potential increase in integration in older adults, the modulation by context and attention could display larger amplitude in older participants. On the other way round, it could be forecast that since the visual modality is of particular importance for seniors, the visual input would be exploited and fused even in case of incoherence, hence a decrease in unbinding. Finally, we also wondered whether the difficulty displayed by old subjects to process complex AV scenes could be associated with impaired binding processes.

Therefore, we defined a first objective, which was to measure the binding, unbinding and rebinding effect in older adults (Experiment A). This first experiment was a replication of our first experiment on unbinding and rebinding in younger adults (see Chapter 3) which was

inspired from Nahorna *et al.* (2015). It was expected that an incoherent AV context should decrease the strength of the McGurk effect and increase the amount of auditory responses to McGurk targets and that a coherent reset stimulus should produce rebinding, which would reset the default state of binding. In addition, we predicted that there could possibly exist differences in time constants and dynamics in the binding/unbinding/rebinding mechanism. In summary, firstly there should be modulation of the McGurk effect by various contexts and secondly, the size and dynamics of these effects could be different when compared with a younger population.

A second objective of the present chapter was to explore the potential role of attentional mechanisms in the scene analysis process in older adults (Experiment B) and to compare with the previous results in younger ones (see Chapter 4, Experiment B). Indeed, we recalled in Chapter 1 how attentional processes may decrease audiovisual fusion, and we showed in Chapter 4 how selective attention on one AV source in a mixture could modify the binding process and the output of AV fusion. Interestingly, the increase in multisensory integration in older adults compared to younger ones could be due to older adult's deficits in top-down attentional control, decreasing their ability to use selective attention to control the incoming information and hence increasing multisensory interactions. As a matter of fact, various studies have displayed attentional deficits in older adults and showed how they get distracted by multiple stimuli within or across modalities (Andres *et al.*, 2006; Yang and Hasher, 2007; Healey *et al.*, 2008). However, Hugenschmidt *et al.* (2009) used a cued multisensory discrimination paradigm to show that selective attention focused on one modality was intact in older adults and able to reduce integration.

The results of Experiment B in Chapter 4 showed that in young adults, attentional load put on a given coherent audiovisual source may reinforce binding and increase the McGurk effect. Therefore, we decided to exploit the same experiment with seniors (it will also be

called Experiment B in the present chapter), with the following predictions; 1) the pop-out effect of "Video syllables" should remain in seniors since it is likely a primitive effect associated with syllables salience in the used audiovisual material; (2) the attentional effect for "Video sentences" could be decreased in seniors due to a possible decrease in selective attention – though the data by Hugenschmidt *et al.* (2009) suggest that selective attention could well remain unchanged in older participants.

In summary, the experiments in this chapter were conducted in two parts, Experiment A and Experiment B. Within Experiment A, we explored the binding, unbinding and rebinding mechanism in an older population. In Experiment B, specific instructions were given to put attention either on syllables or on sentences, and we expected partly similar effects of a global increase of the McGurk effect when attention was oriented towards a coherent AV source (syllables or sentences), though possibly with quantitative differences between youngers and elders.

6.2 METHODS AND MATERIALS

6.2.1 Participants

Twenty-five native French speaking older adults participated in the experiments (2 women and 23 men; from 60 to 75 years, 21 right-handed and 4 left-handed, mean age= 65.32 years; SD=3.92 years). None of them reported any hearing, vision (after correction) or neurological disorders. Other details on participants and selection criteria were already presented in Section 2.1.

Further, we performed additional tests on older adults to rule out the participation of hearing and cognitive impairment factors. All the participants were screened for peripheral hearing loss using screening pure tone air-conduction audiometry for the frequencies 250–8000 Hz. The pure tone average (500 Hz, 1000 Hz, and 2000 Hz) for all participants was lower than 20 dB Hearing level (HL) and 35 dB HL in higher frequencies.

6.2.2 Speech, Spatial, and Qualities of hearing scale (SSQ)

In addition to the screening audiometry, we also administered a French version of the Speech, Spatial, and Qualities of hearing scale (SSQ; Gatehouse and Noble, 2004) which is a self-reported questionnaire developed to assess how effectively auditory information is being processed in various everyday listening situations. Recently, this questionnaire has been validated in the French language and found good reproducibility of scores. Inter-subject variability was obtained between French and other languages including the English version that was primarily developed (Moulin *et al.*, 2015) and it was concluded that the SSQ has potential to be used as an International standard for hearing disability evaluation (see Figure 6-1). Typically, these questionnaires were used for subjective assessment of hearing aid and cochlear implant benefits. However, the SSQ includes questions related to speech in quiet and noise, ASA, cognitive abilities and similar abilities which are very relevant to our experimental paradigm (e.g. question on multiple speech streams: "You are listening to someone talking to you, while at the same time trying to follow the news on TV. Can you follow what both people are saying?"). SSQ contains 50 questions, which are divided into three subscales: 1. "Speech hearing" Items (14 items), 2. "Spatial Hearing" (17 items) and 3. "Qualities of Hearing" (19 items). We did not utilize questions from the "Spatial Hearing" sub-scale since it is mainly concerned with spatial abilities such as localization and distance of sound, which were irrelevant to our experiments. We did not either utilize one question from "Qualities Hearing" since it was applicable only to hearing aid users.

For both "Speech Hearing" items (e.g. "You are in a group of persons speaking one after the other. Can you easily follow the conversation without losing track of the intervention of each different person?"), and "Qualities Hearing" items, (e.g. "Imagine you are listening to two different sounds at the same time, such as radio and water pouring outside a wahbasin. Do you feel these two noises as perfectly distinct one from the other?"), participants were

instructed to estimate their abilities by selecting an 11 point response scale ranging from "0" (complete disability) to "10" (no disability). The French version of SSQ can be found in Appendix II. Also, Gatehouse and Akeroyd (2006) divided part of the SSQ items into "pragmatic subscales" depending on the type and nature of the response that the question requires during the assessment. The "Speech Hearing" sub-scale divided speech as 1) quiet (2nd & 3rd question), 2) speech-in-noise (1st, 4th, 5th, & 6th), 3) speech in speech contexts (7th, 8th, 9th, and 11th), and 4) multiple speech streams (10th, 12th, & 14th). The "Qualities Hearing" sub-scale was divided into 1) identification of sound (4th, 5th, 6th, 7th, & 13th), 2) segregation of sounds (1st, 2nd & 3rd) and 3) listening effort (14th, 18th, & 19th).

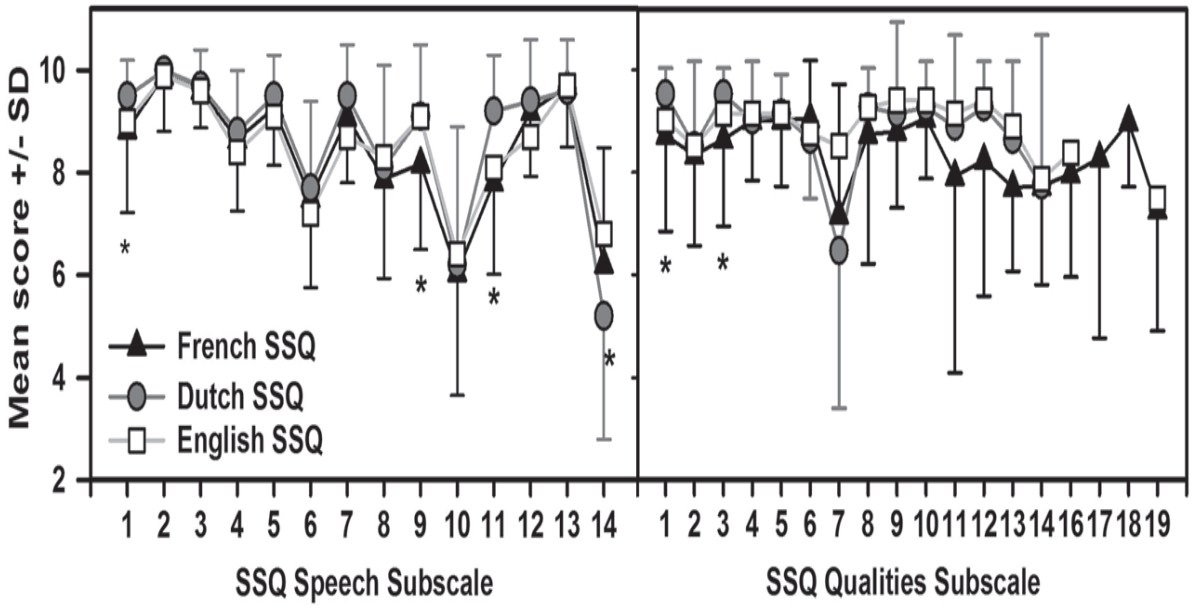

Figure 6-1 Mean scores (+ SD) for each SSQ items for both subscales. The results are from three different languages (French SSQ, Dutch SSQ and English-US SSQ). The figure is taken from (Moulin *et al.*, 2015).

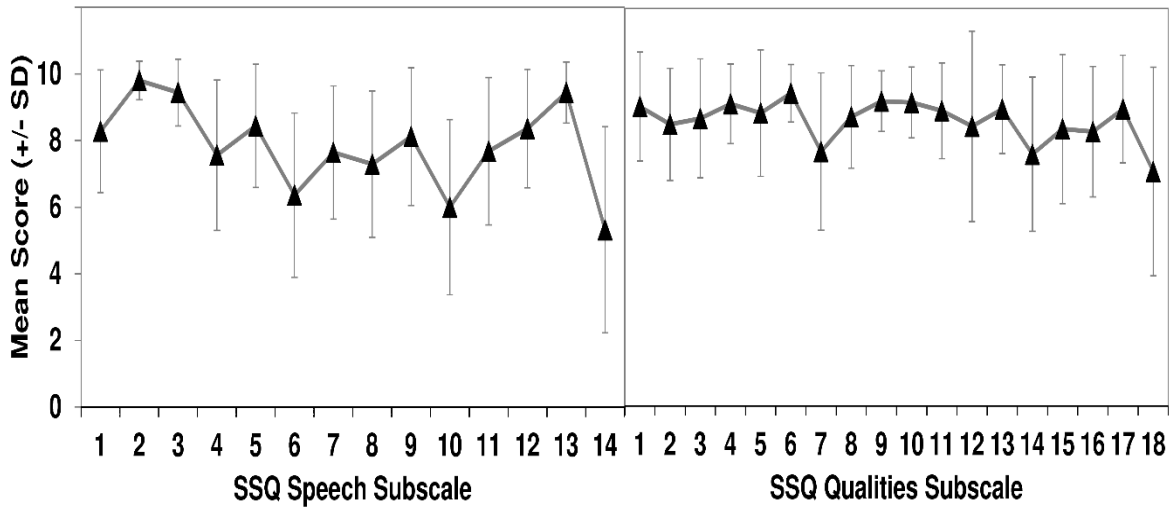

Figure 6-2 Mean scores (+ SD) for each SSQ items for both subscales.

Overall, we obtained average scores respectively equal to 7.8 out of 10 for the "Speech Hearing" sub-scale and 8.6 out of 10 for the "Qualities Hearing" sub-scale (see Figure 6-2), to compare to mean scores from 8.4 to 8.6 in the older English speaking population (Füllgrabe *et al.*, 2015) and from 9 to 9.5 for the younger French speaking population (Moulin *et al.*, 2015). The overall trends among questions were similar to the results obtained with the younger French population (Moulin *et al.*, 2015) (compare Figure 6-1 and Figure 6-2). Additionally, there was minimal difference between the French younger and older group for questions related to speech in speech contexts, multiple speech streams and segregation of sounds, that were pre-requisite skills needed to perform our experiments. The SSQ provided us with additional information on how older adults assess their hearing abilities in everyday listening situation that includes both noise and competing sources, which traditional screening audiometry does not provide us.

6.2.3 Color-word Stroop test

In order to measure participant's attentional control, cognitive flexibility, and processing speed, we administered the French version of the color-word Stroop task (Stroop, 1935). The color-word Stroop test is a very popular measure in the neuropsychological and cognitive

domain, which is theorized to measure various executive functions such as selective attention and cognitive flexibility (Homack and Riccio, 2004; Charchat-Fichman and Oliveira, 2009), interference control (van Mourik *et al.*, 2005), response inhibition (Pocklington and Maybery, 2006) and brain's processing speed (Lamers *et al.*, 2010). In the classical color-word Stroop test, participants are instructed to name the ink color of stimuli as quickly as possible while ignoring the words themselves. The stimuli can either be congruent (the word "red" written in red ink), incongruent (the word "red" written in blue ink), or neutral (a list of "X"). Typically, participants take more time to adequately respond to incongruent than to neutral or congruent stimuli, which is termed as "Stroop Interference". It has been used as a screening tool for various disorders, such as dementia (Koss *et al.*, 1984; Spieler *et al.*, 1996; Fleck *et al.*, 2015), Alzheimer's disease (Hutchison *et al.*, 2010; Bayard *et al.*, 2011), Schizophrenia (Barch *et al.*, 2009), brain damage after a stroke, and Attention Deficit Hyperactivity Disorder (Lansbergen *et al.*, 2007).

We administered the color-word Stroop test, since our experiments on older adults require voluntary control of attention (considering that in Experiment B subjects have to focus their attention on either syllables or sentences) and processing speed (e.g. response time). The Stroop test consists of two conditions, which require an individual to identify the color or name as early as possible: 1) Word naming consists of incongruent stimuli (the word "red" written in blue ink) and neutral stimuli (the word "red" written in gray color), and 2) Color naming consists of incongruent stimuli (the word "blue" written in red ink) and neutral stimuli (list of "X"s in red ink). It was administered in two randomized blocks by using four colors (Red, Blue, Yellow, and Green) and each condition had 36 randomized trials. The practice session was provided for each condition. The Presentation® software (Neurobehavioral Systems Inc., Albany, CA) was used to present stimuli and to collect responses and less than 10 minutes were required to complete the test. We administered the basic French version

of the Stroop test that was available freely with the Presentation software package and mean responses (correct responses and reaction times) were calculated. Stroop Interference (incongruent responses–neutral stimuli) was calculated for both word naming and color naming tasks.

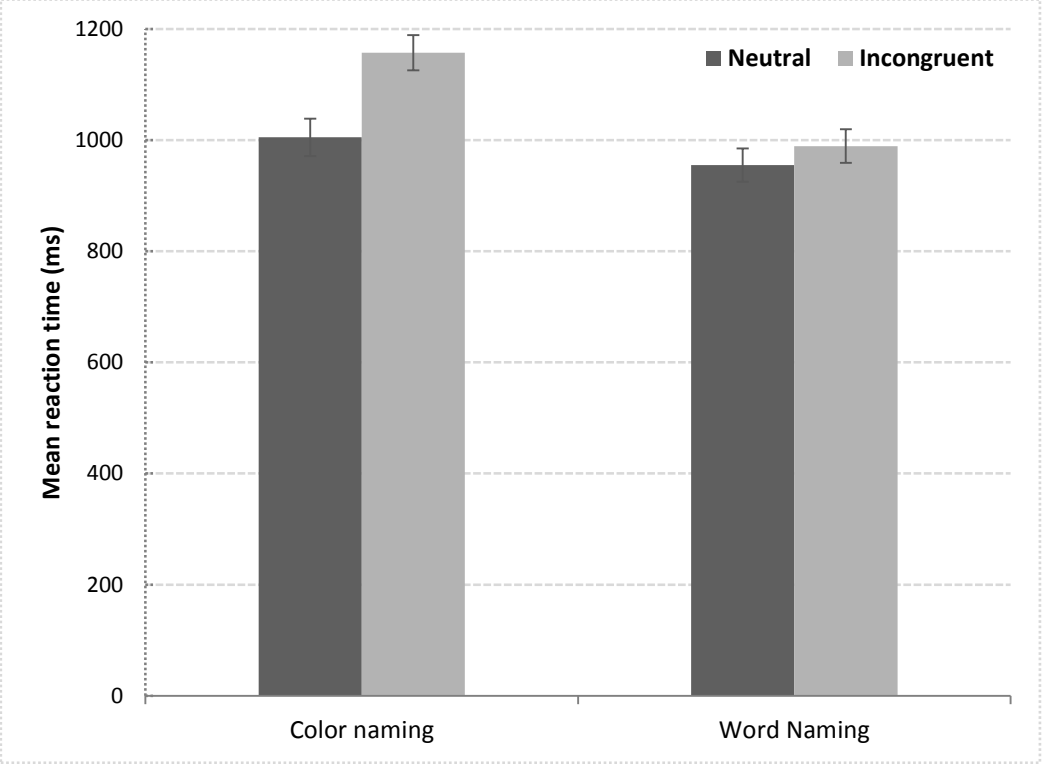

Figure 6-3 Mean reaction time for both Neutral and Incongruent conditions (Color naming and Word naming tasks).

