# Cross-format integration between spoken number words and Arabic digits

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## Abstract

Spoken number words and Arabic digits are the most commonly used numerical symbols. We often transcode numerals from one to another, thus, the correspondence between them should become over-learned and automatic after years of usage. It has been shown that an integration usually exists when pairing of stimulus is over-learned, and is often reflected in the mismatch negativity (MMN). The current thesis conducted two behavioural experiments (Chapter 2) and three EEG experiments (Chapter 3 - 5) to systematically investigate the cross-modal correspondence, i.e., the integration, between spoken number words and Arabic digits in adult participants. In the behavioural experiments, a clear distance effect is shown in an audiovisual matching task. This suggests that an amodal, shared magnitude representation is activated for cross-modal numerals during a matching judgment. Moreover, the distance effect is modulated by stimulus onset asynchrony (SOA). That is, the distance effect becomes smaller with the increase of SOA. This is similar to the data pattern of a common integration effect because an integration usually shows when cross-modal stimuli are temporally close. However, a disadvantage of a behavioural task is that the RTs could be influenced by response-selection or response-execution. Hence, I then used an oddball paradigm in which no responses are required for the cross-modal numerals in my EEG experiments. The results of three EEG experiments showed that an early integration effect exists between spoken number words and Arabic digits in the mismatch negativity (MMN). This result is first to show the presence of a cross-format integration between spoken number words and Arabic digits. However, the integration effect is also modulated by distance as well as stimulus onset asynchrony (SOA), which may suggest that the cross-modal correspondence between audiovisual numerals is more complicated than other kinds of audiovisual stimuli, such as letters and speech sounds.

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## Author’s Declaration

I declare that this thesis is a presentation of original work and I am the sole author with supervision from Dr. Silke Goebel. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

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# Chapter 1 – Literature Review

## 1.1 Brief opening

Understanding the meaning of quantities, comparing magnitudes, are some of the mathematical abilities that are crucial for survival for any species including human beings (Dehaene, Dehaene-Lambertz, & Cohen, 1998). But unlike other species, human beings have a unique gift, the language system, to label magnitudes. The numerals we created from our languages not only become a tool for representing magnitudes, but also possibly shape our mental magnitude representation (Campbell & Clark, 1988). Only with these spoken and written symbols to represent quantities, human beings can precisely deal with the numbers that are necessary for trading and management, which is the basis for developing large and complex societies. Nowadays, people use different kinds of numerical symbols, such as Arabic digits, written number words, and spoken number words, to record, calculate, and communicate with each other. Therefore, the ability to comprehend the meaning of different symbols, and furthermore, the ability to transcode the magnitude information from one notation to another (e.g., hear "five" and then write down "5" on the sheet), are essential for living in the modern society.

Considering the importance and prevalence of numerical symbols in our daily lives, this thesis aims to investigate the relationship between the most common auditory and visual numerical symbols, which are the spoken number words and the written Arabic digits, and how this relationship affects human beings' mathematical ability.

In the following section I will firstly introduce the most cited model for number processing, the triple-code model (Dehaene, 1992), as a starting point for my literature review. The triple-code model offers a good framework about how these numerical symbols might be processed and correspond to each other. The triple-code model inspires many follow-up studies to further investigate numerical cognition, however, it is important to note that it is just one of many models trying to explain number processing.

## 1.2 Triple code Model

The triple-code model (Dehaene, 1992) was first developed based on adult patients with acalculia. A case study showed that there is a dissociation between symbolic processing of numerals and an approximate magnitude representation (Dehaene & Cohen, 1991). A patient who lost all precise number knowledge could not reject 2 + 2 = 5 as false, nor could he judge a digit as odd or even. However, he was able to reject 2 + 2 = 9, which indicated that he could still access the approximate magnitude behind these Arabic digits. Based on this finding, Dehaene then developed the triple-code model, which is the most cited and influential model of number processing to date (Dehaene, 1992).

In the triple-code model, the numerical information can be processed by three different codes, namely, the visual Arabic number form, the auditory verbal word frame, and the analogue magnitude representation (Figure 1-1). The analogue magnitude representation is believed to be used by human beings and other animal species (e.g., Brannon, 2006), whereas the other two codes are especially for symbolic exact numerals and thus specific to humans. The three codes are linked to each other and each code has its own input-output procedures for processing numerical information.

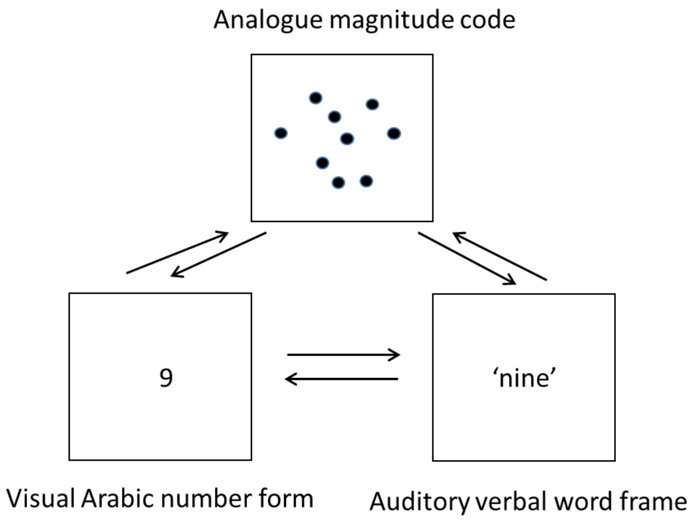


*Figure 1-1.* A simplified diagram of the triple-code model of number processing.

The visual Arabic number form and the auditory verbal word frame are responsible for the notation-specific numerical information. The Arabic digits are identified visually to be mapped onto the existed strings of digits in the visual Arabic number form, whereas the auditory or verbal words are represented with the word sequences (e.g., 'forty', 'five') in the auditory verbal word frame (L. Cohen & Dehaene, 1991). However, the triple-code model assumes that there is no any semantic information in these two number forms. The meaning of numerical symbols is only represented in the analogue magnitude code.

In the analogue magnitude code, the meaning of numerical quantities can be retrieved approximately and at this level the quantities also can be related to other quantities. For example, the number 68 is between 0 and 100, and is close to 70. The level of approximation largely depends on number size. That is, the larger the number size, the more imprecise the numerical representation. It has been widely suggested that the numerical quantities are represented like distributions of activation on an oriented analogical number line, and obey the Weber law (e.g., Nieder & Miller, 2003). This number line is often called the mental number line (Restle, 1970) and is often described as going from left-to-right for the numbers from small to large for Western participants (Dehaene, Bossini, & Giraux, 1993; Zorzi, Priftis, & Umiltà, 2002; but see Göbel, Shaki, & Fischer, 2011, for the cultural and linguistic influences). On the mental number line in the analogue magnitude code, numbers are thought to be represented on a logarithmic scale (Dehaene, 1992; for other suggestions of the scale type, see Cohen & Quinlan, 2016; Ebersbach, Luwel, Frick, Onghena, & Verschaffel, 2008), i.e. the representations of large numbers are closer to each other than the representations of smaller numbers (Figure 1-2). This closer distance in larger numbers causes a larger overlap between mental magnitude representations. This number size effect

In the following sections I will introduce the non-symbolic representation as well as the symbolic representation in turn.

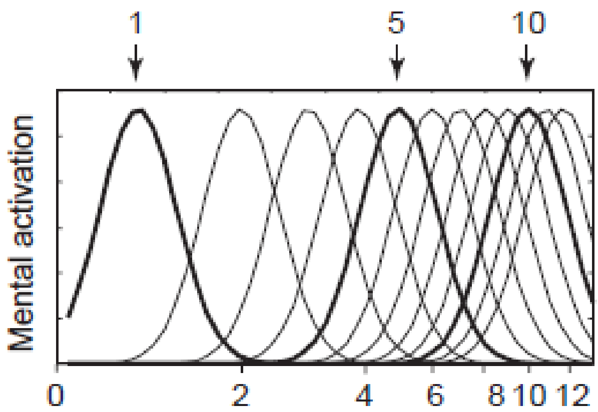


*Figure 1-2.* The logarithmic model with fixed variability for mental magnitude representation (taken from Feigenson, Dehaene, & Spelke, 2004).

## 1.3 The non-symbolic representation

The approximate number sense (ANS) refers to a non-symbolic system to represent and compare the magnitude of sets of objects, which is reported to be present across species (Brannon, 2006) and in the early stage of the cognitive development (e.g., Xu & Spelke, 2000), and is believed to provide an essential basis for developing other higher mathematical abilities later on, such as arithmetic (for a review, see Piazza, 2011; but this is currently controversial, for example, see Göbel, Watson, Lervag, & Hulme, 2014). When comparing non-symbolic magnitudes, several behavioural effects can be observed, one of the most robust basic effects is the ratio effect.

### *1.3.1 Ratio effect*

The ratio effect refers to the finding that response times change with the ratio between the two quantities to be compared: longer RTs for a larger ratio (e.g., 7:8) and the shorter RTs for a smaller ratio (e.g., 1:2). Similar data pattern can also be found in accuracy rates. More errors are made when the ratio is smaller.

Wood and Spelke (2005) used a habituation method, let six-month-old infants look at a puppet jumping on a stage. They found that the infants looked longer on the jumping puppet when the sequences of puppet jumping changed from 4 jumps to 8 jumps (or 8 jumps to 4 jumps); however, the looking time was not different when the sequences of puppet jumping from 4 jumps to 6 jumps (or 6 jumps to 4 jumps), which means that the six-month-old infants can only detect the change from 4 to 8 jumps but not from 4 to 6 jumps. In contrast, nine-month-old infants significantly increased their looking time in both the 4-to-8 and 4-to-6 conditions, which indicates a clear development of infants' ability to discriminate different ratios from imprecise to precise (from 1:2 at six months to 2:3 at 9 months).

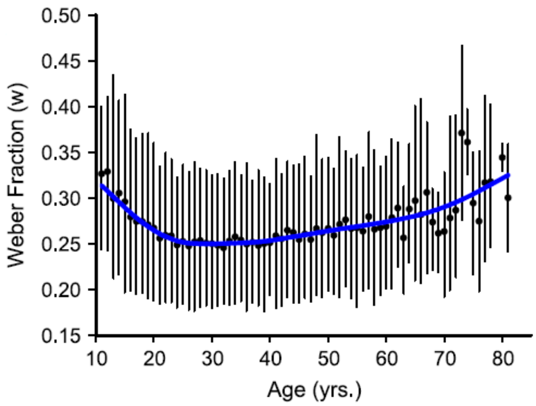


*Figure 1-3.* The Weber fraction across life span (Halberda, Ly, Wilmer, Naiman, & Germine, 2012). The lower Weber fraction indicates a greater ability to differentiate the closer quantities (9:10).

It has been shown that there are individual differences for the ability to discriminate the quantity of a set of items, i.e., the numerosity (Halberda & Feigenson, 2008; Halberda, Mazzocco, & Feigenson, 2008; Pica, Lemer, Izard, & Dehaene, 2004). This ability continues to develop until quite late in adulthood (around 30 year-old, see Figure 1-3; Halberda, Ly, Wilmer, Naiman, & Germine, 2012). Halberda, Mazzocco, and Feigenson (2008) developed a non-symbolic magnitude comparison task for investigating individual precision of the ANS. The task consisted of an intermixed display of blue and yellow dots (Figure 1-4), participants were instructed to judge whether there were more blue or yellow dots by pressing buttons. The dots were area-controlled to make sure that the results could not be explained by the occupied area of dot sets (but see Gebuis & Reynvoet 2012a; 2012b for an alternative explanation). The colour of the set with more dots also varied. Each intermixed display was only presented for 200 ms on screen so it was too short for participants to count sequentially. The ratio between the two sets varied among 1:2, 3:4, 5:6 and 7:8, with between 5 and 16 dots in each set. The Weber fraction is equal to the difference between the two numbers divided by the smaller number (e.g., for a ratio of 7:8, w = (8 - 7) / 7 = .14). For each participant, on the basis of the accuracy rate of different ratios, an individual Weber fraction for correctly discriminating the two colour sets can then be calculated (for details see methods in Halberda et al., 2008). Basically, the smaller and the closer the Weber fraction to zero, the more accurate the participant was in discriminating between the two colour sets in the task. Halberda and colleagues (2008) found that this Weber fraction is diverse across 14-year-old subjects in the ninth grade (the average Weber fraction was 0.265, but the Weber fraction ranged from 0.119 to 0.567 between subjects), which indicated that some participants were able to differentiate the numerical ratio 9:10 (w = 0.11), whereas some of them had difficulties to discriminate the ratio 2:3 (w = 0.5).

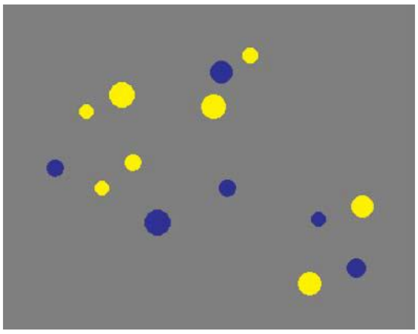

*Figure 1-4.* An example of an intermixed display of dots array in the study of Halberda et al. (2008).

More importantly, a negative correlation was found between the Weber fraction and symbolic math achievement in 3rd grade after other 16 test scores of a variety of cognitive measurements, such as intelligence, verbal IQ, working memory, visual-spatial reasoning etc., are controlled. This result suggests that subjects who are better at discriminating numerosities also have a better math achievement, thus supporting the argument that the ANS is the basis for developing further math abilities (Halberda et al., 2008).

However, recent longitudinal studies did not replicate a similar relation between the ANS and children's math achievement (Göbel et al., 2014; Sasanguie, Defever, Maertens, & Reynvoet, 2014). For example, in Göbel et al. (2014), the non-symbolic magnitude comparison task performance at 6 years was positively correlated with arithmetic skills 11-month later at the first glance. However, after scores of other measurements were controlled, such as earlier arithmetic skills (at Time 1), age, nonverbal abilities, and vocabulary skills, the non-symbolic magnitude comparison scores could no longer predict the arithmetic skills at Time 2. Instead, the result suggests that the number knowledge of Arabic numerals (the ability to identify Arabic digits) is more essential for the development of arithmetic skills.

It is still under debate that whether the ANS is critical for the development of later mathematical abilities. Some meta-analyses have suggested that a stronger association with mathematical performance for symbolic comparison than for non-symbolic comparison (De Smedt, Noël, Gilmore, & Ansari, 2013; Schneider, Beeres, Coban, & Merz, 2016), while a meta-analysis argued that the association between the number acuity and mathematical performance is moderate but significant (Chen & Li, 2014). As the current thesis focuses more on the correspondence between visual and auditory numerals, I will not further address these controversial results. In the next section I will turn to review the literature about symbolic representations.

## 1.4 The symbolic numerical representation

Unlike the non-symbolic numerical representation can be observed in other animal species, the symbolic number representation is based on language systems, thus it is unique for human beings. In the following section I will discuss two effects that are most related to the current thesis: the distance effect and the priming distance effect.

### *1.4.1 Numerical Distance effect*

The numerical distance effect describes the finding that participants take longer time to respond which of two numbers is larger when the two numbers are numerically closer (e.g., ‘7’ and ‘8’) rather than further away (e.g., '7' and '1'). For example, Moyer and Landauer (1967) asked participants to judge which one of the two simultaneously displayed stimuli was numerically larger, and revealed a significant negative correlation between the numerical distance and both the RT and the error rate, that was, the larger the distance, the faster the RT (Figure 1-5) and the fewer mistakes participants made.

The ratio effect introduced in the previous section can be seen as a variation of the numerical distance effect. The biggest difference between them is that people usually only have an approximate idea about quantities in a non-symbolic magnitude comparison task, whereas people can access the exact magnitude of numerals in a symbolic number comparison task.