The average reaction times for both color naming and word naming tasks are shown in Figure 6-3. The Stroop Interference was 152.37 ms for incongruent color naming and 34.09 ms for word naming, respectively. The percentage of errors was higher for incongruent color naming (5.2%) than for incongruent word naming (3.99 %). Overall, the Stroop Interference, mean reaction time as well as error rate for both word naming and color naming were within the normal range when compared to other similar studies on normal older healthy adults (Spieler *et al.*, 1996; Hutchison *et al.*, 2010). For example, Spieler *et al.* (1996) obtained Stroop Interference ranges around 175-177 ms for color naming, and 19-43 ms for word naming, and error rates for color naming ranging from 1.3 to 3.8 % for the neutral condition and

from 3.9 to 7.2 % for the incongruent condition. Our data suggest that all the participants may have normal processing speed and executive functional skills.

6.2.4 Experiment A – Stimuli

To measure binding, unbinding and rebinding in older adults (Experiment A), we utilized stimuli which were prepared to measure the effect of context and noise in younger adults. In this experiment, we excluded the noise block and used only the block which contained context, reset and target material in silence.

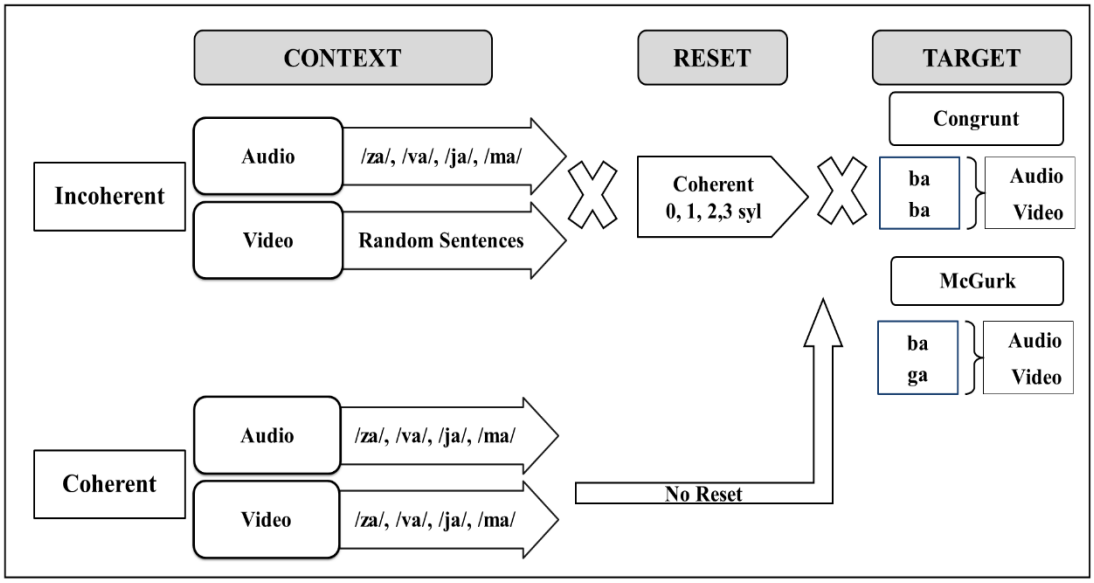

Figure 6-4 Description of the AV material for Experiment A.

The stimuli are described in Figure 6-4. They are typically comprised of (Figure 6-4, top):

- An incoherent context (2 or 4 acoustic syllables);
- Followed by a reset stimulus consisting in 0, 1, 2 or 3 coherent AV syllables;
- Followed by a target which can be either a congruent AV "ba" or a McGurk stimulus consisting in an audio "ba" dubbed on a video "ga".

A control stimulus, aimed at providing a reference for the McGurk effect, is provided by (Figure 6-4, bottom):

- A coherent context (2 or 4 coherent AV syllables);
- Followed by a target which can be either a congruent AV "ba" or a McGurk stimulus.

More details on preparation of stimuli and other technical details can be found in Section 3.2.2.

6.2.5 Experiment B - Stimuli

Experiment B included two auditory streams competing for binding with a single video stream in the contextual stimulus provided before a McGurk target and aimed at evaluating in seniors the effect of attention on modulation of the binding stage. This experiment exactly replicated Experiment B in Chapter 4 (see Sections 4.2.2 & 4.2.3). To recall, the experiment included two types of contexts followed by a target. The target was either a congruent AV "ba" syllable or an incongruent McGurk stimulus. There were two types of contexts, i.e. "Video syllables" (Figure 6-5, top) or "Video sentences" Figure 6-5, bottom) prepared from the AV "sentences" and "syllables" material. In both contexts, the set of audio stimuli was the same. It consisted of a sequence of 2 or 4 syllables (A-syl-2 or A-syl-4) mixed with utterances from the sentences material with the same duration (A-sent-2 or A-sent-4). The video component was the video counterpart of either the audio syllable material or the audio sentence material.

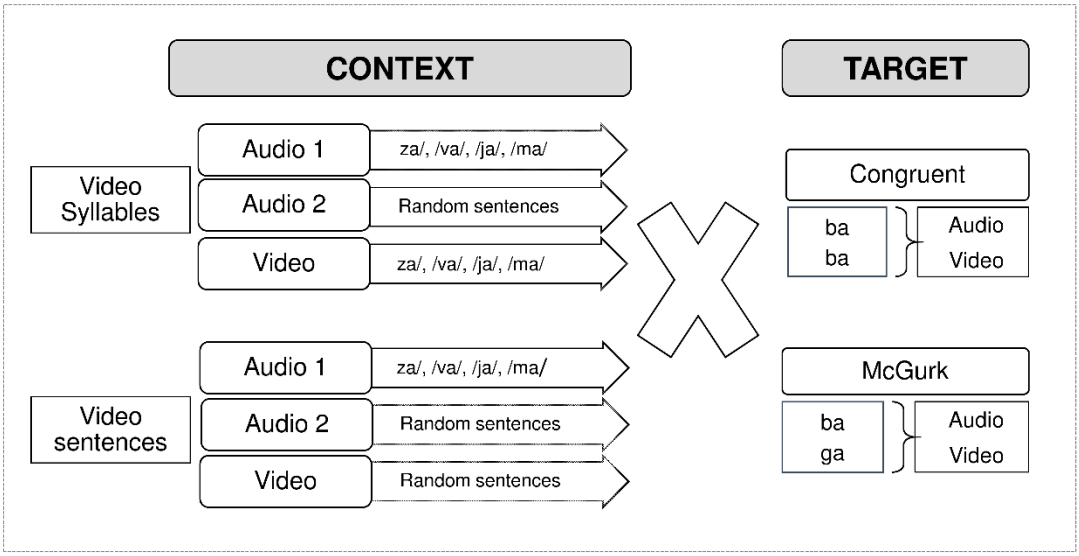

Figure 6-5 Description of the AV material for Experiment B.

6.2.6 Procedure

The study on older adults included two consecutive experiments, Experiment A followed by Experiment B (always in this order). The films were presented on a computer monitor with high-fidelity headphones set at a comfortable fixed level.

In Experiment A, the participants were involved in a monitoring paradigm in which they were asked to constantly look at the screen and monitor for possible “ba” or “da” targets by pressing an appropriate key, as in previous experiments.

In Experiment B the monitoring “ba” vs. “da” task remained the same (with a different order of the 120 stimuli in the film), but in addition, specific instructions were given to participants, either to put more attention to syllables (“Attention syllables”) or to put more attention to sentences (“Attention sentences”). To increase the efficiency of the attentional demand and to control it to a certain extent, participants were informed that they would be questioned on the content of either the “syllables” or the “sentences” material at the end of the experiment. The questions were of the type “did you perceive the syllable ‘ja’ or ‘va’?” in the syllables attention task, or “did you perceive the word ‘triangle’ or ‘line’?” in the sentences attention task. Most participants were indeed able to recall specific syllables or words. The procedure is described in more detail in Section 4.2.3.

6.2.7 Processing of response

The processing of responses for both experiments was similar to previous experiments (see Section 2.6 for more details). Correct responses were computed within the [200-1200 ms] window, from which a global behavioral response and a mean response time were calculated for each participant in each condition and subjected to statistical analysis for each experiment.

Firstly, repeated-measures ANOVAs were performed on the proportions of “ba” responses over the total number of “ba” plus “da” responses, processed with arcsine square

root [asin (sqrt)] transform to ensure quasi-Gaussian distribution of the variables; and considering response times, ANOVAs were performed on the logarithm of these values for ensuring normality of the distributions. Then, for each experiment, the transformed proportion of "ba" responses and transformed response times were compared with those obtained with young adults in similar paradigms (from Chapter 3 for Experiment A and Chapter 4 for Experiment B) and a Mixed-Model ANOVA was performed between groups. In the Mixed-Model ANOVA, the assumption of homogeneity of variances was tested using Box's M test of equality of covariance matrices and Leven's test of equality of level variance. The Greenhouse-Geisser correction was applied in the case of violation of the sphericity assumption. *Post-hoc* analyzes were used with Bonferroni corrections, and only differences significant after Bonferroni correction were reported ($p<0.05$).

6.3 RESULTS

6.3.1 Individual data and No response data

The individual data of "ba" scores for McGurk targets are shown in Figure 6-6 for Experiment A. Similarly to our previous experiments, participants with more than 90% "ba" scores in the "coherent condition" for McGurk targets in Experiment A were considered as subjects with a poor level of AV fusion, and hence excluded from the statistical analysis for both experiments. Overall, 8 participants were excluded (see Figure 6-6), and the remaining 17 participant's data were subjected to statistical analysis for both Experiments A and B.

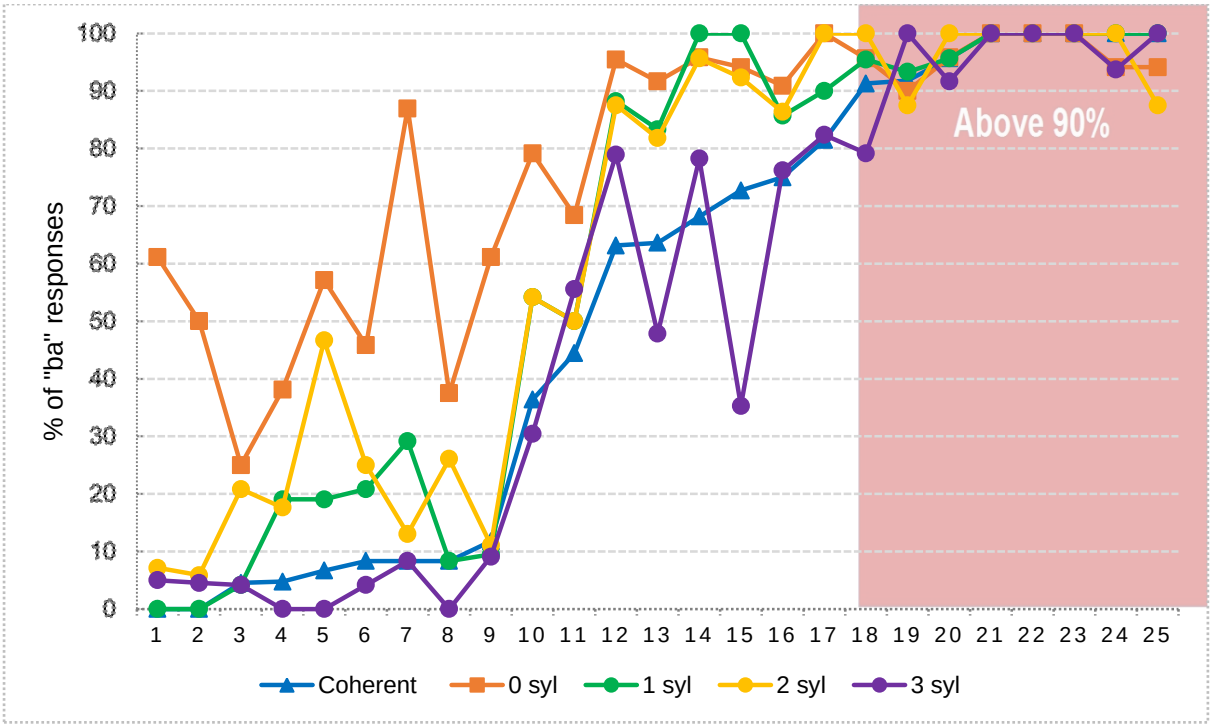

Figure 6-6 Individual "ba" scores for McGurk targets with coherent context and with incoherent context with reset at 0, 1, 2, or 3 syllables in Experiment A. The subjects are ordered by increasing score in the "coherent" condition.

More details about the participant's responses for each condition can be found in Appendix I. Overall, there was only a small amount of missed targets with 8.9% % of the cases with either "no response" or "multiple different responses" within the acceptable temporal window, for the whole experiment in 31 subjects. The experiment A produced more errors (14.8%) compared to the experiment B. The scores were also much larger in seniors than in youngers (respectively 13.9% vs. 3.9% in Experiment A; and 4.6% vs.2.2% in Experiment B). More details can be found in Appendix I and on Figure 6-7.

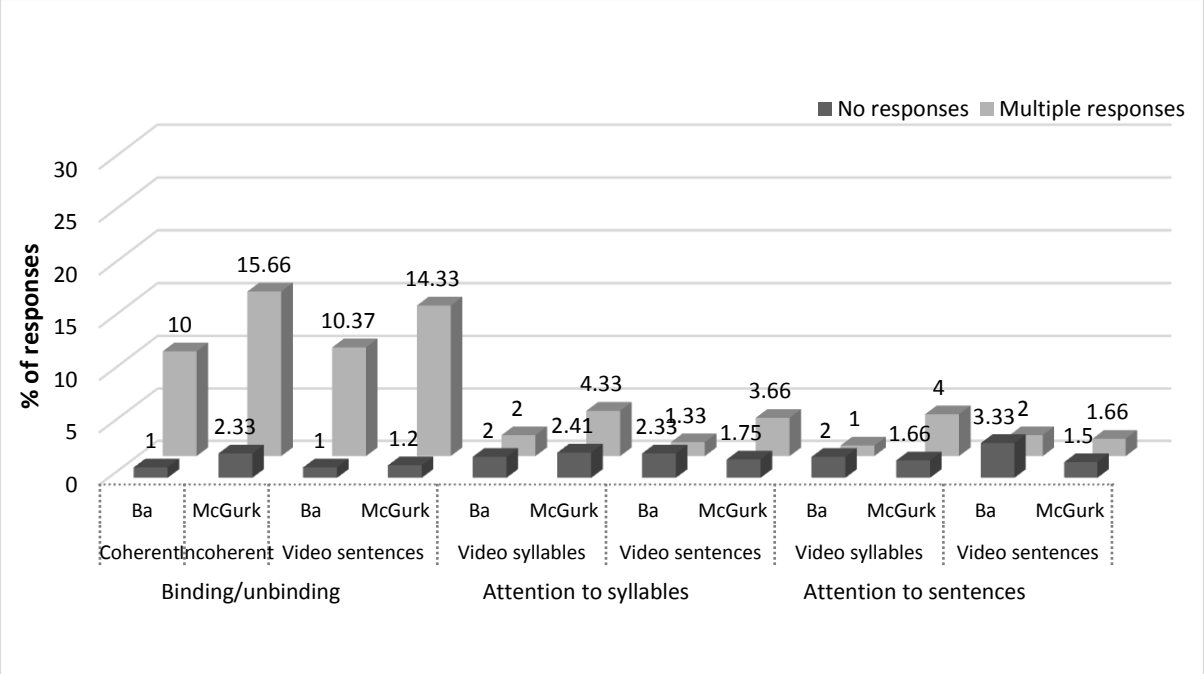

Figure 6-7 Mean number of missed targets averaged over 25 subjects for "no response" (no response/total responses) and multiple responses (multiple responses/total responses) for both Experiment A and Experiment B.

6.3.2 Experiment A: Binding, Unbinding & Rebinding

6.3.2.1 *Analysis of the proportion of "ba" responses*

As in the previous experiments, the proportion of "ba" responses for all "ba" targets was close to 100% in all conditions. Therefore, hereafter only McGurk targets will be considered in the statistical analysis (Figure 6-8). Two factors, context/reset type (coherent vs. incoherent with 4 reset durations, hence 5 possibilities altogether), and context duration (two vs. four syllables) were analyzed using repeated-measures ANOVA. The effect of context duration [F (1, 16) =14.43, p<0.005], and context/reset type [F (4, 64) =35.20, p<0.001] were significant. Interaction between context/reset type and context duration was not significant.

We hence replicate the binding/unbinding/rebinding effect (Nahorna *et al.*, 2015), since the amount of "ba" responses is higher for incoherent (without reset: see data for "0 syl") than for coherent contexts, which means that the McGurk effect is decreased; and it comes back to its coherent value when reset duration increases from 0 to 3 syllables. Indeed, *post-*

hoc analyzes show that the score for the coherent context is significantly different from the score for the "0 syl" incoherent condition and the amount of unbinding is 37% (see orange arrow in Figure 6-8). Also, the *post-hoc* analysis confirms that until "3 syl" reset duration unbinding is not completely recovered (see green arrow in Figure 6-8): the score for the coherent context is significantly different from the score for the "1 syl" reset duration (12%) and for the "2 syl" reset duration (16%) while there is no significant difference between coherent context and "3 syl" reset duration. Considering context duration, we also replicate previous findings showing that the proportion of "ba" responses is higher (with less McGurk fusion) for the shorter context duration (47%) than for the longer context duration (42%).

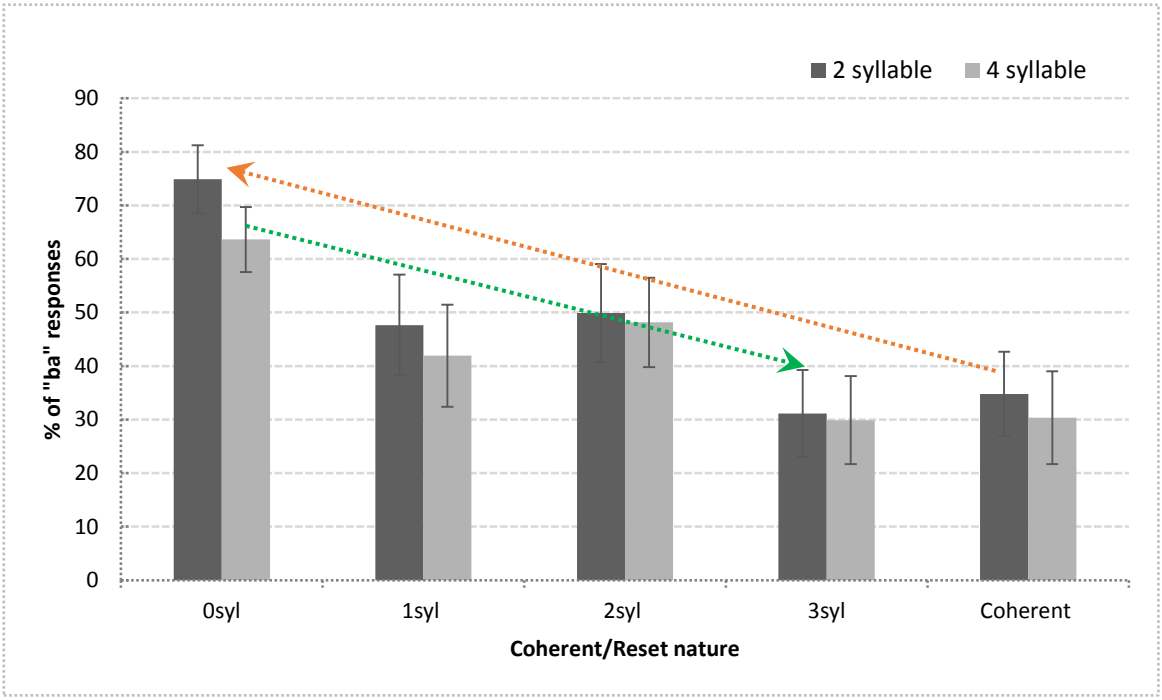

Figure 6-8 Proportion of "ba" responses for "McGurk" targets for incoherent context with four reset durations (0syl, 1syl, 1syl or 3syl), compared with coherent context, and for both context durations (2 or 4 syllables). Standard errors are displayed for all conditions. Unbinding and rebinding are displayed by colored arrows (see text).

Then, the present data on older adults were compared with our previous data on younger adults in Chapter 3 (condition without noise). Interestingly, the modulations of the McGurk effect with the context in Figure 6-9 appear larger for older participants. A mixed ANOVA

was conducted to compare "ba" scores between younger and older group according to the context/reset nature (0, 1, 2, 3 syl incoherent reset durations & coherent condition). Though there was a significant main effect of context/reset nature and a significant interaction effect between context/reset nature and group, we could not report the results due to a violation of homogeneity of variance. The Box's M test of equality of covariance matrices and Leven's test of equality of level variance were both significant which indicates violations of the assumption of homogeneity of variance.

Since we are particularly interested in evaluating the modulation of binding from the coherent to the incoherent conditions, we considered only the coherent context and the incoherent context without reset (0 syl reset duration) and performed a two-way (2x2) mixed ANOVA. The independent variables included one between-group variable (age) with two levels (young vs. adult) and one within-subject variable, the amount of "ba" scores in McGurk targets, with two levels for context (0-syl incoherent vs. coherent condition).

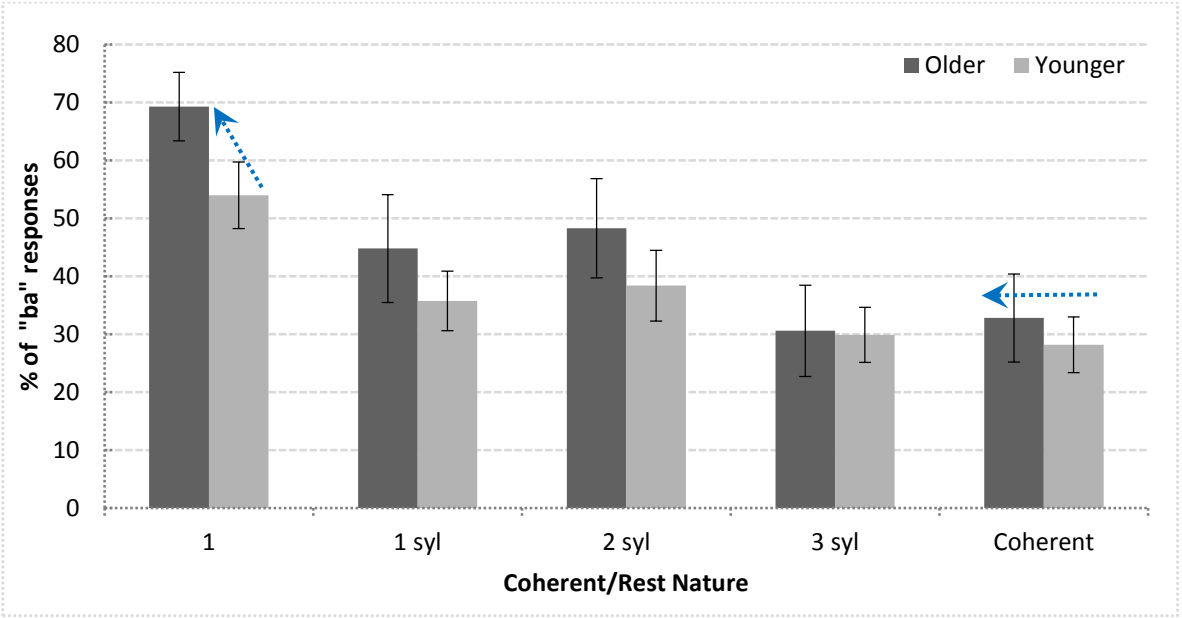

Figure 6-9 Proportion of "ba" responses for "McGurk" targets for incoherent context with four reset durations (0syl, 1syl, 1syl or 3syl), compared with coherent context, for younger vs. older adults. Standard errors are displayed for all conditions.

In this case, the assumption of homogeneity of variances was not violated since Box's M test of equality of covariance matrices and Leven's test of equality of level variance were not significant. There was no significant difference between groups, but the context effect was significant [F (1, 36) =121.84, p<. 0001] and there was a significant interaction between context and groups [F (1, 36) =3.19, p<. 01]. *Post-hoc* analysis shows that there was a significant difference between older and younger groups for the incoherent condition "0 syl" reset duration and a non-significant difference for coherent condition (see blue arrows in Figure 6-9). Interestingly, since the scores for coherent context were not significantly different between groups, the larger increase in "ba" score with the incoherent context in older subjects shows without ambiguity that the dynamics of unbinding by incoherent context is larger for the older participants.

Overall, the results produce three important outcomes. Firstly, they provide a replication of the "unbinding" and "rebinding" effects in older adults. Secondly, the effect of context duration (two vs. four syllables) was also replicated. Thirdly and most importantly, the unbinding effect appears much larger in older adults compared with younger ones. Indeed, while fusion scores are similar in the coherent context, the increase in "ba" responses due to unbinding is around 37% in older adults vs. 25 % in younger adults. The rebinding dynamics seem similar (around 3 syllables) though a direct comparison of the rebinding dynamics between groups could not be afforded in a mixed ANOVA.

6.3.2.2 ***Analysis of response time***

Response times are displayed in Figure 6-10, averaged over participants and over the two context durations. The data were analyzed in a two-way repeated-measures ANOVA with factors target ("ba" vs. McGurk), context duration (2 syllables vs. 4 syllables) and context/reset type (coherent vs. incoherent with 4 reset durations, hence 5 possibilities altogether). The ANOVA shows an effect of target [F (1, 16) =4.46, p<0.05], context/reset type [F (4,

64) =4.21, p<0.005], and context duration [F (1, 16) =46.17, p<0.001], but no interaction between any variables. As in our previous experiments, the responses were quicker for all "ba" targets compared to "McGurk" targets (31 ms average difference, see green arrows in the Figure 6-10) and the mean response time for the "4 syl" context duration was quicker than for the "2syl" context duration (70 ms average difference). Similar to younger adult's data, the context without reset had larger response times than the context with 3-syllable reset by 48 ms. Importantly, the lack of interaction between target and context/reset type shows that the effect of AV incongruence in the McGurk target produces the same amount of delay compared with a congruent "ba" target, whatever the context/reset type. This is compatible with a general finding in all the previous experiments by Nahorna *et al.* (2012; 2015) and in our own data (see Chapter 3 and Chapter 4).

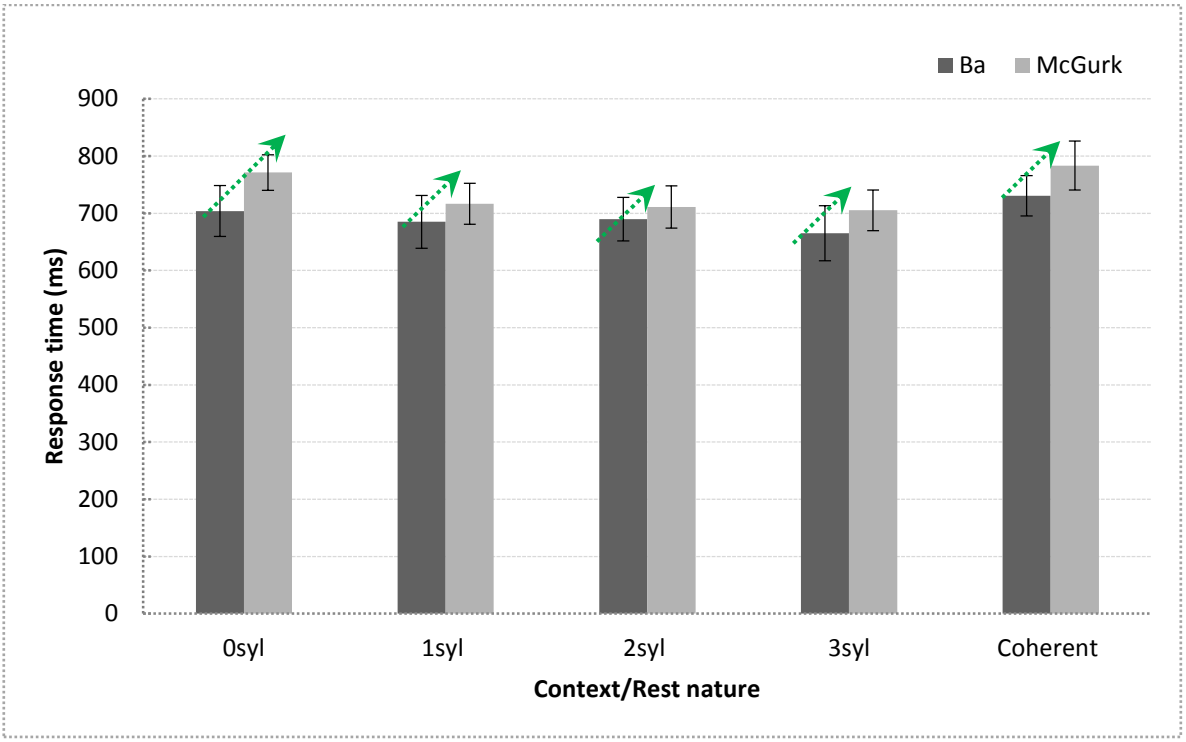

Figure 6-10 Mean response times for "Ba" and "McGurk" targets for the incoherent context with the four reset durations (0syl, 1syl, 1syl or 3syl), compared with the coherent context. Values are averaged over the two context durations (2 and 4 syllables). Standard errors are displayed for all conditions.

Then, the response times for older adults were compared with those for younger adults. A mixed ANOVA was conducted comparing targets and context/reset nature between younger and older groups. There was a main effect of target [F (1, 36) =19.07, p<0.001], context/reset nature [F (4, 144) =6.12, p<0.005], with no interaction effect between variables within groups nor any significant effect of group, either alone or in interaction. Hence, importantly, in both groups the McGurk targets took more time, consistently with previous findings.