The distance effect is seen as evidence that the magnitude representation for both quantities is overlapping: the closer the two magnitudes, the more the two representations overlap, and therefore it is more difficult to differentiate the two magnitudes (also see van Opstal, Gevers, de Moor, & Verguts, 2008 for a neural network model supporting this argument about an overlapping numerical representation). Hence, the distance effect is widely recognized as evidence that the mental magnitude representation is activated during the task performance.

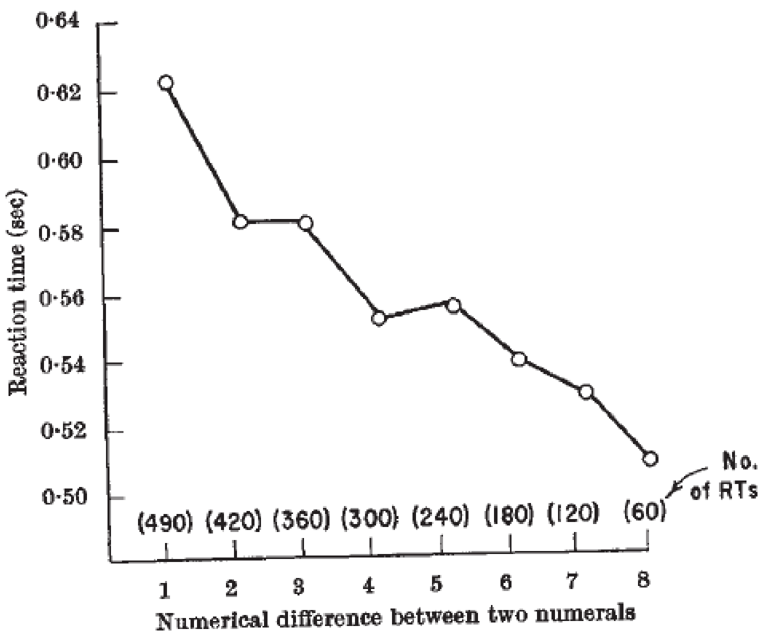


*Figure 1-5.* The distance effect of RT (taken from Moyer & Landauer, 1967).

The numerical distance effect has been reported in a wide range of tasks. The number comparison task and the same-different (matching task) are the two most common tasks for studying the distance effect. In one type of number comparison task participants are asked to compare two stimuli in magnitude and choose the stimulus which is larger or smaller in magnitude (e.g., Moyer & Landauer, 1967), while in another type of number comparison task participants are asked to compare a numerical stimulus to a fixed reference number (e.g., Van Opstal, Gevers, De Moor, & Verguts, 2008), for example is it larger or smaller than '5'. The same-different task (matching task) asks participants to judge whether two stimuli are the same or different in magnitude (e.g., van Opstal & Verguts, 2011). The distance effect was widely discovered in these tasks. However, the distance effect does not always increase when the two numbers are closer in magnitude. An inverse distance effect was found in priming paradigms.

### 1.4.2 Priming Numerical Distance effect

In a numerical priming paradigm, a prime number is displayed very briefly and then followed by a target number. The prime is usually displayed subliminally, lasting less than 60 ms. Hence, the display of primes is typically unknown for the participants (but the prime does not have to be subliminal to induce a priming distance effect, for example, see Reynvoet & Ratinckx, 2004). Participants are instructed to respond to the target, for example by naming the target number (e.g., Brysbaert, Fias, & Reynvoet, 2002), judging the target's parity status (odd or even) (e.g., Reynvoet & Brysbaert, 2004) or judging whether the target is larger or smaller than 5 (e.g., Kouider & Dehaene, 2009). The results of this number priming paradigm were initially surprising, because the distance effect is inverted. That is, the larger the numerical distance between the prime and the target, the slower the RT (e.g., Brysbaert et al., 2002; Kouider & Dehaene, 2009; Reynvoet & Brysbaert, 2004; see Figure 1-6 for a graph of priming distance effect), which is opposite to the numerical distance effect introduced earlier.

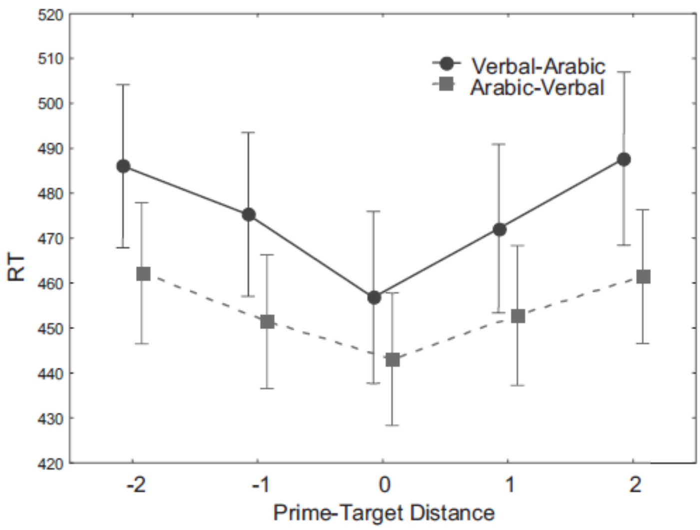


*Figure 1-6.* The priming distance effect in the study of Reynvoet and Brysbaert (2004). The V-shape graph of distance effect was usually found by using the numerical priming paradigm. In this study, the authors used the different notations, digits and written number words, for the primes and the targets, and still found the priming distance effect.

The general explanation for this inverse distance effect is that the prime number triggers the corresponding mental magnitude representation first, and then ‘spread’ to the neighbouring magnitudes on a mental number line because their magnitude representation are close to the primed representation. The activation of neighbouring magnitudes decreases with a function of numerical distance (Notebaert, Pesenti, & Reynvoet, 2010), and this priming distance effect is usually more obvious in a distance of 2 between prime and target numbers (Roggeman, Verguts, & Fias, 2007). Neurophysiological studies on monkeys also support this explanation because the neurons which were maximally active with a given numerosity also partially active when a numerically close numerosity was displayed (Nieder & Miller, 2003, 2004).

To date the studies that have been mentioned are mostly based on Arabic digits. However, in our daily lives we move easily between Arabic digits and number words, especially between Arabic digits and the spoken number words. For example, a clerk needs to read aloud the number shown on the cashier machine to tell customers how much they should pay. This ability to quickly find the corresponding numbers in another modality looks natural to us, however, it is not an innate ability of human beings. In fact, to learn the correspondence between spoken number words and Arabic digits, and to access the numerosities (quantity meaning) of these numerical symbols, are essential skills for number processing (Landerl, Bevan, & Butterworth, 2004; Rousselle & Noël, 2007). In the following section, I will in turn discuss studies about number words, and which role number words play in the development of numerical cognition.

### *1.4.3 Number words*

The number words are the first symbols children use to map their innate number concepts on. To map these initial concepts onto specific number words, children have to understand some basic principles (Gelman & Meck, 1983), and hence they can develop the earliest symbolic strategy, *counting*, for solving mathematical problems.

The triple-code model suggests that verbal number words, in written and auditory format, are processed by 'general-purpose language modules', so that a verbal number word should be coded and manipulated mentally analogue to a word sequence (Dehaene, 1992). For example, to successfully comprehend or produce a verbal number word, one should firstly retrieve the correct lexicon of numerals (e.g., retrieve 6, but not retrieve 2, when see '6'); secondly, one needs to understand the syntactic rules of number word construction. It has been shown that the lexical and syntactic errors in a transcoding task are dissociated in some patient studies (L. Cohen & Dehaene, 1991; Jefferies, Bateman, & Lambon Ralph, 2005). Some patients mistakenly produce the digits, such as naming '450' as 'three hundred and fifty'; while others have no problem to process the digits individually, but just literally transcribe the digits, such as writing down '10009100' for 'one thousand nine hundred'. These transcoding errors also indicate the importance of the correspondence of Arabic digits and spoken number words to mathematical abilities.

It should be noted that the written number words have also been studied in numerical cognition research, for example, Damian (2004) compared the processing of written number words and Arabic digits, found that number words were named faster but processed slower in a magnitude comparison task than Arabic digits. The results showed that the phonological characteristics of number words, but not its semantic meanings (quantities), are more automatically perceived than for Arabic digits. In contrast, the meaning of an Arabic digit is perceived more automatically than the phonological features. However, the current study focuses on the spoken but not written number words for two reasons: First, spoken number words are the earliest exact symbols that children learn as they start to count, which makes children build up their initial symbolic numerical representation. The written number words are learnt even later than

Arabic digits. Second, as Arabic digits are convenient for recording the numerosities, it is rare for people to use written number words after they have learned Arabic digits. So, the natural and the most frequent transcoding in everyday life is between Arabic digits and spoken number words. In the next section, I will introduce how children learn the meaning of spoken number words, initially through counting.

#### *1.4.3.1 Counting*

The counting ability starts to develop around 2 years old, and is often developed for small numbers between 3 – 4 years. Counting is a bridge that connects the non-symbolic and the symbolic representation. Gelman and colleagues (e.g., Gelman & Gallistel, 1978; Gelman & Meck, 1983) proposed five principles for children to develop their counting ability from the non-symbolic representation, they are described as follows: (1) The one-to-one correspondence principle: each item in a set needs to be labelled with one and only one tag (e.g., a set of spoken number words). (2) The stable-order principle: the tags for counting must have a consistent sequence that subjects can use across conditions. (3) The cardinality principle: the last number tag used in a count represents the quantities in the set. (4) The abstraction principle: the items in a set to be counted can belong to different categories. (5) The order-irrelevance principle: the items can be tagged in different orders and this does not affect the counting result.

Verbal counting is the first symbolic strategy for children to do arithmetic. Before knowing digits or being able to spell verbal number words, and even before understanding the exact meaning of the spoken number words, children start to use spoken number words to indicate the quantities. For example, children may count objects as "one, two, six, eight, eleventeen", though neither the sequence nor all number word constructions are entirely correct, they speak these number words when counting (Wynn, 1992). Learning to count helps children to understand the meaning of auditory number words. Also, counting skills have been found to be highly correlated with mathematical ability. For example, Geary, Bow-Thomas, and Yao (1992) found that children with mathematical disabilities could not understand the essential part in counting strategies, making them unable to detect the errors they made in the addition problems. However, counting skills become inefficient when children are able to retrieve more mathematical facts when doing arithmetic. For example, Geary and colleagues (1991) tested 26 typically developing children and 12 children with mathematical disabilities (all children in the first or second grade) by giving them simple addition problems. After 10 months, they tested the same participants again and found that the typically developing children increased their reliance of mathematical facts retrieval, whereas children with mathematical disabilities still relied on their counting skills to solve the addition problems.

In summary, spoken number words play an important role in counting. These auditory symbols give us the first symbolic representation for numerosities and also offer the earliest basis that we can map the visual symbols onto, such as Arabic digits, and hence we are able to solve more complicated questions with the visual symbols. In the next section, I will focus on the main interest of my thesis, the correspondence between the visual Arabic numerals and spoken number words.

## 1.5 Correspondence between visual Arabic numerals and spoken number words

In the triple-code model, there are two pathways to achieve the transcoding between verbal number words and visual Arabic numerals (Dehaene, 1992). One pathway is an indirect path through the analogue magnitude code. For example, digit ‘5’ is transferred as its quantity first, then mapped into the correspondence verbal words, /five/, resulting in activating the magnitude representation. This semantic pathway is similar to other models, for example, McCloskey’s model (McCloskey, 1992), which postulate that an amodal, abstract magnitude representation must be activated for calculation and magnitude processing (see also Noél & Seron, 1992 for another model proposing an abstract magnitude representation). The other pathway is through an asemantic pathway, which does not activate the magnitude representation of numerals as it does not pass through the analogue magnitude code. A case study on a deep dyslexic patient with an impairment of number reading supported this multi-route hypothesis (L. Cohen, Dehaene, & Verstichel, 1994). The patient was unable to read unfamiliar numerals, but was able to read aloud familiar numerals. Hence, the authors suggest that in the patient, a 'surface' asemantic route that follows the rules of number reading did not work so that he could not read an unfamiliar number word; whereas a 'deep' semantic route was intact, making him able to read familiar numerals (see also Cipolotti, Warrington, & Butterworth, 1995).

Colomé and Laka (2010) demonstrated another empirical evidence supporting the presence of the asemantic route between Arabic digits and verbal number words. They found that the language (number word system) can affect the speed of calculation (which is in Arabic digit), but not the semantic representation. They tested Basque-speaking participants whose number word system is a base-20 system instead of a common base-10 system. In a two-digit addition task, Basque speaking participants responded faster when an addition problem fit the structure of a 20-base system (e.g., 20 + 15) compared to an addition which does not fit (e.g., 25 + 10); whereas the same effect was not observed in Catalan or Italian speaking participants whose language is a 10-base system. Furthermore, both Basque and Catalan speaking participants showed a similar distance effect in a two-digit number comparison task. These results indicate that different language systems do not affect the abstract magnitude (semantic) representation of numbers as the distance effect is not different between languages, but possibly influence the asemantic transcoding between Arabic digits and verbal number words which led to the faster responses for Basque speakers in the addition task.

The triple-code model suggests that the asemantic transcoding between verbal number words and Arabic digits is a two-way route, i.e., Arabic-to-verbal or verbal-to-Arabic (Dehaene, 1992). Some studies have pointed out that the transcoding between verbal number words and Arabic digits may be asymmetric (Damian, 2004; Fias, Reynvoet, & Brysbaert, 2001). For example, Fias and colleagues (2001) found that when asking participants to name an Arabic single-digit, the RTs became longer if an incongruent written number word was simultaneously presented compared to when a congruent number word was presented; whereas the RTs were not affected when naming a verbal number word with a simultaneously presented, incongruent Arabic digit. This finding shows that naming a verbal number word does not necessarily activate the semantic magnitude representation, whereas naming an Arabic digit automatically triggers the mental magnitude representation. Hence, the authors suggest that the asemantic route for Arabic digits to verbal number words may not exist or is too slow to influence the naming response.

The studies mentioned above provide some ideas about the correspondence between verbal number words and Arabic digits, however, most of these works only used written numerals but ignored spoken number words. Although spoken number words are one of the most commonly used and the earliest numerical symbols we learnt when developing our number knowledge, they were not systematically examined in any of these studies, and had not been examined until recently.

To the best of my knowledge, the study of Cohen and colleagues (2013) was the first study that directly and systematically investigated the correspondence between spoken number words and Arabic digits. They argued that the numerical distance effect shown in various tasks, typically explained by representational overlap, can alternatively be explained by the physical similarity between numerals, and thus is not an indication of the semantic magnitude representation of numerals. To be more specific, for example, they represented Arabic digits in a format that is shown on an electric alarm clock (D. J. Cohen, 2009). In this way, the longer RT when conducting numerical judgment for numbers close to each other may be only due to the similar appearance (e.g., number 5 and 6 in Arabic digit format are similar in appearance, see Figure 1-7), but has nothing to do with the numerical distance.

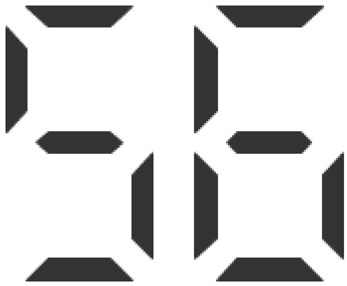

*Figure 1-7.* Examples of Arabic digits in digital clock format (5 and 6).