6.3.3 Experiment B-On the interaction between context type and attention focus

6.3.3.1 *Analysis of the proportion of "ba" responses*

Percentages of "ba" responses to McGurk targets in Experiment B (involving explicit attention towards one or the other source) are displayed on Figure 6-11. A repeated-measures ANOVA was administered on these percentages with three factors, context type ("Video syllables" vs. "Video sentences"), context duration (2- vs 4-syllables) and attention ("Attention syllables" vs. "Attention sentences").

The effect of context type [F (1, 16) =15.66, p<0.001] is significant, and as in young adults, "Video syllables" produce more McGurk fusion than "Video sentences" (see Figure 6-11, orange arrow). There is no effect of context duration, however the interaction between context and context duration is significant [F (1, 16) =5.93, p<0.05]. It is due to less fusion with the 2-syllables duration relative to the longer 4-syllable duration, but only for "Video syllables", while there is no significant difference between context durations in the "Video sentences" context.

The attention factor alone is not significant, but its interaction with context type is significant [F (1, 16) =5.01, p<0.05]. *Post-hoc* analyses with Bonferroni corrections show that there is no significant difference between the two attention conditions for the "Video syllables" context type (see Figure 6-11, purple arrow), while there is a significant difference for the

"Video sentences" condition with a 15% lower "ba" percentage (a higher McGurk effect) in the "Attention sentence" condition (see Figure 6-11, red arrow). Interestingly, *post-hoc* analysis shows that while the "ba" percentage is significantly higher for the "Video sentences" than for the "Video syllables" condition when attention is put in syllables (18%) there is no significant difference when attention is put on sentences between "Video sentences" and "Video syllables". Finally, the three-way interaction between context type, context duration, and attention is close to significance [F (1, 16) =4.10, p=0.06], remembering that the three-way interaction was present in young adults.

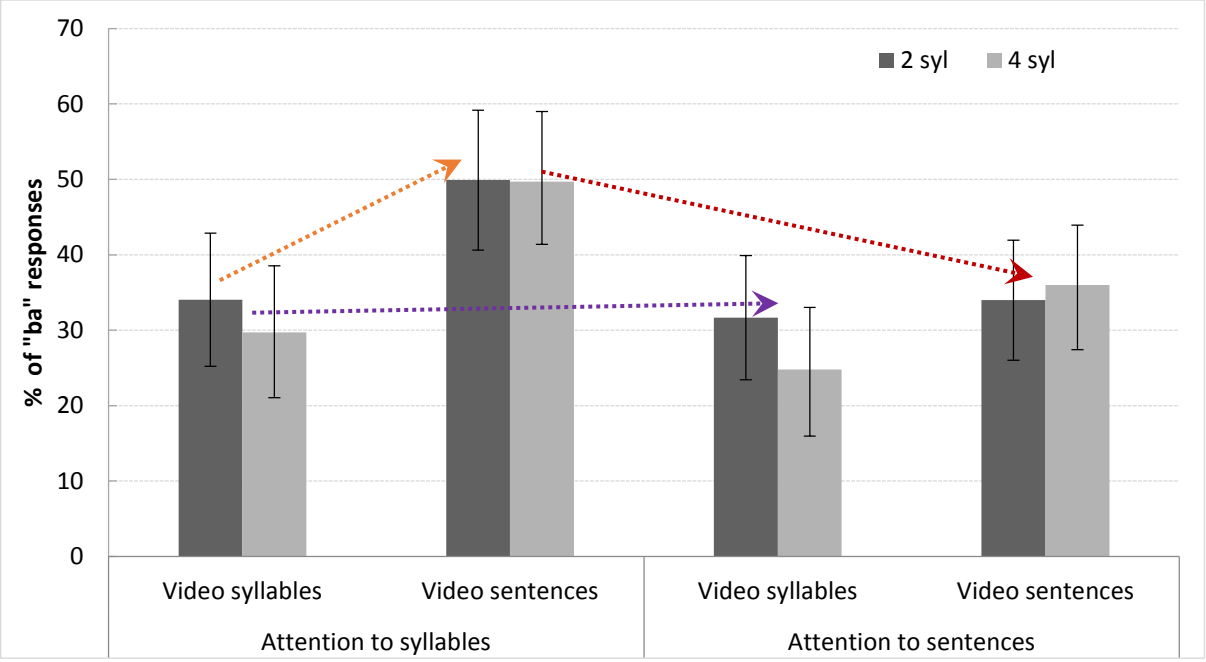

Figure 6-11 Percentage of "ba" responses for "McGurk" targets in the "Video syllables" vs. "Video sentences" contexts in Experiment B. The arrows display the significant effects of conditions (see text). Standard errors are displayed for all conditions.

Then, the proportion of "ba" scores was compared with our previous data on younger adults (Figure 6-12). A mixed ANOVA was carried out on context and attention between older and younger adults. The assumption of homogeneity of variances was met since the Box's M test of equality of covariance matrices and Leven's test of equality of level variance were not significant. The main effect of attention within groups was significant [F (1, 36)

=4.5, $p<.05$], such as the effect of context [F (1, 36) =29.27, $p<.001$] together with the interaction between context and attention [F (1, 36) =15.96, $p<.001$]. *Post-hoc* analyzes display a significant difference between the "Video syllables" and 'Video sentences" when attention is put on sentences (Figure 6-12, red arrows), no significant effect of attention for "Video syllables" (Figure 6-12, purple arrows) for both groups but an effect of attention for "Video sentences" similar in both groups (Figure 6-12, red arrows).

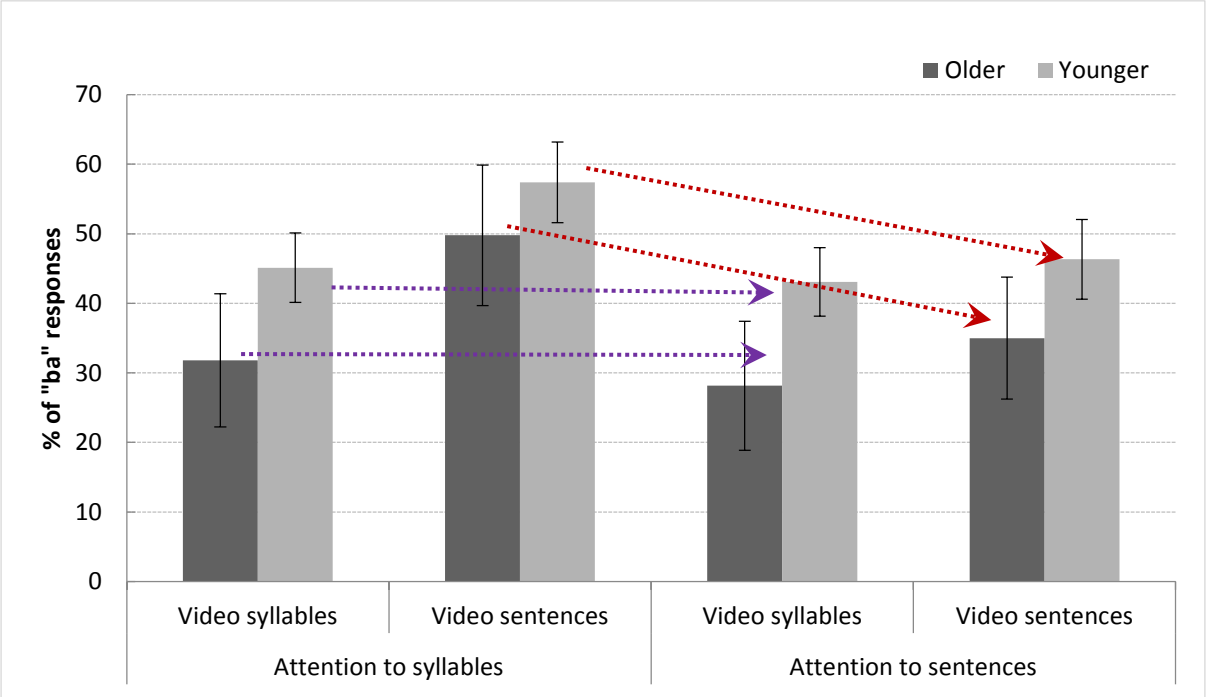

Figure 6-12 The percentage of "ba" responses for "McGurk" targets in both contexts and both attention conditions, in Experiment B, for older compared with younger participants. Standard errors are displayed for all conditions.

6.3.3.2 ***Response time***

Mean response times for the two experiments are displayed in Figure 6-13. The results are consistent with our previous experiments and the previous findings (Nahorna *et al.*, 2012) in which response times were larger for McGurk targets (see green arrows in Figure 6-13), independently on context. In both attention conditions and in all contexts, the processing of "ba" responses was indeed quicker compared to McGurk responses. A four-way repeated-measures ANOVA on context type, context duration, attention and target in Experiment B

displays once again an effect of target (120 ms quicker response for "ba" targets, F (1, 16) =132.76, p<0.001) and no other significant effect of other factors, alone or in interaction.

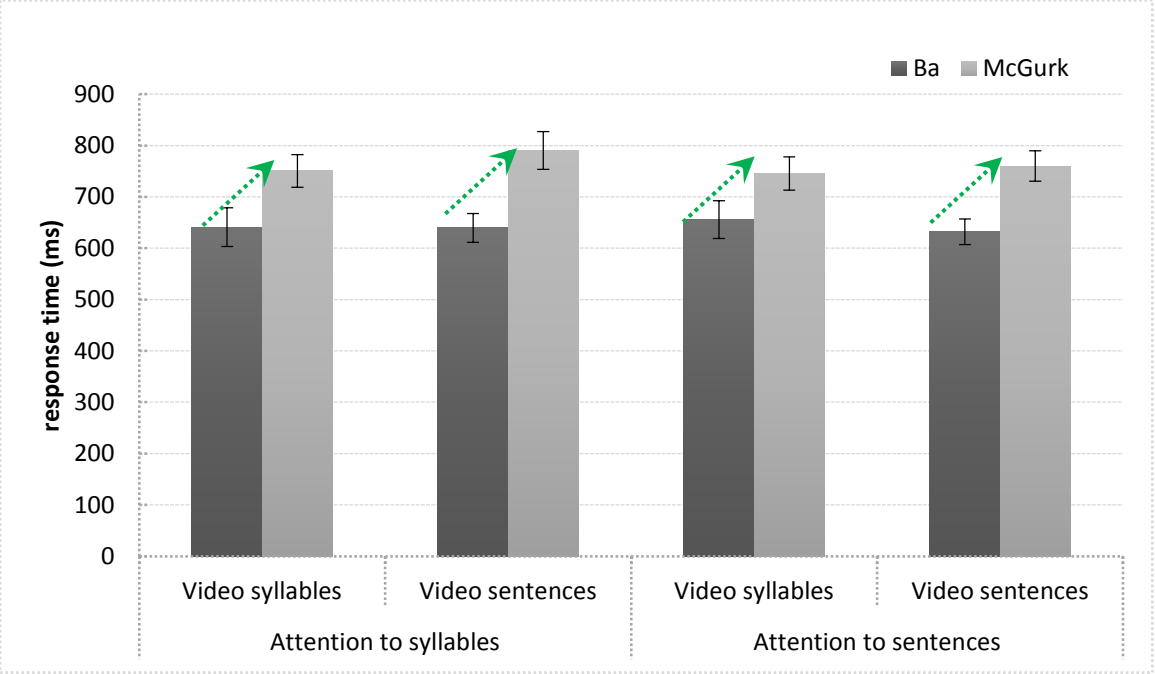

Figure 6-13 Mean response times for both conditions, averaged over both context durations, in Experiment B. Standard errors are displayed for all conditions.

Then, a mixed ANOVA was conducted to compare targets, attention, and context between younger and older participants. None of the variables was significant apart from targets [F (1, 36) =29.39, p<0.001)]. The McGurk target took a longer time for both older (120ms) and younger adults (80 ms) when averaged over all conditions.

6.3.4 Correlations with cognitive variables

Pearson product-moment correlation coefficients were computed to assess the relationship between the SSQ and Stroop values for senior participants and a number of characteristics of their behavior in Experiments A and B (e.g. mean amount of McGurk responses, amount of unbinding in Experiment A, role of attention for sentences in Experiment B, differences in response times between "ba" and McGurk targets in both experiments). No correlation was found in any of these tests.

6.4 DISCUSSION

The present experiments (Experiment A and Experiment B) replicate the findings of our previous experiments and confirm once again that context matters in AV integration. The results in older adults support our hypotheses about AV binding and the two-stage model introduced by Nahorna *et al.* (2012; 2015).

Experiment A displays unbinding and rebinding effects in older adult and shows that the amount of unbinding is larger in older compared with younger adults (Figure 6-9). Importantly, the difference between groups occurs with the incoherent context without rebinding, while there was no statistical difference between groups in the coherent context condition, which makes a comparison between unbinding effects clearer.

The first difference between both groups in Experiment A could come from unisensory performances. Concerning auditory perception, to minimize the effect of age-related hearing loss, we performed audiometry and considered only the participants with good hearing sensitivity. Considering visual perception, we saw previously that lip-reading abilities seem to diminish as age increases, but this decline is more prominent for words and sentences than syllables, and rather above 70 years at least for CV utterances (Shoop and Binnie, 1979; Dancer *et al.*, 1994; Sekiyama *et al.*, 2014). In our experiments, target stimuli were always syllables with CV contexts and the majority of participants fall under the age of 70's (out of 17 participants, 9 were under 65 years, 5 were under 70 years, and only 3 were above 70 years). Therefore, it is likely that there was only a minimal effect of aging-related decline in lip-reading in our data. Finally, the fact that the amount of fusion in the coherent context was similar between older and younger participants in our data means that the difference is mainly due to the way the incoherent context and the cognitive inferences it produced were processed.

Indeed, Experiment A suggests that the incoherence of the audio and video streams could lead older subjects to selectively decrease the role of the visual input in the fusion process more than younger ones. This seems rather contradictory with the observation that they might exhibit more dependency on visual information (Sekiyama *et al.*, 2014). Sekiyama *et al.* (2014) suggest that this heightened visual influence could be due to a delay in auditory processing, in agreement with data showing that older adults exhibit slower auditory processing for both speech (Tremblay and Ross, 2007) and non-speech (Schroeder *et al.*, 1995) stimuli. Sekiyama *et al.* (2014) propose a "visual priming hypothesis" according to which the contribution of visual cues would be larger for individuals who process visual speech faster than auditory speech when compared to individuals who have the same speed for both modalities (Sekiyama and Burnham, 2008). In this context, the larger effect of unbinding in older subjects could be related to the fact that under cognitive load, integration reduces (see Alsius *et al.* 2005; 2007). Indeed, it could be assumed that in the case of incoherence, a certain amount of attention is required for keeping audition and vision bound together and hence produce binding. If the ability to maintain this amount of attention is decreased in seniors, this would result in less fusion and more unbinding, which is actually what happens in Experiment A. In our data, it appears that the large AV incoherence in the incoherent context leads the older subjects to select only the dominant auditory input rather than to attempt to integrate auditory and visual inputs that seem unlikely to come from the same source. This means that the "visual priming hypothesis" would depend on the state of the AV coherence mechanism, so that if coherence appears too low, integration is more or less disrupted.

The results from Experiment B provide a more coherent pattern between older and younger groups. Attention plays a role only for "Video sentences" but not for "Video syllables" even in older adults. This shows that in this experiment older adult's present attentional control similar to the younger group. As in younger adults, we suggest that in these stimuli

AV binding could be pre-attentive in “Video syllables” because of their strong, salient AV co-modulations making them pop-out as strong bottom-up AV primitives.