They calculated the function of physical similarity for spoken number words and Arabic digits separately, as well as the Welford function which accounted for the numerical distance effect in RTs logarithmically. In their audiovisual experiments, each trial was composed of two sequentially displayed numerical symbols with 500 ms interval. Participants were instructed to respond whether the second stimulus was numerically larger or smaller than the first stimulus in the number comparison task, and whether it was the same or different in quantity compared to the first stimulus in the same-different task. There were two conditions in each task: digit-digit and auditory word-digit. The results of mixed regression analyses showed that in the same-different task, the Welford function (the function of numerical distance effect) did not predict the RTs of any conditions, instead, the function of physical similarity for Arabic digits significantly predicted the RT performances in both the digit-digit and the auditory word-digit condition. In the number comparison task, both the Welford function and physical similarity function of auditory number words significantly predicted the RT performances of both conditions. Based on these results, the authors suggest that before a decision is made, the numerical symbols are transformed into a common format. For example, when judging whether the spoken number word /two/ and the visual digit '5' are same or different, the auditory number word is firstly transformed into the Arabic-digit format (from /two/ to '2'), then the decision will be made according to the physical similarity between '2' and '5'. A similar suggestion about transcoding between different number formats has been made in the preferred entry code model (Noél & Seron, 1992). It proposes that participants always transcode numerals to a preferred code (either verbal or Arabic format) based on idiosyncratic experience.

However, Cohen's model is different as it suggests that the decision is made according to physical similarity after transcoding (D. J. Cohen et al., 2013). Similar steps also apply to the number comparison task. The authors argue that the numerals must be transformed into one common format before magnitude comparison, otherwise the physical similarity function would not also predict the RT performances in the number comparison task. Some limitations and questions remain in this physical similarity hypothesis. For example, it cannot explain why in the same-different task the RTs are predicted by the physical similarity of Arabic digits, whereas in the number comparison task the RTs are predicted by the physical similarity of auditory number words as well as the Welford function. Thus, more research is needed to further explore this hypothesis. Nevertheless, it still demonstrates an explanation about the cross-modal correspondence between spoken number words and Arabic digits.

Sasanguie and Reynvoet (2014) published another study investigating the correspondence between spoken number words and Arabic digits. In their study, the spoken number words and Arabic digits were displayed simultaneously. This was different from the study of D. J. Cohen et al. (2013) where the interval between numerals was always 500 ms which might encourage participants to transform the numeral from one format to another as the 500 ms interval was relatively long. In their digit-number word matching task, participants had to judge whether the auditory number word and the visual written digit were matched (i.e., 3 and 'three') or mismatched (i.e., 3 and 'five') in terms of their magnitudes. They did not find the distance effect in this matching (same-different) task, which was in agreement of the results from D. J. Cohen et al (2013) that participants did not need to access the semantic magnitude representation of numerals for making a same-different judgment for the visuo-audio numerals. Moreover, they found a negative correlation between the RTs of the digit-number word matching task and individual mathematical achievement, showing that people with better mathematical performance responded to the matching task faster. They thus concluded that participants make matching/non-matching responses without accessing to an amodal, non-symbolic magnitude representation. Instead, the judgment is based on a fast, automatic correspondence between spoken number words and Arabic digits.

These findings are very inspiring to the current thesis because they raise two key questions: First, does this fast and automatic processing imply a special relationship, i.e., an integration, between spoken number words and Arabic digits? The multi-sensory integration is referred to as special neural processes that synthesise information from cross-modal stimuli (Spence, 2011; Stein & Stanford, 2008). The evidence of integration has been reported between overlearned pairings of artificial symbols, such as letters and speech sounds (e.g., Blau et al., 2010; Froyen, van Atteveldt, Bonte, & Blomert, 2008). Since we also use and transcode spoken number words and Arabic digits very often, an integration may also exist between these numerical symbols. Second, is this correspondence between spoken number words and Arabic digits important to mathematical abilities or numerical cognition development? Previous electrophysiological studies have shown either an absent or attenuated integration effect between letters and speech sounds on both dyslexic children (Froyen, Willems, & Blomert, 2011; Žarić et al.,

2014) and dyslexic adults (Mittag, Thesleff, Laasonen, & Kujala, 2013). Hence, if an integration exists between visual and auditory numerals, perhaps a similar relationship between the integration effect and mathematical performance can also be observed.

## 1.6 Neural correlates for number processing

One of the reason that the triple-code model became the most influential model is because it also illustrates an anatomical model for number processing (Dehaene & Cohen, 1995). About a decade after the triple-code model had been proposed, Dehaene and colleagues proposed three parietal circuits which may account for the different codes of number processing by reviewing functional magnetic resonance imaging (fMRI) and neuropsychological studies (Dehaene, Piazza, Pinel, & Cohen, 2003). They suggested that the horizontal intraparietal sulcus (hIPS) is for analogue magnitude processing, while the left angular gyrus is for verbal number words. However, they failed to locate the specific visual system for coding Arabic numerals, which might be due to the strong fMRI signal dropout in the assumed brain area, the inferior temporal gyrus (Shum et al., 2013). A visual number form area specifically for Arabic digits has only been identified very recently in the inferior temporal gyrus (Grotheer, Herrmann, & Kovacs, 2016; Shum et al., 2013). In the following sections, I will review the neural evidence for each code in turn. Also, because the main interest of this thesis is the correspondence between visual Arabic digits and the spoken number words, I will focus on these two specific numerical symbols, as well as the interaction and correspondence between them.

### *1.6.1 Magnitude processing*

The bilateral IPS has been suggested as the critical brain area processing quantities (Dehaene et al., 2003). IPS activation is observed not only with non-symbolic dot arrays (Lussier & Cantlon, 2017; Piazza et al., 2007; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004), but also with numerical symbols, such as Arabic digits (Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Piazza et al., 2007; Pinel, Piazza, Le Bihan, & Dehaene, 2004), written number words (Cohen Kadosh, Kadosh, et al., 2007; Lussier & Cantlon, 2017), and spoken number words (Eger et al., 2003). Hence, it has been suggested that this IPS activation, i.e., magnitude processing of numbers, is independent of number format (Dehaene et al., 2003; Piazza et al., 2004). However, some research suggests that at least part of the IPS activation reported during number comparison tasks can be explained by task demands, difficulty and response selection, but not because of magnitude processing. For example, compared to the brain activity of a difficulty-matched control task, which is unrelated to numbers, there was no additional IPS activation from the number comparison task with Arabic numerals (e.g., Göbel, Johansen-Berg, Behrens, & Rushworth, 2004).

Cohen Kadosh and Walsh (2009) further challenged the neural evidence supporting the abstract magnitude representation view. They commented that most studies which supported the abstract representation view were due to either explicitly asking participants to compare the magnitudes of number stimuli, such as in a number comparison task, or due to an experimental design which encourages participants to attend to the quantity of numerical stimulus. Hence, the results supporting a shared magnitude representation might be just because of a general cognitive processing.

As the task demands might largely influence the results of previous fMRI experiments, recent neuroimaging studies focusing on numerical stimuli processing usually either used a carefully-designed control task (e.g., Holloway, Price, & Ansari, 2010), or a passive paradigm which does not require participants to respond to the numerical stimuli (e.g., Holloway, Battista, Vogel, & Ansari, 2013; Notebaert, Nelis, & Reynvoet, 2010; Vogel, Remark, & Ansari, 2015).

To date whether there is an abstract or non-abstract representation for quantities is still under debate. Some recent studies suggest that both common and distinct network may co-exist to support the processing of both non-symbolic and symbolic numerical stimulus (e.g., Holloway et al., 2010; Sokolowski, Fias, Mousa, & Ansari, 2017). Moreover, a more recent study have suggested that the numerical magnitude processing is not limited to the bilateral IPS, but should engage a wider parietal network, including the bilateral inferior parietal lobules, the bilateral precuneus, and the left superior parietal lobules (Sokolowski et al., 2017).

Interestingly, Sokolowski and colleagues (2017) indicate that the frontal cortex may also be important for basic number processing. The authors conducted a meta-analysis focusing on simple numerical tasks, such as number comparison task, matching task, and passive viewing paradigm (but not calculation or arithmetic task). They found that the superior frontal gyrus was usually activated during symbolic magnitude processing, whereas the right medial frontal gyrus and cingulate gyrus were activated during non-symbolic magnitude processing. The activation in the frontal cortex is usually interpreted as the involvement of a domain-general process, for example working memory, because it is usually found in a calculation task (for a review, see Arsalidou & Taylor, 2011). However, only simple number tasks were included in the meta-analysis, the authors thus suggest that the activation in the frontal cortex is also important to support the magnitude processing for both symbolic and non-symbolic numerical stimulus. The importance of prefrontal cortex for magnitude processing has also been indicated from the results of single-neuron studies on monkeys (for a review, see Nieder & Dehaene, 2009).

In summary, the bilateral IPS is the most frequently reported area when using numerical stimulus as stimuli regardless of formats, thus it likely represents the magnitude processing of numbers. More recent findings suggest that not only the IPS, but also other regions within the parietal cortex support magnitude processing. In addition, the frontal cortex may also play a role in a simple number task. On the other hand, the brain activation is sensitive to task demands, thus a well-designed control task or a passive paradigm is required for studying the 'pure' processing of numerical stimulus. Both format-specific and format-general representations are found for numerical stimulus, however, to date it is still not clear whether the magnitude representation is abstract for all formats of numbers or whether multiple magnitude representations exist for different formats. In the following sections I will review the neural evidence specifically for visual Arabic digits and auditory number words.

### *1.6.2 Visual Arabic digit*

As mentioned earlier, although a separate neural system for coding visual Arabic digits has been proposed for more than 20 years in the triple-code model (Dehaene & Cohen, 1995), the visual number form area in the inferior temporal gyrus (ITG) has not been identified until very recently (Grotheer et al., 2016; Shum et al., 2013). This is surprising because visual digits are the most frequently used symbols for fMRI studies to investigate numerical representation. Shum and colleagues (2013) suggested that the null effect for Arabic digits in the previous fMRI studies was possibly due to the severe signal dropout in the ITG because of the surrounding structure, i.e., the air-bone interface within the petrous bone as well as the venous flow of the transverse sinus. They avoided the blood-oxygen-level-dependent BOLD signal problem by testing subjects with intracranial electroencephalography (EEG). In their first experiment, participants were instructed to press a keypad button indicating whether they could read the displayed stimuli. Arabic digits, letters, and false fonts including scrambled symbols and foreign numerals (i.e., Devanagari, Tibetan and Thai numerals for English speaking participants) were used in the experiment. In the second experiment, participants were instructed to name aloud the displayed visual digits (single and double digits), number words, and non-number words. The number words had the same quantity as the Arabic digits, and the non-number words were pronounced similar to the number words (e.g., 'won', 'too', 'tree', etc.). The results showed that there are neurons preferentially responding more to the Arabic digits than to letters, false fonts, non-number words and even number words in the ITG. However, because the electrode coverage within their subjects was less in the left ITG than the right ITG, it was not clear in this study whether there is a laterality effect for coding Arabic digits in the ITG. Moreover, the authors pointed out that the number form area they discovered was anatomically close, but separate from the visual word form area (Nobre, Allison, & McCarthy, 1994). This thus suggests that separate neurons responding to visual Arabic digits and words rely on the similar anatomical network to communicate with other brain regions for further processing, such as language function.

This finding of a visual number form area was further extended to congenitally blind subjects by using a special visual-to-music sensory substitution for the stimuli (Abboud, Maidenbaum, Dehaene, & Amedi, 2015). The 2D x-axis and y-axis of a picture were transformed into time and pitch frequency column by column of pixels, respectively. The colour of a picture was substituted by different timbres of instruments. For example, a trumpet for a picture in blue, a violin for a picture in yellow. The blind subjects were trained 25 to 30 hours to understand this special visual-to-auditory transformation before being tested in an fMRI experiment. In the experiment, subjects were instructed to select a correct numerical meaning (1, 5, or 10), letter forms (I, V, or X), or colours (blue, red, or white) of Roman numerals in different runs. The same Roman numerals were used in all tasks. The authors managed to overcome the signal dropout issue (Shum et al., 2013) by using a special signal thresholding method which ensured that the analysis did not contain the voxels with attenuated signal intensity. The results showed that the activation in the right ITG was larger when contrasting the number task to the other two tasks. Moreover, the authors tested the functional connectivity of the visual number form area and visual word form area in the ITG in blind and sighted subjects. They found that the number form area was connected to the IPS, whereas the visual word form area was connected to language-processing area, which is in line with a magneto-encephalographic (MEG) study showing separate pathways for letters and Arabic numerals originated from the occipital-temporal area (Carreiras, Monahan, Lizarazu, Duñabeitia, & Molinaro, 2015). Also, the functional connectivity results of the blind and control groups were extremely similar. This shows that the visual experience of numerals is not necessary for numeral processing, and implies that our brain does not work like a set of sensory-based systems, but is more flexible task-based and sensory-independent (see also Reich, Maidenbaum, & Amedi, 2012).

The recent study of Grotheer and colleagues (2016) was the first which successfully demonstrated the visual number form area in normal subjects. They used several methods, such as a high spatial resolution 64-channel head coil, additional localised shimming, and liberal smoothing, to decrease the fMRI signal dropout and increase the signal-to-noise ratio in the ITG. They tested participants with Arabic numerals, letters, objects, false fonts of Arabic numerals and letters, and scrambled noise of Arabic numerals and letters. Participants were instructed to detect immediate repetitions (1-back task). The results showed that a larger activation in the bilateral ITG for Arabic numerals than false Arabic numerals (look similar to Arabic digits). However, because the data acquisition method was limited to the IT cortex, it was not possible to examine the brain activity in the IPS for the Arabic numerals in the same study. In addition, a larger activation in the left ITG, which was overlapped with the number form area, was also found for letters than false letters. Hence, an alternative explanation for the bilateral ITG activation is that it does not specifically reflect the visual processing of Arabic numerals, but actually prefers the numbers and familiar symbols in general (Merkley, Wilkey, & Matejko, 2016).

It is important to note that the Arabic numerals, as well as words and letters, appeared very recently in terms of the long timeframe of human evolution. Hence, our brain should have not evolved to specifically process these symbols. Instead, these symbols may make use of some existing brain networks which are appropriate for processing these symbols. A recent paper has suggested a biased connectivity hypothesis that the form areas (e.g., visual number form area and visual word form area) emerge in the cortical areas with a greater structural connectivity to other cortical sites which are critical for the specific processing, such as IPS for numbers and perisylvian language areas for words (Hannagan, Amedi, Cohen, Dehaene-Lambertz, & Dehaene, 2015). A similar point of view can also be seen in the neuronal recycling hypothesis (Dehaene & Cohen, 2007). Since the biased connectivity hypothesis predicts that the brain network already exists before symbols are learned, thus, a straightforward examination would be to test the structural connectivity of children who have not learned, or have little experience with the symbols (see a discussion in Hannagan et al., 2015).

In summary, although the triple-code model predicted the existence of visual number form area 20 years ago, however, possibly due to the technical difficulties it has just been identified in the ITG very recently. Moreover, to date it is still not clear whether the number form area in the ITG represents the visual processing of numerals, or reflects a more general preference to familiar symbols as so far only one study has been done on normal subjects. More studies are needed to discover the nature of the visual representation of Arabic numerals. In the following section I will introduce the neural research so far has been done about spoken number words.

### 1.6.3 Spoken number word

The triple-code model suggests that the auditory number words are processed by a ‘general-purpose language module’ (Dehaene, 1992), and indicates that the left angular gyrus, which is in connection with the left perisylvian language area, supports the manipulation of the verbal code frame (Dehaene et al., 2003). This argument was mainly based on calculation tasks and written number words. For example, a larger activation in the left angular gyrus was usually reported in a multiplication task compared to other kinds of number-related task, such as subtraction, number comparison, or digit-matching task. Dehaene and colleagues (2003) therefore suggested that the activation in the left angular gyrus was because fact retrieval during multiplication calculation required verbal memory. To the best of my knowledge, there were only two fMRI studies using spoken number words at that time (Eger et al., 2003; Le Clec'H et al., 2000).

Le Clec'H et al. (2000) tested bilinguals (French as first language for half participants and English for the other half) with French and English written and spoken number words in a symbolic number comparison task. The authors found a right-lateralised brain network, including the IPS, postcentral sulcus, and the insula for numerals which were independent of input modalities and language.

Eger and colleagues (2003) used numbers, letters and colours as target stimuli. Participants were instructed to press a key button as soon as they saw one of three targets showed in either visual or auditory modality (could be seen as a same-different task). The targets were varied between participants. The results showed that when contrasting the auditory number words and visual Arabic digits, more activation in the auditory associative areas for auditory number words, such as the bilateral superior and middle temporal gyrus; whereas more activation in the visual associative areas for Arabic numerals, such as the superior parietal lobule and the bilateral fusiform gyrus and inferior occipital gyrus. Moreover, the IPS activation was not modulated by input modality.

To summarise, the results of these two studies suggest that the same number magnitude representation in the IPS can be accessed independently by different formats and modalities of numerals. However, as mentioned earlier, without a carefully-designed control task, the IPS activation can always be explained by other general cognitive process unrelated to magnitude processing, such as response-selection (Göbel et al., 2004). In addition, the numerical distance between numerals was not investigated in these two studies. Thus, it is not conclusive from these two studies whether there is an abstract representation of magnitude processing for numbers.

In a more recent work, Klein and colleagues (2010) compared the brain responses to auditory number words in three kinds of tasks with different extents of intentionality of magnitude processing: a passive listening paradigm, a parity task, and a number comparison task. It was not a surprise that the parity task and number comparison task, showed the bilateral IPS activation compared to the baseline condition. The novel finding was that the bilateral IPS activation was also observed for auditory number words compared to auditory pseudowords with similar number of phonemes and syllables in the passive listening paradigm. This finding supports the idea that the numerical magnitude of auditory numerals is automatically coded by simply presenting the stimuli, which is consistent with the findings of visual Arabic digits (e.g., Holloway et al., 2013; Vogel, Goffin, & Ansari, 2015). Interestingly, brain activity in the frontal cortex, such as bilateral cingulated gyri, bilateral middle frontal gyri, and left medial frontal gyrus, was also found when comparing auditory number words to pseudo-words in the passive listening paradigm. These activations could not be interpreted as the involvement of domain-general cognitive processing, such as working memory, because participants were not instructed to manipulate the auditory number words. Thus, this finding may suggest a role of the frontal cortex in the automatic processing of auditory number words, which is possibly related to magnitude processing (Nieder & Merten, 2007; Nieder & Miller, 2003).

A very recent fMRI study further tested auditory number words by using an adaptation paradigm (Vogel et al., 2017). The idea of the adaptation paradigm in an fMRI study is a two-step procedure. First, the BOLD signal decreases after a repetitive display of a stimulus, which is due to an adaptation of the neuronal population to the stimulus. Second, some property of stimulus change (i.e., a deviant stimulus) would lead to recovery of the BOLD signal, and thus indicating that the adapted neuronal population are sensitive to the change. In contrast, if the BOLD signal remains adapted, then it shows that the neuronal population is invariant to the attribute (Grill-Spector & Malach, 2001).

Vogel and colleagues (2017) tested English-speaking participants with an adaptation to Arabic numerals, as well as German-speaking participants with an adaptation to both Arabic numerals and German spoken number words. They also manipulated the ratio of numerical distance of the adapted stimulus and the deviant. More specifically, number 6 was the stimulus-to-adapt, whereas the numbers 3, 4, 5, 8, 9, 12 were the deviants for both visual Arabic numerals and auditory number words. It was assumed that the numbers in a small ratio to the adapted number 6, such as number 3 and 12 (i.e., the ratio is 0.5 for both 3/6 and 6/12), shared smaller overlapping of representational space with the adapted number, compared to the numbers in a large ratio, such as number 4 and 9 (i.e., ratio is 0.67 for both 4/6 and 6/9). Hence, a smaller ratio between the adapted number and the deviant number should induce a larger BOLD signal recovery compared to a larger ratio, if the adapted neuronal population, for example, the neuronal population in the IPS, is sensitive to the magnitude coding of numbers. The conjunction analysis for the Arabic numerals and spoken number words showed the ratio dependent modulation in the left IPS. However, the authors did not interpret this result as direct evidence that numbers in different modalities automatically access the same magnitude representation, i.e., an abstract magnitude representation of numbers. They mentioned that previous research employing multivariate pattern analysis discovered that although the IPS is important for representing both non-symbolic (dots) and symbolic numerical stimuli (Arabic digits), the voxel-pattern activation of these numeral stimuli was different (e.g., Lyons, Ansari, & Beilock, 2015). Since the spoken number words have not been examined by a multivariate pattern analysis with Arabic digits, it is not clear whether these two numerical symbols share the same magnitude representation.

Apart from the IPS activation, Vogel et al. also found the ratio dependent modulation for auditory number words in the cingulate cortex, left prefrontal cortex, and left insula. This shows that the frontal as well as temporal cortex may also play a role for the magnitude processing for spoken number words. However, as mentioned earlier very little research has been carried out for spoken number words. More research is needed to understand the processing of these symbols which are the earliest numerical symbols we learned.

To summarise, the triple-code model offers a guideline for understanding and investigating the underlying processing and the representation for different formats and modalities of numbers (Dehaene, 1992; Dehaene & Cohen, 1995). For example, as predicted by the model, the visual number form area in the ITG was identified very recently (Grotheer et al., 2016; but see comments in Merkley et al., 2016). However, accumulated evidence also suggests some adjustments for the triple-code model. For example, the bilateral IPS is frequently activated for number processing regardless of formats or modalities, but whether it represents an abstract representation of numerical quantity is still under debate (e.g., Lyons et al., 2015; for a thorough discussion, see Cohen Kadosh & Walsh, 2009;). A recent meta-analysis also suggests the role of frontal cortex in number processing (Sokolowski et al., 2017). Moreover, there are also some parts in the triple-code model which still lack evidence for neural correlates, that is, the representation of spoken number words, and how it interacts with Arabic digits as the transcoding between these symbols are very frequent.

### *1.6.4 Electrophysiological studies on number processing*

So far most of neural evidence I have mentioned above is from fMRI research. FMRI offers a good spatial resolution of brain structure, it is thus easy for people to understand the general picture about the network of number processing between different brain regions. However, the fMRI does not have a good temporal resolution. Though a number-related task may look simple, there might be several mental stages involved in. For example, for a symbolic number comparison task with visual numerals, there are identification and comparison stage before a response is made (Dehaene, 1996; Dehaene & Akhavein, 1995). Since the RTs are usually below a second in a symbolic number comparison task, and even faster in a number matching task; hence, it is not easy to understand these multiple stages, especially an early stage of number processing by using only fMRI. In contrast to the blood oxygen level change which is used in an fMRI study with a temporal resolution in seconds, the EEG technique have a temporal resolution in milliseconds. This makes the EEG technique a better tool for the investigation which needs precise timings to unravel the different stages of processing (e.g., Dehaene, 1996).

By placing electrodes on the scalp, the electrical neural activities can be collected through electrodes with a precise temporal resolution. However, the continuous EEG signals contain all ongoing brain processes and the electrical field gets attenuated by the skull (Luck, 2014). Thus, to isolate the neural responses for specific events (e.g., an event can be a flash light, a speech sound, or an Arabic digit), the same event must be repeated various times so that the neural (electrical) signals for specific events can be averaged to reduce the random noise and hence increase the signal-to-noise ratio (Luck, 2005). These isolated neural responses for specific events are called event-related potentials (ERPs). A definition of an ERP is given by Luck (2014) as ‘a scalp-recorded neural signal that is generated in a specific neuroanatomical module when a specific computational operation is performed.’ (p. 66).

One of the earliest identified ERP components which demonstrates the distance effect is the P2p, which means the second positivity (P2) in the posterior/parietal electrodes (Dehaene, 1996). The P2p shows a larger positivity for a close-distance numeral than for a far-distance numeral in a symbolic magnitude comparison task (judging whether the numeral is larger or smaller than 5). In

Dehaene's study (1996), both written number words and Arabic digits induced the similar distance effect in the P2p, but an earlier ERP response was found for Arabic digits. The distance effect for Arabic digits initiated just after the N1 component (174 ms after stimulus onset), and continued to show in the P2p (206 – 230 ms), whereas there was no distance effect for written number words before the P2p (Dehaene, 1996). Since both number formats show a similar distance effect in the P2p, it supports the idea that an amodal, shared semantic magnitude representation is activated during the comparison stage. Also, the earlier initiation of the distance effect for Arabic digits compared to written number words also show a notation difference in the identification stage. Hence, Dehaene's study demonstrates a good example that the EEG/ERP technique is a powerful tool to study the timing of number processing.

This distance effect in the N1-P2p transition and in the P2p has been replicated by other studies using a similar numerical comparison task (e.g., Cao et al., 2010; Jiang et al., 2010; Libertus et al., 2007). Since the latency of these components (from N1 to P2p) is usually between around 100 to 200 ms post-stimulus onset, these early onsets thus also support the idea of an early magnitude processing of numerals.

Although there are many studies investigating number processing using an EEG/ERP experiment with visual numerals, it is a surprise that very little EEG/ERP research has investigated the numerical distance effect with spoken number words. To the best of my knowledge, only four EEG studies included spoken number words in their experimental design when looking into the numerical distance effect (Pinhas, Donohue, Woldorff, & Brannon, 2014; Szűcs & Csépe, 2004a, 2004b, 2005b).

Compared to visual digits and written number words, spoken number words induce very different EEG responses (Szűcs & Csépe, 2004a). The distance effect within spoken number words does not show in the N1-P2p transitions. The P2p showed the comparison distance effect for spoken number words only in one study; however, a similar distance effect in the P2p was also reported for auditory letter names in the same study showing that this distance effect might not be specific for numerals (Szűcs & Csépe, 2004b). Instead of the P2p, a distance effect in the N2 component was found in two studies which both conducted a symbolic number comparison task (Szűcs & Csépe, 2004b, 2005b), thus this may suggest that the N2 component is essential for the magnitude processing of spoken number words. However, both EEG studies with spoken number words originate from the same research group and there were some inconsistent results between these two studies, so any conclusions would be preliminary.

I will introduce these experiments in more details in the introduction of Chapter 4 in which I manipulated numerical distance in an oddball paradigm with an EEG measurement.

As mentioned earlier, so far there is little research investigating the correspondence between spoken number words and Arabic digits; hence, in the following section I will review the cross-format integration literature about speech stimuli, especially between letters and speech sounds, as they are also artificial symbols and the correspondence between them is also overlearned just like the relationship between spoken number words and Arabic digits.

## 1.7 Cross-format audiovisual integration

Multi-sensory integration can happen when stimuli in different modalities are displayed temporally or spatially proximate, and the temporal proximity seems more important than the spatial proximity (Koelewijn, Bronkhorst, & Theeuwes, 2010). This means that our brain can integrate stimuli which are simultaneously displayed, such as flash light (visual) and white noise (auditory). However, integration in the current thesis focuses on the overlearned pairing of symbols. As mentioned earlier, because we are very familiar with the transcoding between spoken number words and Arabic digits, the perceptual representations of these numerical symbols may be activated from one to another via an asemantic route (Dehaene, 1992).

So far, to the best of my knowledge, no research has systematically investigated the cross-modal integration between spoken number words and Arabic digits, hence, I will start by reviewing the similar overlearned pairing of symbols, that is, the speech stimuli.

One of the most famous visual-audio integration effect comes from the language field, and is called McGurk-MacDonald effect or McGurk effect (McGurk & MacDonald, 1976). In this original experiment, participants saw a video of lip movements and heard speech sounds simultaneously. There were four kinds of stimuli: visual 'ba-ba' and auditory 'ga-ga' or vice versa, as well as visual 'pa-pa' and auditory 'ka-ka' or vice versa. Three groups of participants were recruited, children 3-5 years old, 7-8 years old, and adults 18 – 40 years old. The results showed that participants usually reported they heard 'da-da' when actually seeing 'ba-ba' and hearing 'ga-ga', and heard 'ta-ta' when actually seeing 'pa-pa' and hearing 'ka-ka', which were fusions of synchronously displayed visual and auditory stimuli. These misperceptions showed that the simultaneously displayed visual and auditory stimuli were somehow integrated. More importantly, the adult group showed more fusion responses than the groups of children. Hence, these fusion responses, i.e., integration responses are seen as evidence showing an overlearned relationship among speech sounds and corresponding lip movements.

The fMRI studies further indicate that the left superior temporal sulcus (STS) is the heteromodal cortex which integrates the visuo-audio information. For example, supra-additive activation in the left STS was observed for semantically congruent audiovisual stimuli, whereas sub-additive activation in the left STS was found for semantically incongruent audiovisual stimuli (Calvert, Campell, & Brammer, 2000). A more recent fMRI study also showed that the amplitude of the activation in the STS was positively correlated with the likelihood of perceiving the McGurk effect (Nath & Beauchamp, 2012). The left STS is also activated when non-speech information such as an object picture and a corresponding sound the object produces is displayed, e.g., a picture of hammer and a 'bang-bang' sound (Beauchamp, Lee, Argall, & Martin, 2004). This shows that the STS has a more general role for multi-sensory integration but not only for the speech-related stimuli.

The integration effect between letters and speech sounds, in terms of larger brain activation for congruent letter and sound pairs than for incongruent is also observed in the bilateral STS as well as in the superior temporal gyrus (STG) (van Atteveldt, Formisano, Goebel, & Blomert, 2004). In a follow-up study, the activation in the STS was larger for bimodal stimuli than for unimodal stimuli, but the STS was not sensitive to temporal synchrony. In contrast, the activation in the anterior superior temporal plane and the planum temporale was larger when the congruent letters and speech sounds were displayed simultaneously than with a 150 or a 300 ms stimulus onset asynchrony (SOA) (van Atteveldt, Formisano, Blomert, & Goebel, 2007). The same study therefore suggests that the STS integrates the letters and speech sounds and then sends the feedback of the congruency information to the auditory association cortex, i.e., the anterior superior temporal plane and the planum temporale.

Because the integration between letters and speech sounds is assumed to be fast and automatic, Blomert and colleagues chose to use an auditory mismatch negativity (MMN) paradigm with the recording of EEG which has high temporal resolution to study this overlearned correspondence (e.g., Froyen et al., 2008). This method became popular in recent years to study the letter-sound integration (Froyen, Bonte, van Atteveldt, & Blomert, 2009; Froyen et al., 2008, 2011; Mittag, Takegata, & Kujala, 2011; Mittag et al., 2013; Žarić et al., 2014, 2015). Hence, I will introduce the MMN as well as review literature which investigates the audiovisual integration between letters and sounds with measuring the MMN.

### 1.7.1 MMN and Integration between letters and speech sounds

The MMN is a negativity in the EEG response which usually appears when detecting the change of sounds. It has been suggested that the MMN is an index which traces back the auditory sensory memory (for a review, see Näätänen, Paavilainen, Rinne, & Alho, 2007). An auditory oddball paradigm is usually used to induce the MMN. That is, a deviant sound follows a few repetitions of a standard sound. The deviant sound, i.e., the mismatched sound, typically generates a more negative electrical signal (see Figure 1-8). Difference waves between the brain responses for the standards and for the deviants are usually calculated to emphasise the appearance of the MMN. The MMN is normally found between 150 and 250 ms after change onset, and the MMN amplitude can be modulated by different changes of acoustic features, such as intensity, frequency, and duration (Näätänen et al., 2007). The strongest MMN amplitude is usually found in the midline anterior electrodes, such as in the Cz and the Fz electrodes. In addition, the auditory oddball paradigm used for inducing the MMN does not require responses, thus it is ideal to investigate the 'pure' processing of stimuli, which is free from the possible influence of response-selection (e.g., Göbel et al., 2004).