Overall, our results are in line with the global architecture for multisensory integration proposed by Talsma *et al.* (2010), introducing bidirectional interplay between attention and multisensory processing. Moreover, both experiments provide additional information on the AVSSA process in older adults. The two experiments in this study provide confirmation and development to the view that AV fusion in speech perception includes a first stage of AVSSA, rather similar in young and in older adults. Their theoretical consequences will be further analyzed in the general discussion.

Chapter 7

7. General Discussion

In the previous chapters, we have presented our objectives, results, and discussion for each experiment. In this section, we will propose an overall discussion within the perspectives of our assumptions and goals for the thesis. This will lead us to submit a tentative new version of our "two-stage model for AV speech perception", based on the analysis and likely interpretations of the behavioral and neurophysiological experimental data presented in this document. We will conclude with a number of possible further developments and perspectives to strengthen the proposed AVSSA process.

7.1 Summary of the Major Findings of this Work

Let us begin by summarizing the main results of our behavioral and EEG experiments into three parts as per our objectives.

7.1.1 Behavioral characterization of the AV binding process

Previous experiments from Nahorna *et al.* (2012; 2015) demonstrated that AV fusion is decreased by an incoherent context presented prior to the McGurk stimuli. This effect is robust, being replicated in various experiments within the two pioneer papers, and it supported the authors' assumption about the existence of an "AV binding stage" within the framework of a "two-stage model" of AV perception. However, the stimuli that were developed by Nahorna *et al.* (2012, 2015) always consisted of a single source for each sensory modality. To assess the functioning of the binding mechanism in more realistic situations involving a competition between sources inside the audio modality, we first adapted the "unbinding/rebinding" paradigm by Nahorna *et al.* (2015, Experiment 2) with an important

variant by adding acoustic noise only in the context while the target remained uncorrupted with noise (see Chapter 3). This corresponds to having two audio sources, with one source being stationary noise, which is a rather specific case of source mixture.

The experimental results (see Figure 7-1) provided confirmation about the unbinding process (orange arrow on the Figure) and rebinding process (green arrow in the Figure) similar to the ones obtained by Nahorna *et al.* (2015). However, the novel finding was the global decrease in the percentage of "ba" responses (hence the global increase in the rate of AV fusion) associated with acoustic noise added on the context (blue arrow in the Figure). Since the target was not noisy, the effect likely occurred at the level of the fusion process. This shows that participants are able to evaluate both the level of acoustic noise and AV coherence and to monitor the AV fusion accordingly.

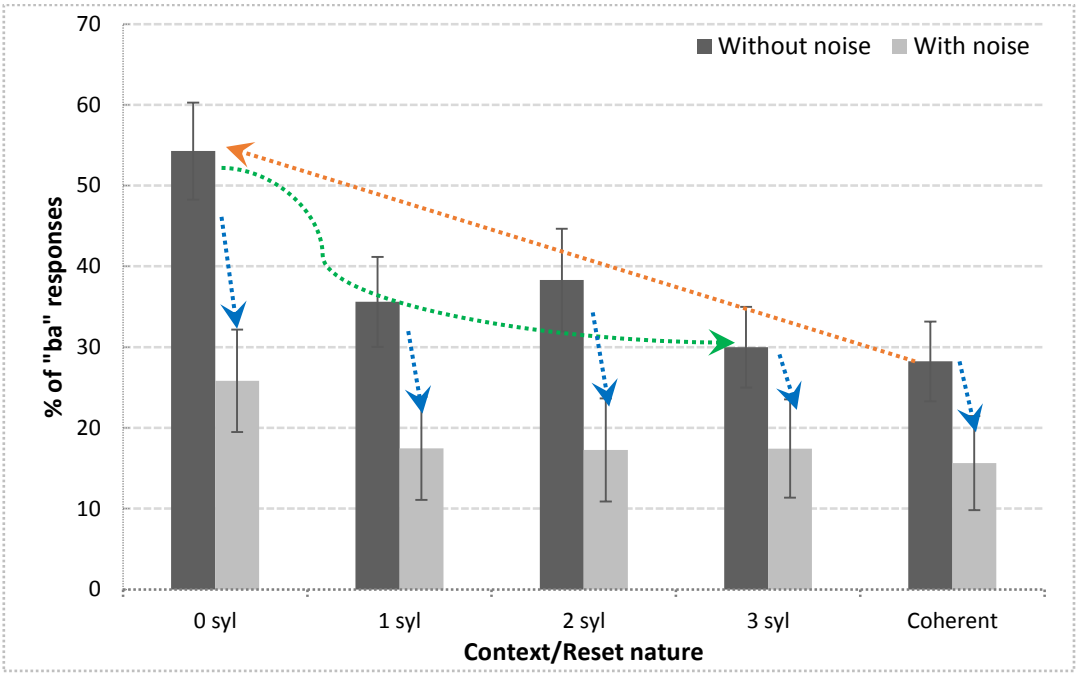

Figure 7-1 Percentage of "ba" responses for "McGurk" targets, without noise or with noise in the context, and for incoherent context with four reset durations (0syl, 1syl, 2syl or 3syl), compared with coherent context (context durations averaged). Standard errors are displayed for all conditions. Unbinding, rebinding and effect of noise are displayed by colored arrows (see text).

Then, in the two experiments in Chapter 4, we presented a context made of a mixture of speech sources to explore the possibility that a multisensory scene analysis process would take place in the course of AV fusion. Within the mixture of two audio sources, one was coherent with the video input, and we expected the "coherence box" to compute partial correlations required for adequate AV binding, and also necessary to assess the binding state modulating AV fusion. In the first experiment (Experiment A) the objective was to explore the way a context made of a mixture of sources would modify the McGurk effect, and in the second one (Experiment B) the objective was to explore the potential role of attentional mechanisms in the AV scene analysis and fusion process.

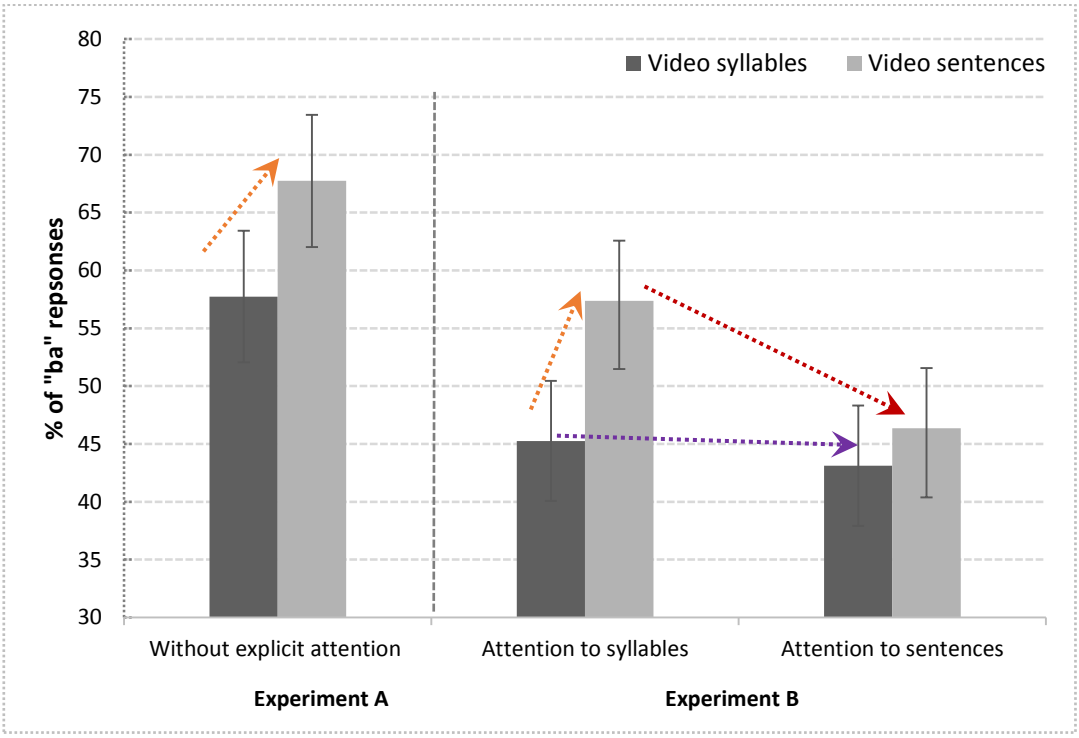

Figure 7-2 Percentage of "ba" responses for "McGurk" targets in the "Video syllables" vs. "Video sentences" contexts in Experiment A and Experiment B (context durations averaged). The effects of context and attention are displayed by colored arrows (see text).

The two experiments in Chapter 4 confirmed once more that context matters in setting the amount of AV fusion. However, they also shed important light on the relationship between the two-stage model and AVSSA (see Figure 7-2). Experiment A showed that the

"Video syllables" context leads to a higher amount of binding and fusion (orange arrow in Figure 7-2). This could be due in our reasoning to global binding/unbinding, with both higher correlations for syllables than for sentences and higher streaming of the McGurk target with syllables than with sentences. Experiment B further showed that selective attention on one AV source rather than the other can modulate binding and hence fusion. Attention intervened for "Video sentences" (red arrow in Figure 7-2) but not for "Video syllables" (purple arrow in Figure 7-2), probably because syllables are more salient and hence do not require attention in the binding and fusion process.

Altogether, experiments A and B suggest that the AVSSA process enables to both (1) evaluate the coherence between auditory and visual features within a complex scene, in order to properly associate the adequate components of a given AV speech source, and (2) provide to the fusion process an assessment of the AV coherence of the extracted source. Moreover, it appears that attention may increase the perceived coherence of the attended AV source and hence increase fusion accordingly.

7.1.2 Neurophysiological characterization of the binding mechanism

The second objective of our doctoral project in Chapter 5 was to search for a neurophysiological correlate of early binding/unbinding in AV interactions, by adding either a coherent or an incoherent AV context before an auditory, congruent AV or incongruent AV speech target and measure the effect of context on amplitude and latency of the N1/P2 component of the ERP response to the target. Our assumptions were that (1) coherent context should replicate the results of previous EEG studies on the auditory N1/P2 response (decrease in amplitude and latency in the AV vs. A condition) and (2) an incoherent context should lead to unbinding, with the consequence that the visual influence on the auditory stimulus should decrease. Hence, the N1/P2 latency and amplitude in the AV condition should increase

(reaching a value close to their value in the A condition) in the incoherent context compared with the coherent context.

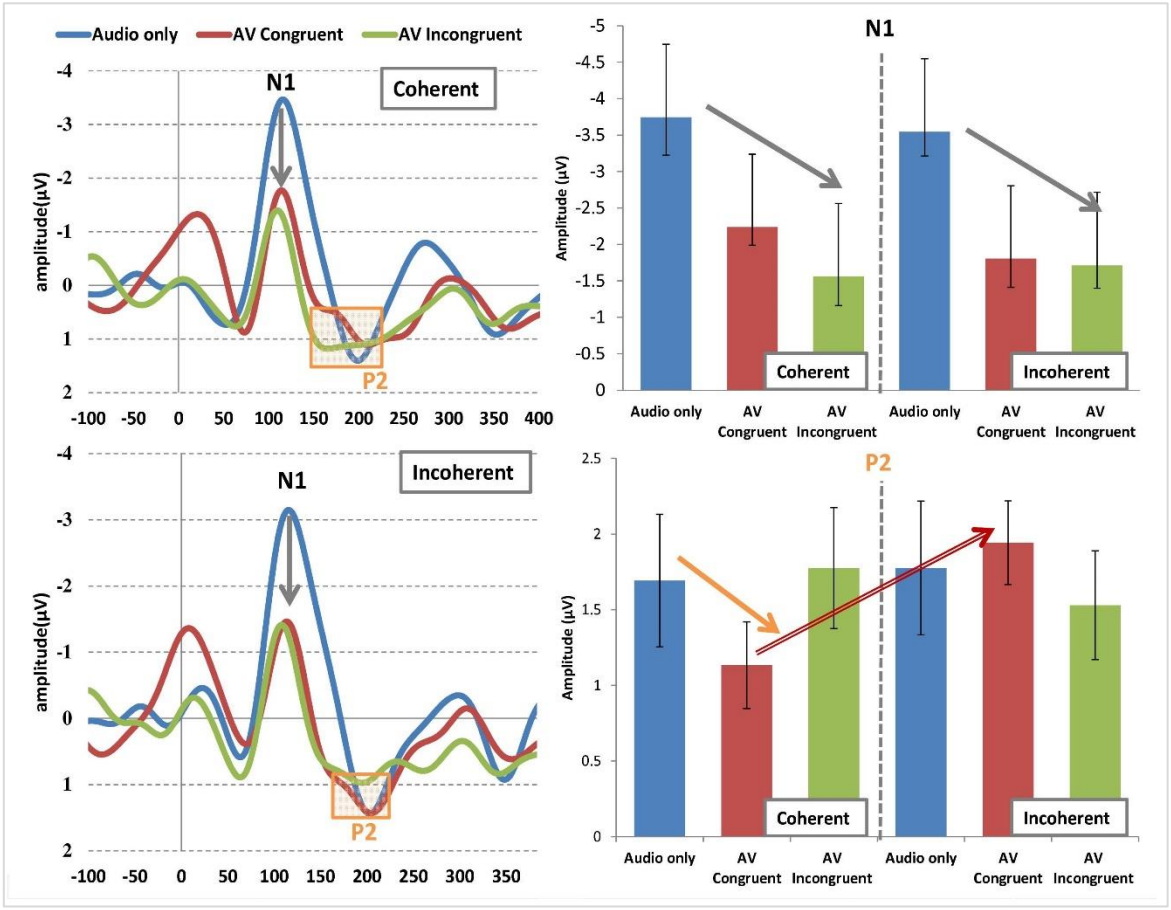

Figure 7-3 Grand-average of auditory evoked potentials for the six electrodes (frontal and central) on the left column; and mean N1 and P2 amplitude for coherent vs. incoherent contexts on the right column.

The main findings are the following. For the N1 component, there was an amplitude reduction in both AV congruent and incongruent conditions compared to the audio-only condition, as in previous studies, and for both coherent and incoherent contexts (Figure 7-3), while there was no significant effect of the visual input on latency in any condition of target congruence or context coherence (Figure 7-4). For the P2 component, the decrease in amplitude and latency from the audio-only to the AV congruent condition (Figure 7-3 and Figure 7-4) is also in line with previous studies. However, the novel finding in our study is the significant effect of context for P2 between coherent and incoherent contexts in the AV congruent condi-

tion, alone for latency and in interaction with modality for both latency and amplitude. *Post-hoc* tests showed that these effects could be due to a suppression of the decrease in amplitude and latency from the audio-alone to the AV congruent condition when the context is incoherent (Figure 7-3 and Figure 7-4).