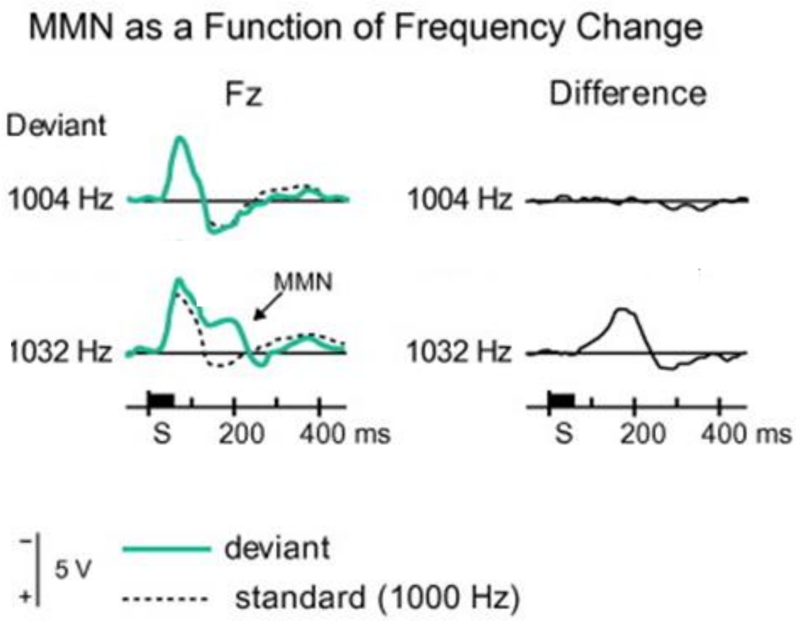


*Figure 1-8.* A figure of the typical MMN (modified from Näätänen et al., 2007, the original results was from from Sams, Paavilainen, Alho, & Näätänen, 1985). Standard tones were 1000 Hz (80%). The MMN only appeared when the difference between deviant tones and standard tones could be detected, when the deviant tone was 1032 Hz.

Blomert and colleagues chose the MMN as an index for investigating the integration between letters and speech sounds because they assumed that the letter-sound integration is early and automatic, which fits the characteristics of the MMN which is usually evoked early and pre-attentive (Tiitinen, May, Reinikainen, & Näätänen, 1994). In their first MMN study, they measured EEG and analysed the MMN induced by the 10% of incongruent trials of an auditory oddball paradigm. The results indicated a clear enhancement of the MMN (more negative MMN amplitude) during the incongruent trials, and the enhancement linearly decreased with the increase of SOA. Since the MMN is an early component of neural activity and is widely seen as an automatic brain response to the change of auditory stimuli, the authors argue that letters and speech-sounds are processed as compound stimuli early and automatically (Froyen et al., 2008).

More importantly, in a follow-up study they compared the MMN activities of participants with different reading abilities (Froyen et al., 2009). The results showed that compared to the condition displaying speech-sounds only, the MMN of adult readers was enhanced significantly in incongruent trials when the letter and the sound were displayed simultaneously. However, this relation was absent in beginning readers (with 1-year instruction), more specifically, no significant differences were found in the brain activity between the speech-sounds-only and the letter-sound-simultaneously condition. For the advanced readers (with 4-year instruction), an enhanced MMN was found when the letters were displayed 200 ms earlier than sounds (Froyen et al., 2009). These results showed that it takes long time (more than 4 years) to establish the automatic integration between letter and speech sounds. Also, this result implied that the letter-sound integration can possibly be used as an indicator for reading abilities.

Indeed, it has been found that the integration of letters and speech sounds is critical for the development of language fluency.

That is, the letter-sound integration effect, i.e., the larger MMN amplitude for the mismatched letter-sound pair, is absent in 11-year old dyslexic children (Froyen et al., 2011) as well as in dyslexic adults (Mittag et al., 2013). A reduced letter-sound integration effect in the planum temporale and the STS for 9-year old dyslexic children was also reported in an fMRI study (Blau et al., 2010; for a review about the relation between the letter-sound integration and reading fluency, see Blomert, 2011).

In summary, the evidence of the letter-speech sound integration inspires the idea of the current thesis that a similar integration might be observed for numerical symbols because the correspondence between spoken number words and Arabic digits is also overlearned and used daily. Hence, just like letter-sound integration seems to be related to reading ability I propose that the integration between these numerical symbols in auditory and visual modality may also be important to our mathematical competence and will investigate this in detail in my thesis.

## 1.8 Mathematical competence and symbolic numerical representation

Many studies attempted to find the critical factor that influences our mathematical abilities by studying the development of numerical cognition in children (e.g., Barth, La Mont, Lipton, & Spelke, 2005; Gallistel & Gelman, 1992; Jordan et al., 2007; Rousselle & Noël, 2007; Starkey & Cooper, 1980; Wynn, 1990, 1992). Since the math-related skills (e.g., counting, arithmetic, and so on) of children are still growing, the longitudinal approach is a good method to investigate which cognitive factors predict the children's mathematical achievement later on (Göbel et al., 2014; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013). For example, Göbel and colleagues (2014) tested cognitive abilities and mathematical competence in 6-year-old children, and then tested the same group of participants again after approximate 11 months. They used the same standardised test (Numerical Operations subtest of the second U.K. edition of the Wechsler Individual Achievement Test; Wechsler, 2005) to measure children's arithmetic skill. The results showed that first, children performed better on the standardized test after 11 months. Furthermore, the growth of arithmetic skill can be predicted by the number-identification ability, which referred to a task in which children had to identify the corresponding Arabic numeral out of 4 or 5 response options after the experimenter said the target number aloud.

Some other studies focused on adults (e.g., Castronovo & Göbel, 2012; Halberda et al., 2012; Lyons & Beilock, 2011; Sasanguie & Reynvoet, 2014). Although the mathematical competence of adults may not develop anymore, previous studies showed that the individual differences in mathematical abilities are large in adults (e.g., Bynner & Parsons, 1997; Halberda et al., 2012). For example, Bynner and Parsons (1997) tested 1,714 37-year-old adults in the UK with some basic mathematical problems that people encounter in daily life (e.g., calculate the total money you need to pay if you want to order a £19.66 pizza and two video tapes that costs £2.50 each for a party). The results showed that 27% of women and 19% of men were classified as having 'very low' numeracy, whereas 21% of women and 34% of men were classified as having 'good' numeracy. This result indicates a wide range of people's mathematical abilities. Therefore, to find cognitive factors that cause/correlate with the individual differences in mathematical abilities on adults can also help to clarify the nature of mathematical competence.

Before going any further, I want to clarify that the mathematical competence measure used in this study is not measuring a higher understanding about math, such as differential and integral calculus. The measure I use focuses on written arithmetic. The standardized mathematical test I used, the Math Computation of Wide Range Achievement Test 4 (WRAT-4), focuses mainly on simple arithmetic, such as addition, multiplication, subtraction, and division with 1-to 3-digit numbers. This is the math problem we often encounter, on daily basis, for example, when we calculate the change we will get from a £20 note when buying food at a market.

As mentioned earlier, to date more and more research has indicated a stronger correlation with mathematical competence for symbolic numerical representation than for non-symbolic numerical representation (Castronovo & Göbel, 2012; De Smedt et al., 2013; Göbel et al., 2014; Lyons & Beilock, 2011; Rousselle & Noël, 2007; Sasanguie et al., 2013; Schneider et al., 2016) For example, Rousselle and Noël (2007) gave an Arabic number comparison task and an ANS-like task (display bars instead of dots array) to 45 second-grade children with mathematic learning disabilities (29 had mathematical difficulties only, 16 had both mathematical and reading difficulties), and compared their performance with 45 typically developing (TD) children. The results showed that the TD group had a higher accuracy rate and a shorter RT than the mathematical difficulties group in the number comparison task. However, the two groups had a similar accuracy rate and RT in the ANS-like task. They therefore suggested that these children with mathematical learning disabilities had difficulty to access the magnitude from symbols, but had no problem to deal with numerosities. De Smedt and colleagues (2013) further reviewed the past studies focusing on representations and mathematical competence. They found that the relationship between symbolic comparison task (e.g., compare two digits and answer which one is larger) and mathematical competence is robust across studies and populations (For studies on adults, see Castronovo & Göbel, 2012; Lyons & Beilock, 2011) that worse performance of the symbolic task correlates with lower mathematical competence and dyscalculia. In contrast, conflicting results were reported in the relationship between non-symbolic task and mathematical competence. These results indicated that symbolic representation, rather than non-symbolic representation, should be closely linked to individual mathematical competence (see also Schneider et al., 2016).

## 1.9 Research questions and hypotheses

The current thesis is inspired by the integration between letters and sounds, and the relationship between such integration and reading abilities. As a similar over-learned correspondence should exist between Arabic digits and spoken number words, I decided to investigate the cross-format integration between them by using a similar method from Froyen et al (2008), inspecting mainly the MMN in an auditory oddball paradigm. However, as the cross-modal integration between numerals has never been investigated systematically, I also conducted behavioural experiments to observe the cross-modal correspondence between numerals before employing an EEG measurement.

In Chapter 2, because it has been shown that the temporal proximity is critical for the presence of an integration (Spence, 2011), I modified the design of Sasanguie and Reynvoet's digit-number word matching task (Sasanguie & Reynvoet, 2014) by adding SOAs between the displays of spoken number words and Arabic digits. If the SOA does have an effect on cross-modal correspondence between numerals, it would show a hint about the relationship between spoken number words and Arabic digits. I also included a standardised mathematical test to investigate how the correspondence between cross-modal numerals correlates to mathematical competence in adults.

In Chapter 3, I followed exactly the experimental design of Froyen et al. (2008). The only difference was that I replaced letters and speech sounds to Arabic digits and spoken number words in an oddball paradigm. If the correspondence between cross-modal numerals is exactly the same as the correspondence between letters and sounds, then the MMN should reflect an early and automatic integration between numerals. That is, the MMN in the bimodal, audiovisual condition should be larger than the unimodal, auditory-only condition.

In Chapter 4, I manipulated the numerical distance between the standard and deviant trials in the oddball paradigm. This can further show that whether the magnitude processing is involved in the cross-modal correspondence between numerals, and in which time-window if it is involved.

In Chapter 5, I further added SOAs between the displays of visual digits and auditory number words in the oddball paradigm. The purpose was similar as in Chapter 2: to observe the influence of the SOA on the correspondence between audiovisual numerals.

To summarise, the current thesis aimed to investigate the cross-format/cross-modal correspondence between spoken number words and Arabic digits by inspecting the influence of distance and SOA manipulations on RTs in the behavioural tasks and ERP responses in the EEG experiments.

# Chapter 2 - The cross-format correspondence between spoken number words and Arabic digits in a matching task

## 2.1 Introduction

In daily life, we easily convert spoken number words into Arabic digits and vice versa. For example, when we ask someone's mobile number, we are writing down the spoken number words we heard in Arabic digits, but not in written words. Despite the ease and efficiency with which we switch between spoken number words and Arabic digits, this is a remarkable achievement both phylogenetically and ontogenetically. Many species show the ability to discriminate magnitude, some of them can even map numerosities to numerals being taught (e.g., Biro & Matsuzawa, 2001; Emmerton, 1998), but only human beings have ever developed symbols, in oral and written forms, to represent magnitude. At the beginning, limited spoken number words may be already sufficient for an indigenous culture (e.g., Gordon, 2004). However, when the population increases, an efficient written form to represent exact and large quantities must be developed for management and trades. Nowadays, Arabic digits have become the most widely used written symbols.

Interestingly, we also learn the numerical symbols in the same way. Spoken number words are the first exact numerical representations children acquire (Wynn, 1992). In a next step and often already before school, children are taught the correspondences between spoken number words and digits. The linkage between numerals and corresponding magnitudes becomes automatic over time (Girelli, Lucangeli, & Butterworth, 2000). Adults can access the magnitude meaning from numerals with efficiency (Holloway & Ansari, 2009; Rousselle & Noël, 2007), failure of which is thought to account for mathematical learning difficulties (Landerl, Bevan, & Butterworth, 2004). A longitudinal study indicated that being able to map Arabic digits to their corresponding verbal labels at age 6 years is a critical foundation for arithmetic development over the next two years (Göbel et al., 2014). Evidence shows that the mapping between the two mostly used symbols, spoken number words and Arabic digits, is essential for numerical cognition development. Nevertheless, only little research has focused on the relationship between the two mostly used symbols, spoken number words and Arabic digits. As a result, the current study aims to investigate the correspondence between those two codes in more details.

A simple way to investigate the nature of numerical representation is to observe reaction times and accuracies in behavioural tasks. The distance effect is one of the most robust effects in numerical cognition, and is generally used to identify the semantic processing of numerical symbols. Typically, participants need more time to respond to two stimuli that are numerically closer (e.g., 2 & 3) than further away (e.g., 2 & 8) (Moyer & Landauer, 1967). A popular hypothesis is that the representations of magnitudes are overlapped on a compressed mental number line. The magnitude representation are represented as Gaussian waves on the number line therefore the nearby magnitudes would be also activated during magnitude processing (Dehaene, 1992).

For investigating the magnitude representation, it is natural for previous studies to use a magnitude comparison task (e.g., Holloway & Ansari, 2009; Maloney, Risko, Preston, Ansari, & Fugelsang, 2010; Moyer & Landauer, 1967; Pinel, Dehaene, Rivière, & LeBihan, 2001). That is, select the larger or smaller number of two numbers. However, van Opstal and colleagues (2008) found that not only numerals, but also letters can induce the distance effect in a comparison task (for a letter, respond if it is before or after the target alphabetically). This implied that the distance effect in a comparison task is not only due to the activation of magnitudes but response codes. More specifically, the distance effect found in a comparison task may be not number specific.

Hence, to study the correspondence between Arabic digits and spoken number words, I used a digit-number word matching task (Sasanguie & Reynvoet, 2014), which I also called as an audiovisual numerals matching task to emphasise that there were spoken, but not written number words in the task. Moreover, I also manipulated the SOA. In this paradigm, the visual (i.e., 5) and the auditory stimuli (i.e., /five/) were both displayed with certain latency in each trial, participants were instructed to judge whether two stimuli were matched or mismatched (same or different).

There are at least three advantages for the current audiovisual matching paradigm: Firstly, both empirical and simulation results have indicated that a matching (same-different) task is more suitable than a symbolic magnitude comparison task for investigating numerical-specific representations (van Opstal et al., 2008; van Opstal & Verguts, 2011). Secondly, an audiovisual matching paradigm can better prevent participants from making a judgment without magnitude processing than a mono-modality matching task. For example, D. J. Cohen (2009) demonstrated that physical similarity, but not the magnitude activation, cause the distance effect in a matching task when the digits are only visually presented. That is, digits with a smaller distance (e.g., 5 and 6) are also more visually similar in shape compared to digits with a larger distance (e.g., 5 and 1). Last, and also the novel design in the current study is the SOA manipulation. SOA here is referred to the latency between an auditory number word and a visual Arabic digit in a trial. SOA manipulation has been widely used to investigate the integration between multi-sensory stimuli input both behaviourally (Hillock-Dunn & Wallace, 2012; Navarra et al., 2005; Stevenson & Wallace, 2013; Stevenson & Zemtsov, 2012; van Wassenhove et al., 2007; Zampini, Shore, & Spence, 2003) and neurally (Bushara, Grafman, & Hallett, 2001; Froyen et al., 2009, 2008; Mittag et al., 2013; Ren, Yang, Nakahashi, Takahashi, & Wu, 2016; Stevenson, Altieri, Kim, Pisoni, & James, 2010; van Atteveldt, Formisano, Blomert, et al., 2007). Evidence showed that an integration process is employed automatically when learned audiovisual pairs (e.g., beep sounds and colours; speech sounds and letters) are displayed simultaneously, and this integration effect is modulated by SOA (e.g., Bushara et al., 2001; Froyen et al., 2009; Navarra et al., 2005; van Atteveldt, Formisano, Blomert, et al., 2007). Hence, as it has been suggested that if there is a fast and automatic correspondence between spoken number words and Arabic digits (Sasanguie & Reynvoet, 2014), perhaps an integration may exist between these two commonly used numerical symbols when they are displayed with a temporal proximity, and thus influence the distance effect.

To date only a few studies have looked at the correspondence between spoken number words and Arabic digits by means of an audiovisual matching paradigm (D. J. Cohen et al., 2013; Sasanguie, De Smedt, & Reynvoet, 2017; Sasanguie & Reynvoet, 2014), but none of them inspected the correspondence systemically by manipulating SOAs.