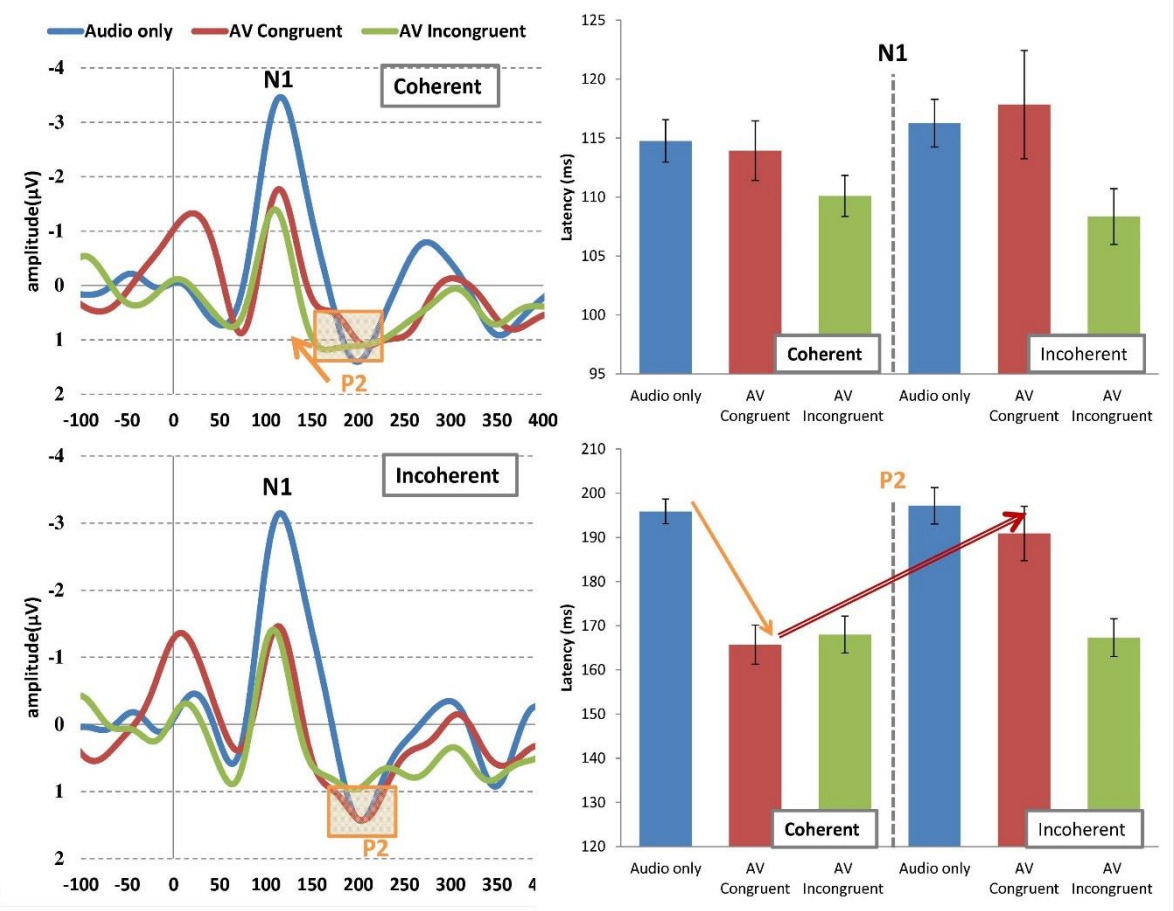

Figure 7-4 Grand-average of auditory evoked potentials for the six electrodes (frontal and central) on the left column; and mean N1 and P2 latency for coherent vs. incoherent contexts on the right column.

In summary, the visual modality produces a decrease in N1 amplitude and possibly latency, probably because of visual anticipation, independently on target congruence and context coherence. A congruent visual input (AVC) appears to lead to a decrease in P2 amplitude and latency in the coherent context, probably because of visual predictability and AV speech specific binding. Due to incoherence context, the effect would be suppressed because

of unbinding due to incoherence. This introduces a new paradigm in ERP studies on AV interactions, based on the role of context.

7.1.3 Dynamics of AV binding in older adults

Our final objective of the thesis was to estimate AV binding and its dynamics in the older population, capitalizing on the experimental paradigms developed by Nahorna *et al.* (2012; 2015) and in the present doctoral work in adults. AV binding in seniors was tested in two experiments that were presented in Chapter 6: binding/unbinding/rebinding processes were assessed in Experiment A while the potential role of attentional mechanisms in the scene analysis process was evaluated in Experiment B.

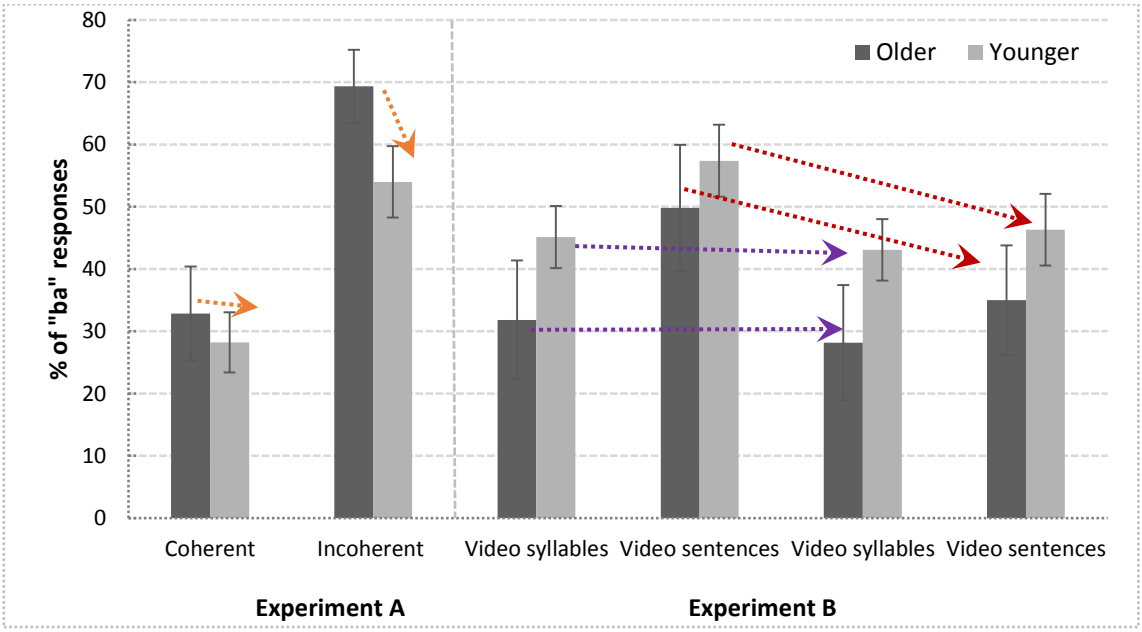

Figure 7-5 The percentage of "ba" responses for "McGurk" targets in both contexts and both attention conditions, in Experiment A & B, for older compared with younger participants. Standard errors are displayed for all conditions.

Experiment A displayed unbinding and rebinding effects with a larger amount of unbinding in older compared with younger adults (Figure 7-5, left). Importantly, the two groups differed in the incoherent context without rebinding but not in the coherent context condition, which made a comparison between groups more straightforward. The data show that the incoherence of the audio and video streams led older subjects to decrease the role of the visual

input in the fusion process more than younger ones. This could be related to the fact that under cognitive load, integration reduces (see Alsius *et al.* 2005; 2007). Indeed, it could be assumed that in the case of incoherence, a certain amount of attention is required for keeping audition and vision bound together and hence produce binding. If the ability to maintain this amount of attention is decreased in seniors, this would result in less fusion and more unbinding, which is actually what happens in Experiment A. The lack of difference between groups in Experiment B (see Figure 7-5, right) could be due to the fact that the attentional focus on a given source could simplify the task and decrease the unbinding effects for both groups.

7.2 Interpretation of the Present Results within the "Two-Stage Model"

The experiments presented in this doctoral work confirm that the preceding context modulates AV fusion in both young and old adults, and shed new light on the AVSSA process. In the following sections, we will firstly attempt to incorporate our results into the "binding and fusion" architecture and propose an improved version of the two-stage model for AV perception by introducing new components based on these results. Then, we will address each component of this enhanced cognitive two-stage model for AV integration in relation to various studies in AV perception, including the outcome of the present work.

7.2.1 Characterization of the AVSSA process

The first set of experiments by Nahorna *et al.* (2012; 2015) provided primary evidence in favor of the "two-stage model" in which a first binding stage evaluating the coherence between sound and face would control the output of the fusion process and hence possibly change the percept (see Figure 1-14). This "AV binding stage" would enable the brain to assess consistency between auditory and visual features in complex mixtures of competing sources. From our results, we will attempt to define this process more precisely (see Figure 7-6, AVSSA process box).

1. Channel reliability & AV coherence: The experimental results from Chapter 3 display two cumulative effects playing a role in AV fusion. Firstly, as in the previous experiments by Nahorna *et al.* (2012; 2015), fusion depends on a binding/unbinding/rebinding process controlled by the coherence of the two sensory sources, resulting in decreasing the role of the visual input if the AV coherence is weak. Secondly, the addition of acoustic noise in the context stimulus before the McGurk target also appears to modify fusion even though there is no noise in the target. Our interpretation is that addition of acoustic noise contaminated the channel by making it less reliable, which resulted in an increase of the relative reliability of the visual input. This suggests that the fusion process also depends on the estimated reliability of each sensory channel controlling their relative weights in the final decision.

Altogether, it hence appears that AV fusion is monitored by the output of two evaluation devices, one estimating AV coherence (and decreasing visual weight in the case of incoherence) and the other estimating channel reliability (and increasing/decreasing channel weights in relation to their relative reliability): see Figure 7-6. Notice that the dynamics of these effects can be quite large: noise increased the amount of the McGurk effect in our data by a factor two (Figure 7-1) and unbinding decreased the amount of the McGurk effect by a factor two in seniors (Figure 7-4).

2. Scene Analysis and Fusion modulation: Experiment A in Chapter 4 suggests a possible decomposition of the AVSSA process in the case of an AV scene consisting of multiple sensory inputs. This experiment involved competing auditory sources together with a visual stream coherent with one of the competing auditory streams. The existence of a larger amount of fusion for "Video syllables" than for "Video sentences" suggests that two subprocesses took place here, one enabling AV source extraction (AV streaming) and the other one computing AV coherence for fusion modulation. This is displayed in Figure 7-6 under the terms "feature extraction" (see Figure 7-6, Ia) and "AV coherence" (see Figure 7-6, Ib).

Under the item "feature extraction" we both mean use of cues from one modality to assist the extraction of cues in another modality, and use of temporal co-modulations to appropriately associate auditory and visual cues belonging to a single AV source. In the case of the experiments in Chapter 4, we assume that there is a first stage of unisensory ASA providing at its output (bottom left box in Figure 7-6) separate audio cues for syllables and for sentences. The "feature extraction" box (Ia) would enable the subjects to associate auditory cues corresponding to either syllables or sentences with the corresponding visible information. The "AV coherence" box (Ib) would then assess the amount of AV coherence for driving the fusion process. For example, "Video syllables" would lead to a high AV coherence and hence a good amount of AV fusion. In contrast, the coherence between audio and video cues for sentences could be relatively lower – considering the fact that the scene analysis process is never perfect – and hence, the amount of fusion was indeed lower. In summary, there would be a first stage of low-level AV interactions followed by regular evaluation of the coherence of the audio and video components of the extracted AV stream.

3. Attention and AV binding: Various studies have shown that attention could intervene in AV fusion through either global attentional control of fusion related to cognitive load (e.g. Alsius *et al.*, 2005; 2007) or specific attentional biases on a single sensory channel, (e.g. vision in Tiippana *et al.* 2004). The results from Experiment B in Chapter 4 suggest that attention may also increase the perceived coherence of the attended AV source and hence increase fusion accordingly. Attention actually appeared to intervene in a bidirectional interplay, either "top-down" (in the case of attention to "Video sentences") with voluntary control on a particular source, or "bottom-up" (in the case of attention to "Video syllables") where the source saliency could pop-out and automatically drive fusion. This led us to modify the two-stage model by introducing two possible roles for attentional processes: 1) a global effect with direct modulation of the decision ("General" arrow in Figure 7-6) and 2) an effect at the

level of the binding stage, in which orientation towards a particular source can influence the output of the "AV coherence" stage ("Scene Oriented" arrow in Figure 7-6). This is the way we interpret the increase in fusion for "Video sentences": the AV coherence would be intrinsically low, but attention towards the sentences would enable the participants to recover some amount of AV coherence and hence increase the visual weight for more McGurk effect.

***4. N1/P2 and AV Binding*:** In our attempt to find neurophysiological correlates of early binding/unbinding in AV interactions, we obtained different effects of context for N1 and P2 components suggesting that these elements could reflect different processing stages. It has been suggested that the AV effects on the N1 component could reflect automatic processes possibly not speech specific and only driven by visual anticipation independently on AV phonetic congruence (Stekelenburg and Vroomen, 2007; Baart *et al.*, 2014). This is in agreement with the lack of effect of context on N1. This effect could be associated with the "AV Feature Extraction" Ia in Figure 7-6. On the contrary, the P2 component would be possibly speech specific, content dependent and modulated by AV coherence (Stekelenburg and Vroomen, 2007; Baart *et al.*, 2014). This fits well with the existence of context effects on both P2 amplitude and latency. This could be part of the "AV coherence" stage Ib in Figure 7-6. This would also fit possibly with the proposal of a dual route for AV speech processing, by Arnal *et al.* (2009) as we will discuss later.

***5. Older Adults and AV Binding*:** The experiments on seniors globally confirm the findings of the earlier studies on younger adults. However, they also suggest that unbinding could result in increasing cognitive load for fusion – which would possibly be easier to tackle by younger than by older participants. This could provide an unexpected link between the experiments by Alsius *et al.* (2005; 2007) on the general role of cognitive load in decreasing fusion – which means to a certain extent unbinding the sources – and our own experiments on binding/unbinding/rebinding processes.

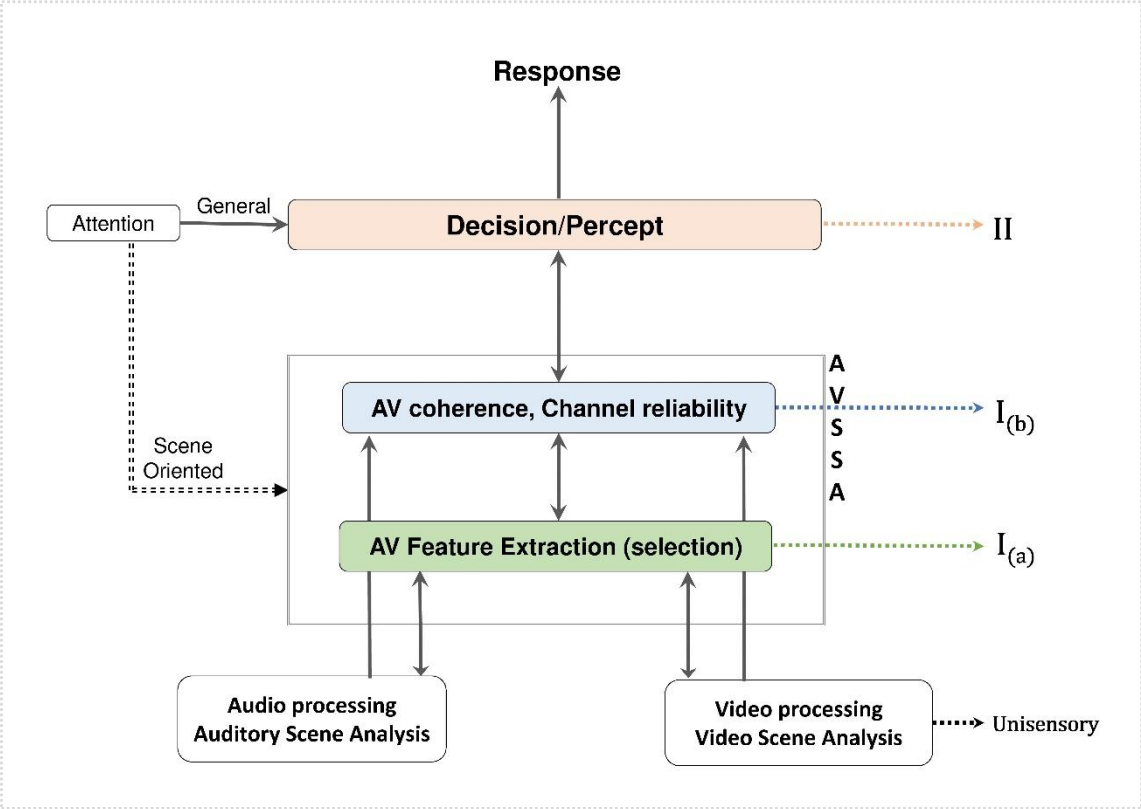

Figure 7-6 A possible cognitive architecture for AV binding and fusion in speech perception.