Sasanguie and Reynvoet (2014) used a digit-word matching task in which participants were instructed to judge whether concurrently presented auditory number words and visual digits were the same in magnitude (i.e., 3 and 'three') or different (i.e., 3 and 'five'). Surprisingly, they did not find a distance effect in both studies. That is, the numerical distance between the Arabic digit and the number word did not significantly affect response times. Some models do indicate asemantic routes in between different modalities of numerical symbols (D. J. Cohen et al., 2013; Dehaene, 1992). For example, the multiple representation model illustrates that in an audiovisual matching task, the numerical symbols would be transformed into one modality and then participants are making judgments without accessing magnitudes of numerals (D. J. Cohen et al., 2013). However, this finding is contrary to the massive evidence for an automatic abstract representation for numerals.

One of the most direct evidence indicating an automatic abstract representation of numerals is the distance effect in a priming paradigm. In a number priming paradigm, a prime is displayed before a target, participants are usually instructed to perform a naming task or a magnitude comparison task. These studies revealed that the response times are affected by the magnitude of prime even when the prime and the target are in different formats (verbal words and digits) (e.g., Dehaene, Naccache, et al., 1998), and different modalities (Kouider & Dehaene, 2009), demonstrating an automatic abstract representation does exist. Furthermore, the response times are modulated by the numerical distance between primes and targets (e.g., Reynvoet, Brysbaert, et al., 2002). Computational studies also simulated the same priming distance effect specifically for numerals. (van Opstal et al., 2008). Interestingly, the direction of priming distance effect is opposite to the classic distance effect introduced above. That is, the larger the numerical distance between a prime and a target, the longer the reaction time. It is commonly interpreted as semantic activation of the prime spread along the mental number line therefore the magnitude of target has been activated when the prime is numerically closer, thus leading to a faster response compared with a target which is numerically further away from the prime (Reynvoet & Brysbaert, 2004).

In addition to the null distance effect, Sasanguie and Reynvoet (2014) reported a novel result that the reaction time of their digit-number word matching task, but not of other control matching tasks (e.g., dots-number word & letter-speech sound matching task), was correlated with individual mathematical performance. The faster participants responded in this digit-number word matching task the higher was their mathematical achievement. This is an exciting finding which emphasises the importance for learning mappings between spoken number words and Arabic digits. However, as this is the only research has ever reported the correlation, replications are needed.

In summary, as the conflicting results were reported about whether the spoken number words and Arabic digits is automatically processed through an abstract representation, the present study aims to shed light on the audiovisual processing of the numerical symbols by using a digit-number word matching paradigm with different SOAs. More specifically, I manipulated SOAs in the current study, from -500 SOA (a visual digit was displayed first) to 0 SOA (two stimuli are displayed simultaneously) to 500 ms (an auditory number word was displayed first). If the judgment for the audiovisual matching task is made without magnitude processing, I should observe no distance effect independently with SOA manipulation. However, if the numerical meaning of spoken number words and Arabic digits are automatically processed, the distance effect should be found. Moreover, if the distance effect is modulated by SOA condition, for example, a stronger distance effect when bimodal numerals are displayed temporally close compared to temporally far. Then it may give a hint that the correspondence between spoken number words and Arabic digits is similar to an integration process. A standardized mathematical test was also included in the present study for examining the correlation between the reaction times of the numerical audiovisual matching task and mathematical performance.

## 2.2 **Experiment 1**

### *2.2.1 Method*

#### ***Participants***

Forty-three native-English speaking students[1] of the University of York (25 female; age range: 18 – 36; mean age = 20.86 years, *SD* = 3.04 years) participated for either monetary compensation (£6) or 1-

[1] Sasanguie and Reynvoet (2014) used a sample with 48 participants, in which they found a significant correlation between the RTs of the audiovisual matching task and mathematical ability ($r = -.36$, $p = .010$). In the current study, a similar correlation ($r = -.36$, $p = .028$) was acquired with less participants (N = 36). However, I did not collect other cognitive abilities which may also contribute to the correlation, such as processing speed and non-verbal IQ. Hence, I decided to stop collecting the current dataset with 43 participants and started the next behavioural experiment with measuring participants' processing speed and non-verbal IQ scores.

hour course credit. The study received ethical approval from the Department of Psychology Ethics committee. All participants gave written informed consent.

### Stimuli and procedure

All participants completed a single digit-number word matching task and the Math Computation subtest of Wide Range Achievement Test 4 (WRAT 4; Wilkinson & Robertson, 2006). The matching task was conducted on a PC with WINDOWS 7 operation system. Participants sat around 40 cm in front of an 18.3-inch screen. The study took around 45 minutes.

1. *Single digit-number word matching task*

Stimuli presentation and data recording were controlled by Presentation® (Version 17.2, www.neurobs.com). Participants were instructed to judge whether the digit they saw and the number word they heard are the same or different in quantity. They were asked to press the corresponding response key ("z" and "/" for match/no-match, balanced between subjects) as fast as possible and also to be as accurate as possible. On each trial, a 500 ms fixation cross was followed by an Arabic single digit (Arial, 48 pt) presented at the center of the screen for 450 ms and a spoken number word played for around 450 ms (mean length of sound = 449.43 ms, *SD* = 2.64 ms, range from 444 to 459 ms).

The interval (SOA) between the auditory and visual number stimuli was manipulated. Nine different SOAs were used: -500, -300, -200, -100, 0, 100, 200, 300, and 500 ms. These manipulations of SOAs led to three types of sequences: visual first-then-auditory condition (VA) with negative SOAs (-500, -300, -200 & -100 ms), the auditory first-then-visual condition (AV) with positive SOAs (100, 200, 300, 500 ms), and the simultaneous display (0 ms) (

Figure 2-1). The inter-trial interval was 500 ms.

The sound for each stimulus was digitally recorded by a British male speaker in a soundproof booth. The sounds were played binaurally through a headphone. The following number words were used: 'two', 'three', 'four', 'five', 'six' and 'eight'. The number word 'seven' was excluded as it contained two syllables. Every combination of each digit for each SOA condition was displayed in a random order across blocks. To balance the same and different responses, the same pair (e.g., see a digit '2' and hear a number word 'two') was displayed five times in each SOA whereas there was only one trial for each 'different pair' (e.g., 2-three, 2-four, 2-five, 2-six, and 2-eight). These settings led to total 540 trials[2], and were separated in 9 blocks. The sequence of stimuli presentation was randomly generated but fixed across participants.

The experiment started with a 12-trial practice block. Participants were instructed to respond by key buttons pressing ('Z' and '/'), 'same' when they saw and heard the same number (matching trials), and to respond 'different' when the written digit and the sound of number word were different (non-matching trials). The buttons were counter-balanced between subjects. The RT and accuracy were measured.

2. *Math Computation test (WRAT-4)*

The WRAT-4 (Wilkinson & Robertson, 2006) is a standardised pencil and paper test. Only the Math Computation subtest was used in the study. Participants were asked to solve as many arithmetic questions as possible in 15 minutes (maximum 40 questions). They were instructed to skip the questions that they were not able to answer. Calculators were prohibited. The age-standardized score of each participant was calculated from the raw score.

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[2] For each number, there were 5 same and 5 different number pairs. Hence, while using 6 numbers (2, 3, 4, 5, 6, & 8) in 9 SOA conditions, there were 10 * 6 * 9 = 540 trials in total.

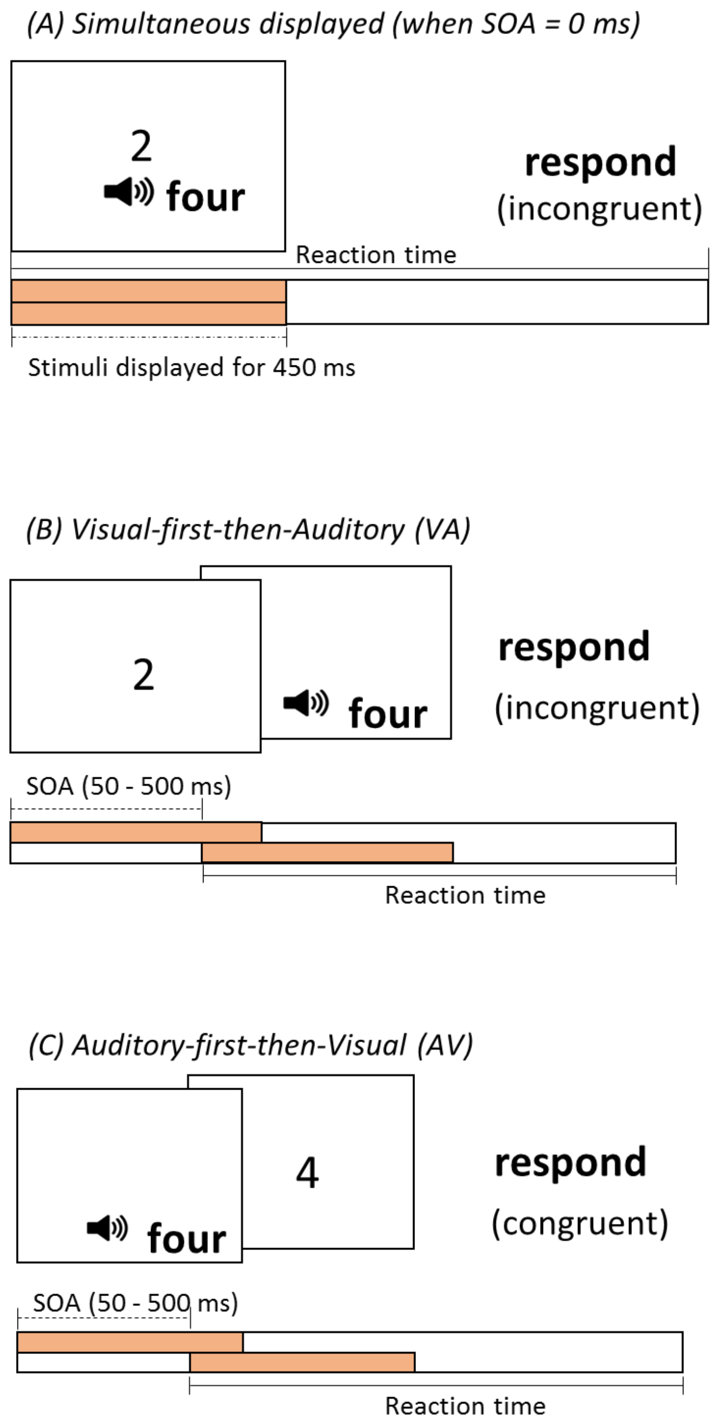


Figure 2-1. *Experimental procedure for the single digit-number word matching task. The upper panel is an example for matched trials with a visual written digit displayed first (VA condition), the middle one is an example for unmatched trials with an auditory number word displayed first (AV condition), and the lower panel is an example for unmatched trials in the condition that both auditory and visual stimulus display simultaneously.*

### *2.2.2 Results*

*Digit-number word matching task*

Two participants were excluded because of too many missing trials (48.9% and 14.6%, respectively) and three due to the experimental program crashing. Trials with RTs smaller than 250 ms and larger than 1500 ms were excluded from further analyses (1.65% of total trials). This task was rather easy for the participants, few errors were made (mean accuracy: 96.6%, $SD$ = 2.3%).

A 2 (matchedness: matching and non-matching) by 9 (SOAs: -500, -300, -200, -100, 0, 100, 200, 300, and 500 ms) was conducted for correct RTs (mean RT = 591 ms, $SD$ = 105 ms). The significant main effect of matching ($F(1,37) = 86.86$, $p < .01$) showed a higher RT for unmatched trials (mean RT = 618 ms, $SD$ = 110 ms) than for matched trials (mean RT = 564 ms, $SD$ = 102 ms). The main effect of SOAs was also significant ($F(8,296) = 194.89$, $p <. 01$). The RTs were longer when closer to 0 SOA. The post-hoc analyses showed that only -500 & -300 and -300 & -200, were not significantly different, other comparisons between an SOA and the one next to itself were all significant (all $ps < .05$). The interaction effect between matchedness and SOAs was not significant ($F(8,296) = 1.79$, $p = .078$) (see Figure 2-2).

*Numerical distance effect*

By definition the numerical distance in the matched trials is zero. Therefore, the data analysis for the distance effect only considered the unmatched trials. A one-way ANOVA of RTs by different numerical distances revealed a significant main effect of distance ($F(5,185) = 9.45$, $p < .01$). The post-hoc analyses showed that except for distance 1 & 2, distance 3 & 4, and distance 5 & 6, other comparisons were significant (all $ps < .05$). The linear trend was significant as well ($F(1,37) = 34.14$, $p < .01$). These results showed that the larger the distances, the shorter the RTs (Figure 2-3), indicating a classic distance effect.

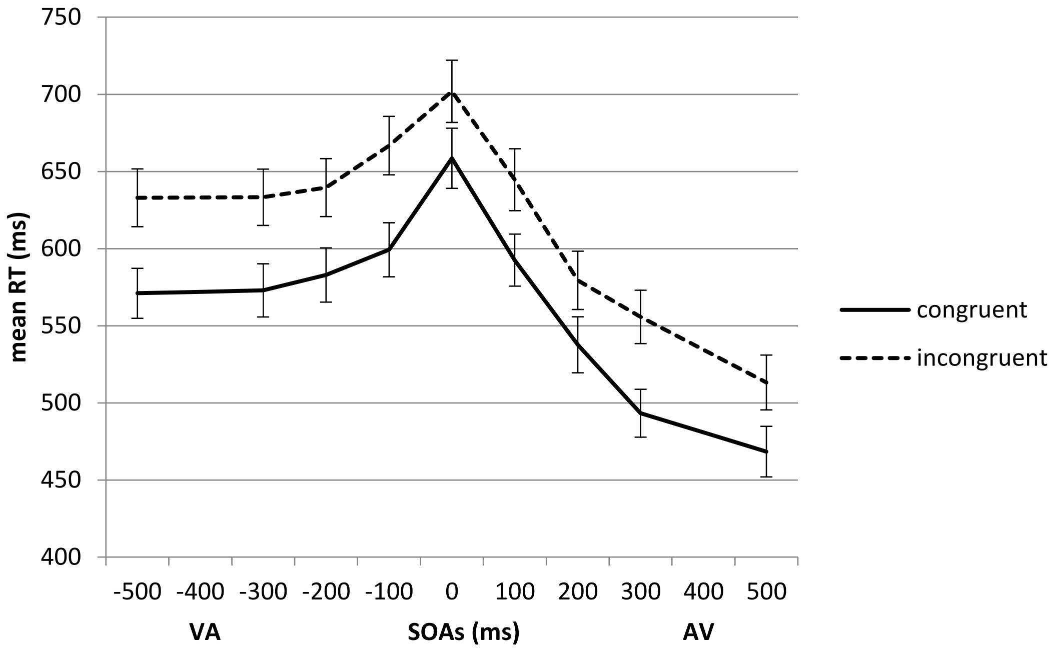


*Figure 2-2.* The RTs for the single digit-number word matching task. The RT for the simultaneous presentation is the highest, and the RTs become shorter with the increase of the SOAs. The error bars indicate ±1 *SE*.

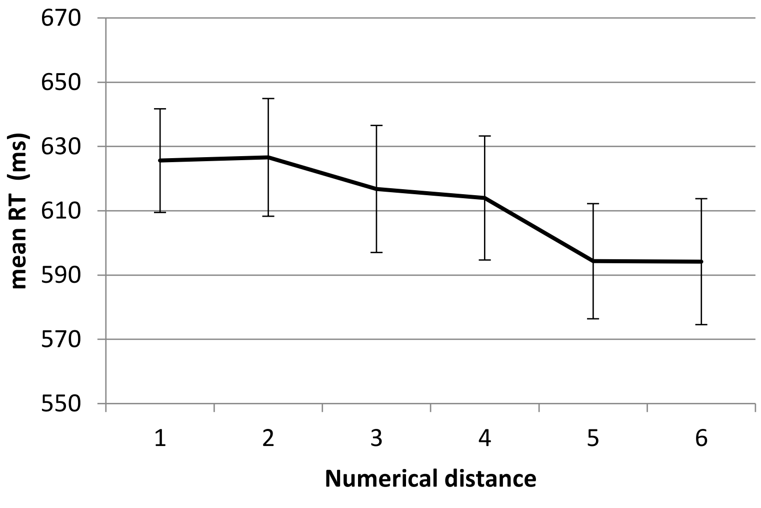


*Figure 2-3.* The numerical distance effect in the single digit-number word matching task. The error bars indicate ±1 *SE*.

To further investigate the individual distance effect under different SOA conditions, I calculated the distance effect for each participant in each SOA condition. Firstly, the data was divided by

SOA for each participant, so figures similar to Figure 2-3 could be acquired, each figure was for each SOA condition. Then a linear regression was conducted for each dataset, so that the beta value for the regression slope was retrieved for each SOA condition (Lorch & Myers, 1990). A negative beta value represented a trend that longer RT happening at smaller distances (see Figure 2-3), indicating a classic distance effect (Moyer & Landauer, 1967) in the current SOA condition. The more negative the beta value was, the steeper the slope became, indicating a stronger distance effect. Then I calculated the mean beta value for each SOA condition (overall mean beta = -.48, SE = .05, 95% confidence interval from -.60 to -.34, see Figure 2-4). Compared to calculate difference scores between RTs of distances, this is a better approach to offer a holistic observation for individual distance effect.

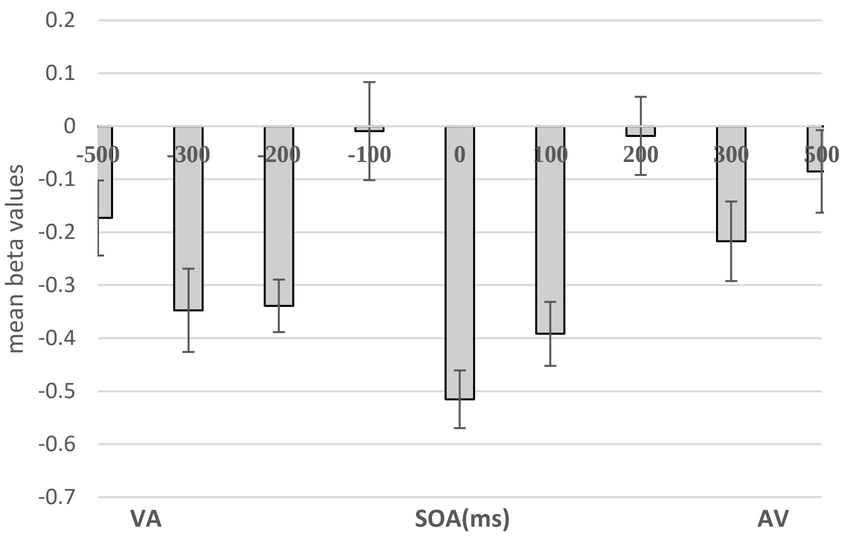


*Figure 2-4.* The mean beta values of numerical distance effect by SOA. The error bars indicate ±1 *SE*. The VA indicates that the visual stimulus (written digit) is displayed first, whereas the AV indicates that the auditory number word displayed before the visual digit.

An one-way ANOVA of beta values by SOAs revealed a significant main effect ($F(8, 296) = 6.34$, $p <. 01$). The data pattern indicated a smaller beta value when the auditory and visual stimuli were displayed simultaneously, and then became larger when the SOA increased. The post-hoc analyses showed that the beta value of 0 ms SOA was significantly smaller than others (all *ps* < .05) except for -300 ($p = .062$) and 100 ms ($p = .121$), and was significant smaller than zero ($t(37)= -9.47$, $p <. 01$) (i.e., a significant distance effect at 0 ms SOA condition). A quadric trend was also significant ($F(1, 37) = 6.17$, $p = .018$), indicating a curved data pattern as described above.

To investigate the relationship between the mathematical competence and the performance in other tasks in the current study (see Table 4 for an overview of performance in all tasks), a Pearson correlation analysis was conducted (mean WRAT standardized score: 108.93, *SD* = 13.45, range from 83 to 143). The results revealed that the WRAT scores were correlated negatively with the overall RT of single digit-number word matching task ($r = -.36$, $p = .028$, see Figure 2-5).

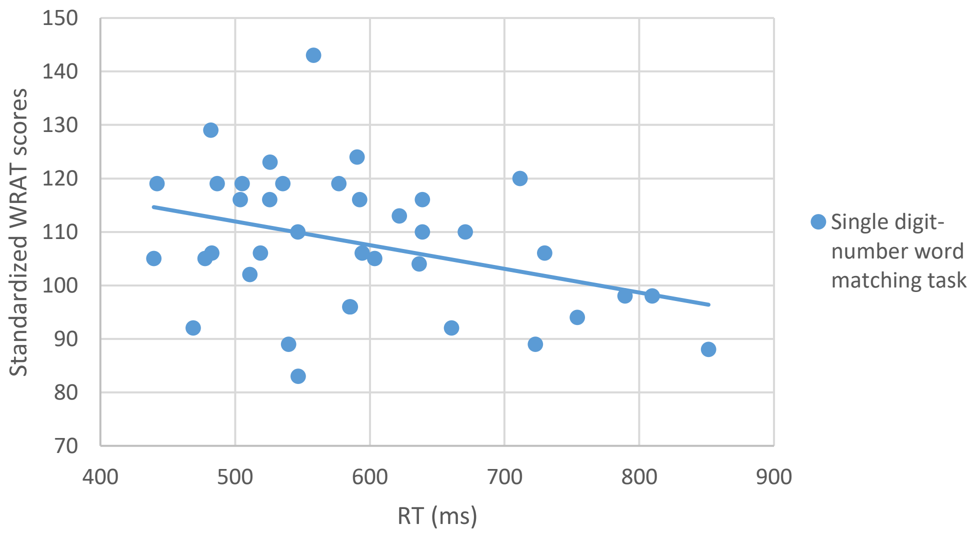


*Figure 2-5.* The correlation between the RTs of the audiovisual matching task and the standardised scores of the WRAT-4 math computation test.

The accuracy rates of the matching task did not correlate significantly with the WRAT score ($r$ = -.01, $p$ =.94). In addition, a significant negative correlation was revealed between the overall distance effect and the WRAT scores ($r$ = -.41, $p$ = .01).

### 2.2.3 Discussion

In the present experiment, the distance effect was discovered with an audiovisual matching task by using spoken number words and Arabic digits. Furthermore, the distance effect was the strongest at 0 ms SOA condition, and became weaker when the SOA increased. In addition, the correlation analyses revealed significant negative correlation between RT of audiovisual matching task and individual mathematical performance.

The current research was the first investigating the audiovisual matching of the numerical symbols by manipulating the SOAs. A linear distance effect of overall RT was found in the audiovisual matching task, indicating longer RTs when the numerical distance between digit-number word pair was larger. In order to compare with the result of the previous study of Sasanguie and Reynvoet (2014), I also checked the distance effect of RT in the 0 ms SOA condition (which is basically the same design of their study) and found that the linear trend was significant as well.

Interestingly, we found the beta values of VA100 and AV200 conditions were not significantly different from zero, which indicated that the distance effect disappeared during these conditions. The VA100 condition happened to be similar to the paradigm used in the number priming studies (e.g., Brysbaert et al., 2002; Reynvoet & Brysbaert, 2004), so the disappearance of distance effect might be related to a different underlying mechanism operating at VA100 condition. However, it is not clear whether the same explanation can apply to AV200 condition since no similar paradigm has been done. Also, the different time-windows for VA100 and AV200 conditions for the disappearance of distance effect might refer to a longer processing time for auditory spoken number words than visual Arabic digits. However, these interpretations cannot explain why the distance effect was present in the synchronous and AV100 conditions.

The correlation between the RTs of single digit-number word matching task and the standardized WRAT scores indicated that retrieving the magnitude from symbols with efficiency is crucial for mathematical competence (Holloway & Ansari, 2009; Rousselle & Noël, 2007). In addition, the correlations between the RTs of each SOA condition and the WRAT scores were consistent and stable (*r*s from -.29 to -.41 across SOA conditions). This supports my initial argument that the efficiency for retrieving the correponding numerosities may be essential to the mathematical performance.

In addition, a significant negative correlation was revealed between the overall distance effect and the WRAT showing that the larger the distance effect (classic distance effects), the better the mathematical performance. This finding is in line with the previous study of Rousselle and Noël (2007), but opposites to the other literature, see De Smedt, Verschaffel, & Ghesquière, 2009; Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2012). Rousselle and Noël (2007) found that the second-grade children with mathematical learning disabilities had a smaller distance effect than the normal developing children. They further explained that it was because the children with mathematical difficulties used other reciting strategies to compensate their performance. However, as the participants were mathematically normal young adults in the current experiment, I have to be careful to accept this explanation for children with mathematical learning disabilities.

The current experiment revealed a distance effect when stimuli were spoken number words and Arabic digits in a matching task, and the distance effect became smaller when the SOA increased. These results implied that firstly, an abstract numerical representation exists across auditory and visual modalities; secondly, the magnitude processing of spoken number words and Arabic digits is automatically activated. In addition, the negative correlation between RT of audiovisual matching task and mathematical performance indicates that learning the mapping between spoken number words and Arabic digits is essential for one's mathematical ability.

There are also questions remain unanswered in this experiment. Firstly, I cannot find a good explantion for the disappearance of distance effect in VA100 and AV200 conditions. Secondly, since the RT of the matching task can be possibly interacted with the factors other than matchedness, such as individual general proccessing speed and the IQ, these factors should be controlled in the followup studies. As a result, to observe the distance effect with a better temoral resolution, I did the follow-up experiment by using the same audiovisual matching paradigm but with shorter SOAs and shorter intervals. Also, in this experiment, a non-verbal IQ test and a general processing speed task, were added as control tasks for ruling out the possible confounding explanations in the current experiment.

## 2.3 Experiment 2

In experiment 1, I found a correlation between reaction time of audiovisual matching task and mathematical performance as Sasanguie and Reynvoet (2014) indicated. However, I also revealed a distance effect that was different from their results. In addition, the distance effect was correlated with mathematical performance. In the present experiment, I want to replicate these findings. At the same time, (1) observe the distance effect with a closer time frame and (2) see if the correlation still holds when the processing speed and non-verbal IQ are controlled.

### 2.3.1 Method

#### *Participants*

Fifty-one native English-speaking students of the University of York (41 female; age range: 18 – 30; mean age = 19.84 years, *SD* = 1.83 years) participated for either monetary compensation (£6) or 1-hour course credit. The study received ethical approval from the Department of Psychology Ethics committee. All participants gave written informed consent.

#### *Stimuli and procedure*

All participants completed four tasks. The sequences of first two tasks were fixed: Single digit-number word matching task was followed by a General processing speed task. Then half of participants (n = 25) took the Math Computation subtest of WRAT-4 first, then the Matrix Reasoning subtest of Wechsler Abbreviated Scale of Intelligence - Second Edition (WASI-II; Wechsler, 2011). The other half (n = 26) took the reasoning test first then the mathematical test. The first two tasks were conducted by a PC with WINDOWS 7 operation system. Participants sat on an adjustable chair around 40 cm in front of an 18.3-inch screen. The overall tasks took around 50 minutes to an hour to complete.

1. *Single digit-number word matching task*

The same procedure and paradigm as Experiment 1 was used, but in the current experiment, stimuli presentation and data recording were controlled by MATLAB with Psychophysics Toolbox extensions instead (Matlab Psychtoolbox-3; www.psychtoolbox.org). Nine shorter SOAs were used in the present experiment, which were -200, -150, -100, -50, 0, 50, 100, 150, and 200 ms.

2. *General processing speed task*

Participants were instructed to press the space bar as fast as possible as soon as they saw a white square displayed on a black screen. The square was 50 x 50 pixels in size and was represented in the central of screen. The square was then removed after responses and was followed by a blank screen with an inter-stimulus interval from 600 to 1400 ms. A 5-trial practice block was given before the 20-trial main block, the mean RT was measured as personal processing speed. The whole task took about a minute to complete.

3. *WRAT (Math computation subtest)*

Same as in Experiment 1 (on page 63).

4. *WASI-II (Matrix reasoning subtest)*

I used the matrix reasoning subtest The Wechsler Abbreviated Scales of Intelligence-II (Wechsler & Hsiao-pin, 2011) for measuring non-verbal IQ. A series of shapes with one missing part were displayed to participants. There were 30 questions in total. Participants had to choose a(n) shape/element that completes the pattern of shapes they saw. The experimenter tested each participant by following the test manual. There was no time-limit for this test. Testing was stopped after three consecutive errors. One point was given for each correct answer, the raw scores were then transferred to standardised T-scores based on age norms.

### 2.3.2 Results

*Digit-number word matching task:*

Two participants were excluded due to low accuracy rates (lower than 3 standard deviations of the mean). RTs smaller than 250 ms and larger than 1500 ms were excluded in further analyses (0.7% of total trials). This task was easy for the participants, not many errors were made (mean accuracy: 94.9%, *SD* = 3.0%).

A 2 (matchedness: matched and unmatched) by 9 (SOAs: -200, -150, -100, -50, 0, 50, 100, 150, and 200 ms) ANOVA with the same factors was conducted for correct RTs (*M* = 624 ms, *SD* = 80 ms). The significant main effect of matchedness ($F(1, 48) = 84.71$, $p < .001$, $\eta_p^2 = .64$) showed a higher RT for unmatched trials (*M* = 646 ms, *SD* = 76 ms) than for matched trials (*M* = 602 ms, *SD* = 86 ms). The main effect of SOAs was also significant ($F(8, 384) = 207.24$, $p <.001$, $\eta_p^2 = .81$). The data pattern showed that the RTs became longer when they were closer to 0 SOA. The post-hoc analyses showed that the comparisons between an SOA and the one next to itself were all significant (all *ps* < .05), i.e., RT of 0 SOA was the longest, and then decreased with the increase of SOA. The interaction effect between matchedness and SOAs was also significant ($F(8, 384) = 2.50$, $p = .012$, $\eta_p^2 = .05$). The interaction was due to the different patterns between matched and unmatched trials from -200 to -100 SOA conditions. This indicated a slightly steeper slope for the matched trials from -200 to -150 ms but flatter from -150 to 100 ms, whereas the pattern for unmatched trials here was reversed, flatter from -200 to -150 ms but steeper from -150 to -100 ms. (Please see Figure 2-6 for more details). The quadric trend was significant ($F(1, 48) = 4.53$, $p = .038$, $\eta_p^2 = .09$), indicating a curved data pattern with a peak in the middle.