7.2.2 Assessing the "Two-stage" model

The previous reasoning hence results in the tentative and hopefully improved "two-stage" model for AV integration displayed in Figure 7-6. Though we do not claim this model to be either complete or totally fixed, we will attempt in the following to describe each component in a bottom-up sequence in relation with available behavioral, neurophysiological and neuroanatomical data.

1) Unisensory processing

Inputs from both the auditory and visual modality undergo some amount of grouping within their respective modality. This corresponds to unisensory scene analysis processes that involve segmenting separately the auditory and video scenes into sensory elements that should be grouped within their common source mostly through bottom-up primitives in both the visual and auditory domains (Bregman, 1990). This fits with the experimental studies that highlight cases where unimodal perceptual grouping precedes multisensory integration

(Sanabria *et al.*, 2005; Keetels *et al.*, 2007). However, at this stage, each unisensory input could receive feedback from the other modality through low-level interaction between modalities, as will be discussed in the next section (see the bidirectional arrows to and from the "AV Feature Extraction" box).

2) *AVSSA process as a first stage in AV fusion*

In the context of the two-stage model of AV fusion, Nahorna *et al.* (2012; 2015) incorporated a "coherence box" as a first processing stage proposing that the brain would continually evaluate the coherence of both inputs to determine whether they result from the same source. The results from the present work led us propose to decompose this box into two sub-processes.

2a) AV Feature Extraction & Selection (Figure 7-6, I_a)

Our results from Chapter 4 led us to incorporate an additional sub-stage within AVSSA process which we termed as "AV Feature Extraction and Selection". This process would be in charge of correctly associating auditory and visual cues on the basis of low-level temporal co-modulations. It appears as a necessary step in any experiment involving various AV sources (e.g. Alsius and Soto-Faraco, 2011). It would be involved in the experiments related to the "AV speech detection advantage" showing the benefit of good temporal AV correlations for the detection or processing of speech in adverse conditions (e.g. Grant and Seitz, 2000; Kim and Davis, 2004; Schwartz *et al.*, 2004; Alsius and Munhall, 2013).

It could be argued that this stage is mostly non-speech specific, since it consists of low-level interactions based on timing and not phonetic information. However, it is important to notice that some studies show an enhanced role of the visual input for natural moving lips compared with exactly the same temporal information provided in a non-speech mode (e.g. a bar whose amplitude varies with either lip opening or acoustic envelope: see Bernstein *et al.* (2004); Schwartz *et al.* (2004); Basirat *et al.* (2012)).

A number of studies analyzed the AV co-modulation and particularly correlation in time between some audio (typically global envelope or envelope of particular spectral bands) and video (lip or face parameter) cues (e.g. Munhall and Vatikiotis-Bateson, 1998; Yehia *et al.*, 1998; Barker and Berthommier, 1999; Jiang *et al.*, 2002; Chandrasekaran *et al.*, 2009), and correlation in time between rms energy (particularly in the mid-to-high frequency energy-envelope) and lip area has been considered a critical factor in the AV speech detection advantage (Grant and Seitz, 2000; Kim and Davis, 2004).

Globally, this stage would be in charge of the "AV scene analysis" mechanisms likely to result in multisensory rather than unisensory grouping, as in the experiments in Chapter 4. Indeed, various behavioral studies have suggested that the presentation of a visual stream can enhance segregation or integration by affecting primary auditory streaming (e.g. Rahne *et al.*, 2007; Marozeau *et al.*, 2010; Devergie *et al.*, 2011; Berthommier and Schwartz., 2011; Maddox *et al.*, 2015).

Neuroanatomical and neurophysiological correlates

We will now attempt to discuss potential neuroanatomical and neurophysiological correlates of the "AV Feature Extraction and Selection" stage – though we acknowledge that it is a difficult and risky exercise.

It is now increasingly clear that AV interactions, which begin at a pre-cortical stage, mostly in the superior colliculus (Stein and Meredith, 1993), can occur directly at the level of primary cortices and then through a number of cortical systems (see Driver and Noesselt, 2008). Various EEG and fMRI data actually suggest that AV speech interactions may occur at the earliest functional-anatomic stages of cortical processing (e.g. Calvert *et al.*, 1997; Calvert *et al.*, 1999; Besle *et al.*, 2004; Van Wassenhove *et al.*, 2005; Okada *et al.*, 2013). Even pure lip-reading (i.e., visual speech without auditory stimulation) activates the auditory cortex (Bernstein *et al.*, 2002; Calvert and Campbell, 2003; Hall *et al.*, 2005) and congruent visual

speech increases the activity in response to auditory speech in the auditory cortex (Okada *et al.*, 2013).

In relation with our own data on the lack of context effects on AV interactions in N1, and in relation with other studies showing that suppression and speeding-up of the N1 component are not affected by the AV congruency and mainly depend on anticipatory visual cues (Stekelenburg and Vroomen, 2007; Baart *et al.*, 2014), it could be suggested that N1 is a basic correlate of this first AV interaction stage. It remains unclear if processing at this stage is the result of a direct link between unisensory primary cortices or if it involves a mediating link through the STS (Calvert *et al.*, 1999; Ghazanfar and Schroeder, 2006), see later the "dual route" proposal by Arnal *et al.* (2009).

2b) AV Coherence and Channel Reliability (Figure 7-6, I_b)

The second sub-box in our model would be in charge of evaluating AV coherence for constantly monitoring the coherence of the AV input and weighting the visual modality accordingly. This is a process required by the many studies by Nahorna *et al.* (2012; 2015) and our own work demonstrating that context matters, and displaying unbinding/rebinding processes in which the lower the internal evaluation of AV coherence, the less bound the auditory and visual inputs and the lower the visual weight in the fusion process. Notice that this stage should comprise speech specific components, considering the second experiment in Nahorna *et al.* (2012) showing that temporal co-modulations are not the only elements in AV speech binding. Indeed, this experiment displayed unbinding provided by pure phonetic incoherence with stimuli keeping a perfect timing of the AV co-modulations of lip opening and acoustic envelope. Nahorna *et al.* (2012) suggested that the fine phonetic content of each stream is determined and exploited in the binding process (see Figure 1-15b), hence the bidirectional arrow to and from the decision process in Figure 7-6.

An important and new result in Chapter 3 is the clear demonstration that noise in a given channel decreases the weight of the channel in the fusion process. This had already been observed for both acoustic noise increasing the role of vision (e.g. Sekiyama and Tohkura, 1991; Sekiyama, 1994; Hardison, 1996; see also the effect of decreasing acoustic intensity on Colin *et al.*, 2004) and visual noise decreasing the role of vision (Fixmer and Hawkins, 1998; Kim and Davis, 2011). The new finding here is that the evaluation of the reliability of the sensory channel seems to be constantly realized and used even at a time when there is no more noise in the channel – revealing some inertia in the evaluation process. This has already been introduced in adaptations of computational models for AV speech perception (e.g. Heckmann *et al.*, 2002; Huyse *et al.*, 2013). The results of Chapter 3 suggest that AV coherence and channel reliability can indeed cooperate to modulate the final fusion and decision process.

Neuroanatomical and neurophysiological correlates

A number of studies on the neural correlates of multisensory integration display the role of the superior temporal cortex for both speech and non-speech stimuli. More specifically, increased activation of the left posterior superior temporal sulcus (pSTS) was observed in fMRI as well as TMS studies of the McGurk effect (Sekiyama *et al.*, 2003; Bernstein *et al.*, 2008; Beauchamp *et al.*, 2010; Benoit *et al.*, 2010; Irwin *et al.*, 2011; Nath *et al.*, 2011; Nath and Beauchamp, 2012; Szycik *et al.*, 2012). In the context of our proposal, the STS is proposed as a likely site for processing the AV temporal correspondence, in relation with primary sensory cortices (Noesselt *et al.*, 2007), and as a likely site for AV binding in the McGurk effect (Beauchamp *et al.*, 2010; Nath and Beauchamp, 2012). The supramarginal gyrus (SMG) could also a possible site for analysis of AV incongruency (Bernstein *et al.*, 2008). Interestingly, the STS functional connectivity also seems to be implicated in the perception of noisy speech: indeed, Nath and Beauchamp (2012) displayed an increased functional connec-

tivity between the STS and the auditory cortex when the visual channel was noisy, and on the contrary an increased functional connectivity between the STS and the visual cortex when the auditory channel was noisy.

Based on a study involving both MEG and fMRI data, Arnal *et al.* (2009) proposed the "dual neural routing model" including a first fast corticocortical pathway, not sensitive to AV incongruence, which would enable a direct connection between the visual input and the auditory cortex. This route could be reflected in the N1 component behavior. The second route is compatible with the many neuroanatomical studies cited previously, where the connection between the auditory and the visual cortices would be mediated by a feedback from STS. The STS would be a pivot in AV interactions, estimating the degree of incoherence between the auditory and visual inputs and providing feedback to the auditory and visual cortices. This could reflect the behavior of the P2 component, which would hence reflect the neural consequences of phonetic binding and of the process dedicated to evaluate AV congruency. This was reflected from our results in Chapter 5 as well as in other studies showing that P2 is content dependent and is modulated by the visual input only when there is a certain amount of congruence between the auditory and the visual inputs (Stekelenburg and Vroomen, 2007; Vroomen and Stekelenburg, 2010; Baart *et al.*, 2014).

3) Attentional Effects on the Fusion and Decision process

Several studies have manipulated the participants' attention and indeed shown that attention can influence the McGurk effect (Tiippana *et al.*, 2004; Alsius *et al.*, 2005; Alsius *et al.*, 2007; Talsma *et al.*, 2007; Andersen *et al.*, 2009; Soto-Faraco and Alsius, 2009; Navarra *et al.*, 2010; Alsius and Soto-Faraco, 2011; Buchan and Munhall, 2011; Alsius *et al.*, 2014). Interestingly, all these results were interpreted in the framework of the one-stage model. Indeed, they showed that the fusion/decision stage could be partly regulated by the attentional state of the subject, in relation to any interfering stimulus or task. Using our results from Ex-

periment B in Chapter 4 on younger adults and from Experiment B in Chapter 6 on older adults we could demonstrate that attention can intervene at the level of single AV sources and we suggest that the role of attention should be incorporated into the two-stage model, at two levels. Firstly we keep of course the global role of attention directly modulating decision (top arrow from the "Attention" box in Figure 7-6). Secondly, attention can be oriented towards a particular source and influence the binding process at the level of the "AV coherence" stage (bottom arrow from the "Attention" box in Figure 7-6). This is likely where the attentional effects occur in the experiments by Tiippana *et al.* (2004) or Andersen *et al.* (2009).

Neuroanatomical and neurophysiological correlates

It is out or our reach to introduce here a complete description of the attentional network in the brain. However, it is important to notice here the EEG study from Alsius *et al.* (2014) in which they evaluated the role of attention in the visual modulation of the N1/P2 components. They showed that a visual processing load can modulate early stages of AV processing, and suggested that reduced attention due to cognitive load would weaken integration and hence weaken the visual effects on both N1 and P2. A recent study by Moris Fernandez *et al.* (2015) suggests that the STS could also play a major role in attentional effects at hand in AV integration.

3) Decision/Percept

At the output of the AVSSA process the decision/perception stage produces an output based on the fusion of the two sensory streams. It has been proposed that AV fusion and more generally intersensory fusion was an optimal process driven by a maximum-likelihood integration process (Massaro, 1998; Ernst and Banks, 2002). The data of the present studies and of a number of other studies reviewed previously show that decision is actually mediated by AV coherence, channel reliability and attention. This does not show that a maximal-likelihood process is mistaken, but it indicates that the process is more sophisticated than was

conceived previously – particularly in the classical implementations of the FLMP model by Massaro and coll. More accurate models should indeed introduce a general description of the whole decision process, taking into account AV coherence, channel reliability and attention.

Neuroanatomical and neurophysiological correlates

Here again, it is out of the reach of the present work to describe in detail the cortical networks for decision and percept elaboration. But it is important to notice at this stage the possible neural role of the dorsal route and of the parieto-frontal system in the perception of incongruent stimuli. The dorsal route which connects sensory and motor regions seems to have a strong implication in the perception of incongruent and particularly McGurk stimuli, including frontal and prefrontal areas (Skipper *et al.*, 2007; Benoit *et al.*, 2010; Irwin *et al.*, 2011), insula (Skipper *et al.*, 2007; Benoit *et al.*, 2010; Szycik *et al.*, 2012), and parietal areas (Jones and Callan, 2003; Skipper *et al.*, 2007; Hugenschmidt *et al.*, 2009; Benoit *et al.*, 2010) (see also Moris Fernandez *et al.*, 2015).

7.2.3 Similarity with the theoretical framework by Talsma *et al.* (2010)

Our "two-stage" model shares a number of similarities with the theoretical framework elaborated by Talsma *et al.* (2010) to explain the interactions between multisensory integration and attention. As it can be seen on Figure 7-7, the steps in the proposed architecture for multisensory processing match rather well with our "two-stage" model. The main difference is that our model is focused on the processing of AV speech and aims to characterize and develop the AV binding process in light of our experimental data, while the framework developed by Talsma *et al.* (2010) aims at being general for multisensory processing and more focused on the relation between attention and multisensory processing.

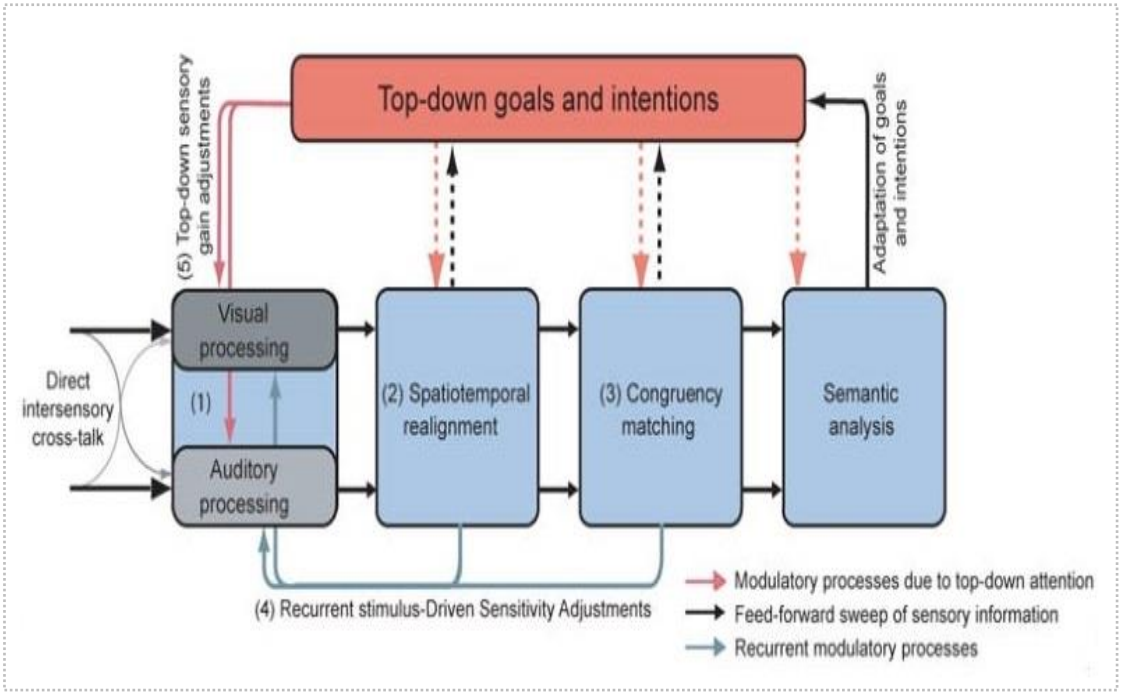

Figure 7-7 A framework for the interactions between multisensory integration and attention. Taken from Talsma *et al.* (2010).

7.3 Future Perspectives

Our proposed tentative AVSSA model in the context of the "two-stage" model for AV fusion is neither complete nor final. There remain many open questions, and even some findings need to be replicated and strengthened by experimental data through numerous experiments by varying stimuli, paradigms, and participants. Overall, the larger goal is to develop a global architecture for the AVSSA process. Hence, we suggest some directions for future development in behavioral, neurophysiological, clinical and computational dimensions.

1) Behavioral studies in normal hearing subjects: Numerous experiments should be planned to understand more about the dynamics of unbinding and rebinding. An important question concerns the role of non-phonetic dimensions in AV binding such as spatial localization, speaker identity, gender, etc. Though previous studies have shown little or no effect of these dimensions in the McGurk effect, the situation could be different in the context of binding processes. For example, could changing the speaker or the global communication setting reset unbinding, or could non-speech incoherent AV material also produce unbinding in further

AV speech targets? We also plan studies on the role of visual noise to check that visual noise added on the contextual part of the stimuli would indeed decrease the weight of the visual input in a further uncorrupted McGurk target.

Another important extension concerns intelligibility in noise, to know if unbinding mechanisms would also decrease the beneficial effect of lip-reading in noise. This would enable us to incorporate the two-stage model inside a general model of the cocktail party effect. In fact, we realized a pilot study to assess such potential binding effects on intelligibility in noise, though the results were disappointing (with no effect of context on intelligibility). The difficulty in such an experiment is to find the appropriate paradigm discarding short-term memory effects in which the visual input might contribute to intelligibility despite a lack of binding.

2) AV binding experiments in the pediatric population: AV integration is known to depend on age, not only for seniors as we saw previously but also with children who display less integration in the first years of age (Sekiyama and Burnham, 2008). In this respect, it would be interesting to study the development of AV binding and unbinding in children. A set of experiments is planned in collaboration with colleagues in ULB in Brussels (C. Colin, J. Leybaert, and C. Bayard).

3) AV binding experiments in HI and CI adults: The next stage should also include testing the binding process in HI and CI subjects. It is well-known that speech perception in noise is challenging for older people with presbycusis or for CI subjects. It is our assumption that part of the problem might result from problems in AV binding, which is a key in the correct association between the audio and the video streams in a complex situation such as what is referred to as the cocktail party effect. Therefore, we aim to test such subjects to see if incoherent contexts do modulate the McGurk effect or the intelligibility of an AV target embedded in noise. This would enable to test the assumption and hopefully, to then propose mecha-

nisms for improving the efficiency of the binding mechanism. If the binding/unbinding mechanisms play a role in multisensory deficits of speech understanding in noise, then we could provide tools for improvement and rehabilitation of these mechanisms.

4) Extending the EEG studies: Our ERP study in Chapter 5 showed an effect of incoherent context on AV binding only for congruent stimuli, while the modulation of binding by context has been displayed in behavioral data on incongruent McGurk stimuli in previous studies by Nahorna *et al.* (2012; 2015) or in this work (Chapters 3, 4 and 6). However, the EEG study in Chapter 5 appears rather preliminary, with a lack of control for pure visual stimuli, and we plan a further set of EEG experiments to replicate and extend our results to incongruent targets. In addition, further time-frequency analysis of EEG data and possibly fMRI studies could produce an enriched support to our behavioral evidence and to our data on neurophysiological correlates for AV binding.

5) Computer Modeling: A general underlying objective of all this experimental work is to develop at some stage a computational two-stage model of AV binding and fusion extending the "Computational ASA" models to AV speech scenes. Such a model would be beneficial in applications which need automatic recognition in multimodal speech systems.

6) AV binding in languages other than French: The amount of McGurk effect differs from one language to another, and some languages have a large vs. smaller amount of fusion (for example, in English, the amount of the McGurk effect is larger than in French). Testing binding and fusion in different languages could help us estimate the reliability and robustness of the AV binding mechanism.

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Appendix I

APPENDIX I- CONFUSION MATRICES

A. Mean responses of 31 participants for without noise and with noise conditions in Chapter 3

Stimuli			Total	Response "ba"		Response "da"		Multiple "ba"		Multiple "da"		No response		Multiple Different	
			n	n	(%)	n	(%)	n	(%)	n	(%)	n	(%)	n	(%)
Without noise	*Coherent*	*Ba*	248	237	95.56	1	0.403	1	0.40	0	0	1	0.40	8	3.22
		McG	744	347	46.63	341	45.83	14	1.88	8	1.07	11	1.47	23	3.09
	Incoherent	*Ba*	992	934	94.15	8	0.806	15	1.51	0	0	11	1.10	24	2.41
		McG	2976	1613	54.20	1176	39.51	54	1.81	14	0.47	39	1.310	80	2.68
With noise	*Coherent*	*Ba*	248	214	86.29	4	1.61	5	2.01	0	0	1	0.40	24	9.67
		McG	744	237	31.85	429	57.66	15	2.01	7	0.94	6	0.80	50	6.72
	Incoherent	*Ba*	992	876	88.30	7	0.705	19	1.91	0	0	6	0.60	84	8.46
		McG	2976	1021	34.30	1615	54.26	50	1.68	37	1.24	20	0.67	233	7.82

B. Mean responses of 29 participants for Experiment A and Experiment B in Chapter 4

		Total	"ba"		"da"		Multiple "ba"		Multiple "da"		No response		Multiple Different	
Stimuli		**n**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**
Experiment A: Without explicit attention														
Video syllables	***Ba***	348	303	87.06	6	1.72	1	0.28	0	0	2	0.57	36	10.34
	McG	1392	773	55.53	409	29.3	13	0.93	32	2.29	24	1.72	141	10.12
Video sentences	***Ba***	348	303	87.06	6	1.72	2	0.57	0	0	1	0.28	36	10.34
	McG	1392	872	62.64	326	23.41	17	1.22	24	1.72	25	1.79	128	9.19
Experiment B:Attention to syllables														
Video syllables	***Ba***	348	334	95.97	3	0.86	0	0	0	0	10	2.87	1	0.28
	McG	1392	712	51.14	628	45.11	3	0.21	2	0.14	36	2.58	11	0.79
Video sentences	***Ba***	348	330	94.82	4	1.14	1	0.28	0	0	12	3.44	1	0.28
	McG	1392	833	59.84	509	36.5	3	0.215	1	0.07	37	2.65	9	0.64
Experiment B: Attention to sentences														
Video syllables	***Ba***	348	343	98.56	4	1.149	4	1.149	0	0	1	0.28	0	0
	McG	1392	697	50.07	566	40.66	667	47.91	6	0.43	15	1.07	6	0.43
Video sentences	***Ba***	348	337	96.83	2	0.57	3	0.86	2	0.57	4	1.14	2	0.57
	McG	1392	751	53.95	535	38.43	618	44.39	2	0.14	13	0.93	6	0.43

C. Mean responses of 29 older adults for Experiment A and Experiment B in Chapter 6

		Total	"ba"		"da"		Multiple "ba"		Multiple "da"		No response		Multiple Different	
Stimuli		**n**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**
Experiment A														
	Ba	200	166	83	3	1.5	8	4	1	0.5	2	1	20	10
Coherent	***McG***	600	242	40.33	206	34.33	22	3.66	22	3.66	14	2.33	94	15.6
	Ba	800	676	84.5	4	0.5	28	3.5	1	0.12	8	1	83	10.35
Incoherent	***McG***	2400	1183	49.29	691	28.79	85	3.54	68	2.83	29	1.20	344	14.3
Experiment B Attention to syllables														
	Ba	300	284	94.66	2	0.66	2	0.66	0	0	6	2	6	2
Video syllables	***McG***	1200	482	40.16	622	51.83	11	0.91	4	0.33	29	2.416	52	4.33
	Ba	300	281	93.66	4	1.33	4	1.33	0	0	7	2.33	4	1.33
Video sentences	***McG***	1200	390	32.5	728	60.66	12	1	5	0.41	21	1.75	44	3.66
Experiment B Attention to sentences														
	Ba	300	285	95	4	1.33	2	0.66	0	0	6	2	3	1
Video syllables	***McG***	1200	660	55	462	38.5	8	0.66	2	0.16	20	1.66	48	4
	Ba	300	276	92	2	0.66	6	2	0	0	10	3.33	6	2
Video sentences	***McG***	1200	499	41.58	644	53.66	17	1.41	2	0.16	18	1.5	20	1.66

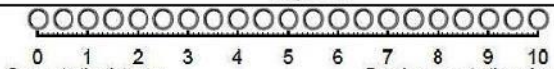
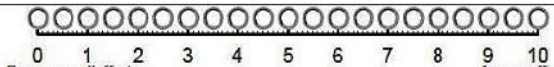
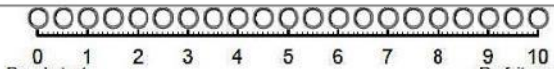
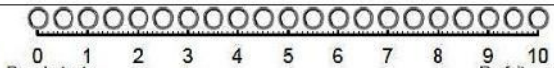
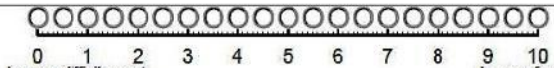
Appendix II

APPENDIX II- SPEECH, SPATIAL, AND QUALITIES OF HEARING SCALE (SSQ)-FRENCH VERSION

1ère partie : Audition de la parole	
Question	**Reponse**
1. Vous discutez avec une autre personne dans une pièce dans laquelle un téléviseur est allumé. Pouvez-vous suivre les propos de votre interlocuteur sans baisser le son du téléviseur?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
2. Vous discutez avec quelqu'un dans un salon calme et dont le sol est recouvert de moquette. Pouvez-vous suivre ce que dit cette personne?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
3. Vous êtes assis autour d'une table avec un groupe de cinq personnes environ. L'endroit est calme. Vous pouvez voir toutes les personnes du groupe. Pouvez-vous suivre la conversation?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
4. Vous êtes assis autour d'une table avec un groupe de cinq personnes environ, dans un restaurant animé. Vous pouvez voir toutes les personnes du groupe. Pouvez-vous suivre la conversation?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
5. Vous discutez avec une autre personne. Il y a un bruit de fond continu (ventilateur ou eau qui coule par exemple). Pouvez-vous suivre ce que dit l'autre personne?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
6. Vous êtes assis autour d'une table avec un groupe de cinq personnes environ, dans un restaurant animé. Vous NE pouvez PAS voir toutes les personnes du groupe. Pouvez-vous suivre la conversation?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
7. Vous discutez avec quelqu'un dans un endroit dans lequel l'écho est important, comme une église ou un hall de gare. Pouvez-vous suivre ce que dit cette personne?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
8. Pouvez-vous avoir une conversation avec quelqu'un si une autre personne parle avec une voix de la même fréquence que celle de votre interlocuteur (aussi aigue ou aussi grave)?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
9. Pouvez-vous avoir une conversation avec quelqu'un si une autre personne parle avec une voix de fréquence différente que celle de votre interlocuteur (plus grave ou plus aigue)?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
10. Vous écoutez la personne qui vous parle tout en essayant simultanément de suivre les informations à la télévision. Pouvez-vous suivre ce que disent les deux personnes?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
11. Vous discutez avec quelqu'un dans une pièce dans laquelle beaucoup d'autres personnes s'entretiennent. Pouvez-vous suivre ce que vous dit votre interlocuteur?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement
12. Vous vous trouvez dans un groupe de personnes qui prennent la parole les unes après les autres. Pouvez-vous suivre facilement la conversation sans rater le début de ce que disent les différentes personnes?	0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout Parfaitement

13. Pouvez-vous converser facilement par téléphone?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
14. Vous écoutez quelqu'un au téléphone et une autre personne se tenant près de vous commence à parler. Pouvez-vous suivre ce que disent les deux personnes?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA

3ème partie : Qualité d'audition	
1. Imaginez que vous entendez deux choses en même temps, par exemple de l'eau qui coule dans un lavabo et la radio. Avez-vous l'impression que ces deux bruits sont parfaitement distincts l'un de l'autre?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
2. Lorsque vous entendez plusieurs sons à la fois, pouvez-vous les distinguer clairement les uns des autres ou avez-vous l'impression qu'il s'agit d'un seul bruit confus?	0 1 2 3 4 5 6 7 8 9 10 (Confus — Distinct) ☐ NA
3. Vous vous tenez dans une pièce et vous entendez de la musique à la radio. Une autre personne parle dans la pièce. Pouvez-vous différencier clairement la voix de la musique?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
4. Pouvez-vous reconnaître facilement les différentes personnes que vous connaissez au son de leur voix?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
5. Pouvez-vous reconnaître facilement les différents morceaux de musique que vous connaissez?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
6. Pouvez-vous différencier certains bruits, par exemple une voiture par rapport à un bus ou de l'eau qui bout par rapport à la nourriture qui frit dans une poêle?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
7. Lorsque vous écoutez de la musique, pouvez-vous discerner les différents instruments?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
8. Lorsque vous écoutez de la musique, est-ce qu'elle retentit de manière distincte et naturelle?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
9. Les bruits quotidiens que vous entendez facilement sont-ils distincts (non brouillés)?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
10. Les voix des autres personnes sont-elles distinctes et naturelles?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
11. Les bruits quotidiens que vous entendez vous paraissent-ils artificiels ou peu naturels?	0 1 2 3 4 5 6 7 8 9 10 (Artificiels — Naturels) ☐ NA
12. Votre propre voix retentit-elle de manière naturelle à vos oreilles?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA
13. Pouvez-vous facilement juger de l'humeur d'une personne au son de sa voix?	0 1 2 3 4 5 6 7 8 9 10 (Pas du tout — Parfaitement) ☐ NA

Question	Reponse
14. Devez-vous vous concentrer intensément lorsque vous écoutez quelqu'un ou quelque chose?	 0 1 2 3 4 5 6 7 8 9 10 NA Concentration intense — Pas de concentration nécessaire
15. Devez-vous faire beaucoup d'efforts pour comprendre ce qui se dit au cours d'une conversation avec d'autres personnes?	 0 1 2 3 4 5 6 7 8 9 10 NA Beaucoup d'efforts — Aucun effort
16. Lorsque vous conduisez, pouvez-vous facilement entendre ce que dit la personne assise à côté de vous?	 0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout — Parfaitement
17. Lorsque vous êtes passager d'une voiture, pouvez-vous facilement entendre ce que dit le conducteur assis à côté de vous?	 0 1 2 3 4 5 6 7 8 9 10 NA Pas du tout — Parfaitement
18. Pouvez-vous ignorer facilement les autres bruits lorsque vous essayez d'écouter quelque chose?	 0 1 2 3 4 5 6 7 8 9 10 NA Ignorer difficilement — Ignorer facilement