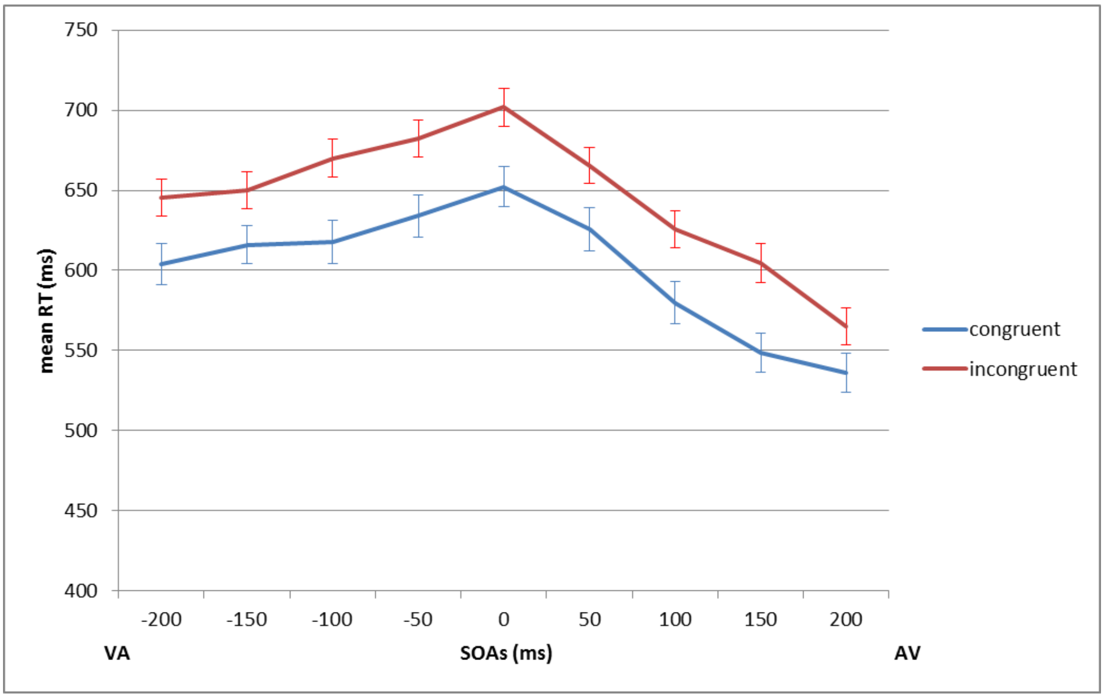


*Figure 2-6.* The RTs for the single digit-number word matching task. The RT for the simultaneous presentation (0 ms) is the longest, and the RTs become shorter with the increase of the SOA. The error bars indicate ±1 *SE*.

An one-way ANOVA of RTs by different numerical distances revealed a significant main effect of distance ($F(5, 240) = 32.57$, $p < .001$, $\eta_p^2 = .40$). The post-hoc analyses showed that except for distance 1 & 2 (p = .11) and distance 3 & 4 (p = .74), other comparisons were all significant (all *ps* < .05). The linear trend was significant as well ($F(1, 48) = 111.86$, $p < .001$, $\eta_p^2 = .70$). These results showed that the larger the distances, the shorter the RTs (Figure 2-7), indicating a classic distance effect.

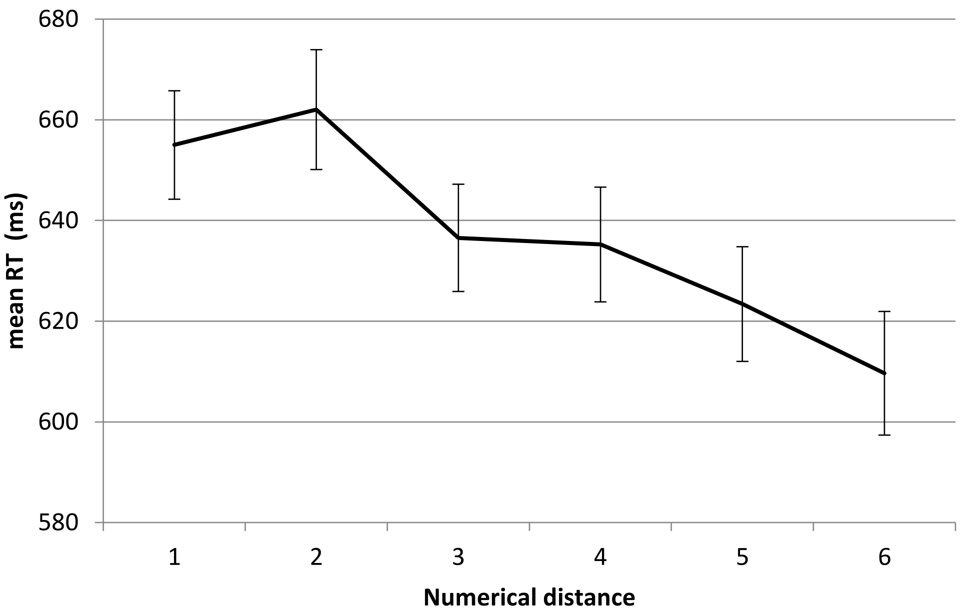


*Figure 2-7.* The numerical distance effect in the single digit-number word matching task. The error bars indicate ±1 *SE*.

The beta values for the numerical distance by SOA were calculated as the same method in experiment 1 (page 68) for each individual (*mean beta value* = -.64, *SD* = .31, range from -.96 to .30) (Figure 2-8). An one-way ANOVA of beta values by SOAs revealed a significant main effect ($F(8, 384) = 3.91$, $p <. 001$, $\eta_p^2 = .08$) (Please see the details of the post-hoc analyses in the footnote[3]). The data pattern indicated a smaller beta value when the auditory and visual stimuli

[3] Only lists the significant comparisons between an SOA and the one next to itself here: -200 & 150, -50 & 0 and 0 & 50 ms conditions.

were displayed simultaneously, and then became larger (less negative) when the SOA increased. The post-hoc analyses showed that the beta value of 0 ms SOA was significantly smaller than others (all *ps* < .05), only the NDE at 200 ms SOA was not significantly different from 0 ($t(48) = -1.48$, $p = .15$)., i.e. significant distance effect at all SOAs but not 200 ms condition. The significant quadric trend further confirmed this observation ($F(1, 48) = 14.67$, $p < .001$, $\eta_p^2 = .23$). To further investigate the possible influence of modality's order on distance effect, a 2 (modality's order: VA and AV) by 4 (SOA: 50, 100, 150, and 200 ms) ANOVA was conducted. A significant main effect found on modality's order ($F(1, 48) = 5.17$, $p = .028$, $\eta_p^2 = .10$), but not on SOA ($F(3, 144) = 2.12$, $p = .10$, $\eta_p^2 = .04$). The interaction between modality's order and the SOA was not significant either ($F(3, 144) = .54$, $p = .66$, $\eta_p^2 = .01$).

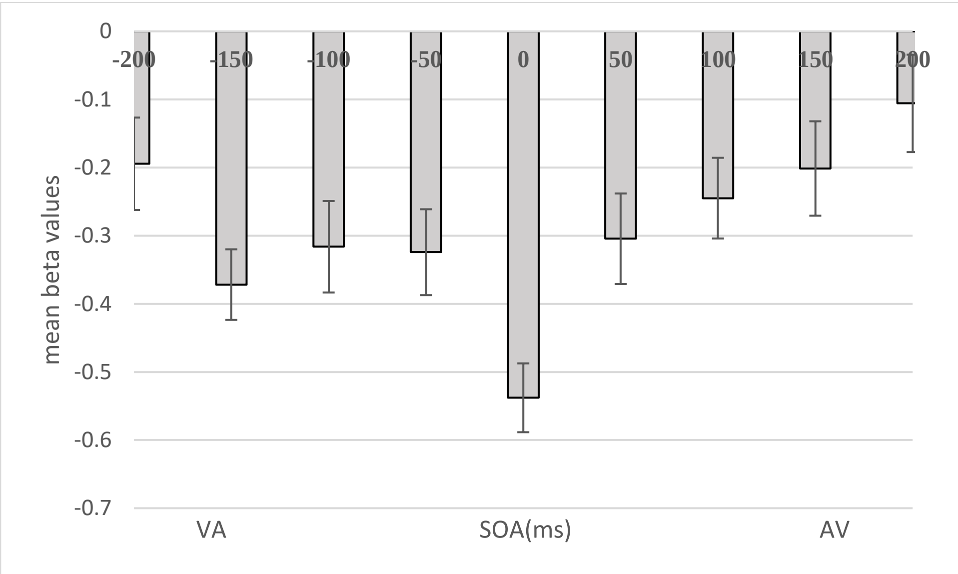


*Figure 2-8.* The mean beta values of numerical distance effect by SOA. The error bars indicate ±1 *SE*. The VA indicates that the visual stimulus (written digit) is displayed first, whereas the AV indicates that the auditory stimulus (spoke number word) is displayed before the visual digit.

The correlational analyses showed that no correlation (*r* = .05, *p* = .75) was found between WRAT standardised scores (mean = 104.76, *SD* = 11.45, range from 87 to 137) and RT of audiovisual matching task, nor between mathematical performance and distance effect (*r* = -.01, *p* = .97). No correlations either the WASI-II Matrix reasoning standardized scores (mean = 55.12, *SD* = 7.99, range from 40 to 73) and processing speed were controlled (mean RT = 270 ms, *SD* = 29 ms).

### 2.3.3 Discussion

In Experiment 2, I observed the distance effect with a better temporal resolution (shorter SOAs, from -200 to 200 ms) and added two control tasks for examining the correlation I found in experiment 1 with a stricter standard. The results showed that (1) the distance effect was found again with a very similar pattern as in Experiment 1. That was, the strongest distance effect at 0 SOA condition, and then became weaker with the increase of SOA. (2) The correlation between RT of audiovisual matching task and mathematical performance were gone in Experiment 2.

The distance effect was replicated in Experiment 2, which again suggesting that firstly, the semantic magnitude activation for spoken number words and Arabic digits are automatic.  Secondly, an amodal, abstract numerical representation exists, at least for spoken number words and Arabic digits. However, the disappearance of distance effect at VA 100 and AV 200 SOA conditions in Experiment 1 was not fully replicated in Experiment 2. Only the distance effect in AV 200 ms was not significant different from 0 in the current experiment.

Correlation analyses in the current experiment showed that, in contrast to the result of experiment 1, the negative correlation between mathematical performance and RT of audiovisual matching task disappeared in Experiment 2. The only different manipulation between Experiment 1 and 2 was the SOA. Shorter SOAs resulted in the RT of Experiment 2 to become generally higher. However, the correlation disappeared even among the repeatedly tested conditions (e.g., -200, -100, 0, 100, & 200 ms), therefore the disappearance of correlation can hardly be explained by the shorter SOA manipulations. Since Experiment 2 had more participants leading to a better power, the null correlation of Experiment 2 should be more plausible. These inconsistent correlations in two experiments indicated an unstable relation or a small effect size in between RT of audiovisual matching task and mathematical performance.

Different from the negative correlation between mathematical performance and distance effect in Experiment 1, no correlation was found between WRAT and distance effect in Experiment 2, even before the individual processing speed and the matrix reasoning ability were used as controlled variables.

## 2.4 General Discussion

The current study is the first investigating the correspondence between spoken number words and Arabic digits systematically with SOA manipulations. The distance effect was revealed in both experiments, especially the distance was stronger when the stimuli in two modalities were presented simultaneously compared with a display of an SOA. However, unlike the findings about the distance effect, the correlation between response times of audiovisual matching task and mathematical performance was less consistent.

The distance effect in the current study supports my hypothesis about automatic processing of semantic activation for both auditory and visual numerical stimuli, which is in line with most of previous empirical studies (Kouider & Dehaene, 2009; Reynvoet & Brysbaert, 2004; Reynvoet, Brysbaert, et al., 2002) and simulation results (van Opstal & Verguts, 2011). Previous researchers found that a matching task can induce the semantic activation of numerical symbols, but not for other symbols (e.g., letters) with ordinality, indicating that the matching task is an appropriate tool for investigating the magnitude representation (van Opstal et al., 2008; van Opstal & Verguts, 2011).

The distance effect found in the current study further extended this same-different paradigm from unimodal, visual stimulus only, to bimodal, audiovisual stimuli.

Furthermore, the distance effect I found also supports that an amodal, abstract representation exists among different numerical symbols (Dehaene & Akhavein, 1995; McCloskey & Macaruso, 1995). Unlike a non-abstract representation model, such as the Multiple Representation Model (D. J. Cohen et al., 2013), an abstract representation model assumes that the magnitude processing always happens when two numerals are comparing in quantities, but not due to other characteristics of stimuli, for example, the physical similarity (D. J. Cohen, 2009). The distance effect found in the current matching task indicates that participants made judgments by processing the magnitude of symbols, therefore the reaction times are modulated by numerical distances between auditory and visual stimuli.

The distance effect by SOA in two experiments both showed a clear pattern that the strongest distance effect happened when audiovisual stimuli were presented simultaneously, and became weaker with the increase of SOA. Similar results have been found in many studies investigating audiovisual integration (but not with numerical symbols) that the integration effect is modulated by SOA (e.g., Bushara, Grafman, & Hallett, 2001; Froyen, Bonte, van Atteveldt, & Blomert, 2008; Navarra et al., 2005; van Atteveldt, Formisano, Blomert, & Goebel, 2007). Two ideas can be discussed from this data pattern. Firstly, it takes time to process magnitude of numerical symbols. That is, when participants are given more time to process magnitudes, the meaning of symbols becomes more solid and specific. Therefore, it becomes easier to differentiate two numerical stimuli even when stimuli are closer semantically, which leads to a smaller distance effect. Secondly, the current result offers another way to look at the distance effect: except for semantic proximity (numerical distance) between stimuli, the distance effect can also be modulated by temporal proximity between stimuli. As a result, when investigating the distance effect, not only numerical distance should be considered (e.g., overall size effect), but also time-related setting should be also carefully set-up, such as the time between stimuli (SOA) and the duration of stimulus, because all these factors can influence the distance effect.

As far as I know, no studies have systematically investigated the timing issue of distance effect. The only studies related to stimulus duration in numerical cognition are the ones investigating the priming distance effect (e.g., Brysbaert et al., 2002; Reynvoet & Brysbaert, 2004). In these studies, the duration of primes was usually controlled subliminally, and the intervals between primes and targets were short. An opposite distance effect was often reported in these priming studies. That is, the larger the numerical distance between primes and targets, the longer the reaction time.

However, although some of the SOAs in the current study were also as short as the intervals in a priming paradigm, the experimental settings in a same-different paradigm are quite different from a priming paradigm. For example, masks are usually used in a priming task to prevent participants from perceiving primes due to sensory memory. Therefore, it is not a surprise that I found a classical distance effect, but not a priming distance effect in my experiments. Future studies can try to systematically manipulate both the SOA and the duration of stimuli, see how these time-related variables can modulate the distance effect.

Though distance effect was observed in both experiments of current study, a few studies employed a similar audiovisual matching task but found absence of distance effect (D. J. Cohen et al., 2013; Sasanguie & Reynvoet, 2014). Two main differences spotted in Sasanguie and colleagues' studies when comparing to my experiments: Firstly, only limited stimuli were used. Using only limited stimuli led to limited numerical distance groups (for example, large and small numerical distance), which made the continuous changes more difficult to be observed within different numerical distance. Secondly, duration of stimuli was relatively longer (1 second in their studies). As mentioned above, a longer duration of stimuli possibly benefits semantic representation, making the representation more specific and solid, which leads to a smaller distance effect. The setting of experiment 3 in Cohen's study was very similar to the 500 ms SOA condition (auditory-first-then-visual) in my Experiment 1. Though I still found distance effect in my 500 ms SOA condition, the effect was quite small, and was significantly smaller than the distance effect at 0 ms SOA condition. Therefore, it is quite possible that Cohen and colleagues would have found a distance effect if they used a shorter SOA in their experiment. However, I can only reasonably guess since they did not test distance effect in different SOA conditions.

The correlations between the RT of audiovisual matching task and the mathematical performance were inconsistent in two experiments. A significant negative correlation was found in experiment 1, indicating that participants who responded faster in the audiovisual matching task performed better in the mathematical standardised test. However, no correlation was found between the mean RT of digit-number word matching task and mathematical performance. As a larger subject pool and extra control tests used in Experiment 2, the null result of Experiment 2 should be more convincing than Experiment 1. An alternative explanation could be due to a small effect size. More specifically, the correlation could not be stably found in an audiovisual matching task. An evidence was that a significant correlation was found, same direction but smaller ($r$ = -.23, $p$ = .031, $N$ = 87; comparing to $r$ = -.36, $p$ = .028, $N$ = 38 in Experiment 1) if two subject groups were combined into one.

The study of Sasanguie and Reynvoet (2014) is the only one which found a similar correlation between the RT of an audiovisual matching task and mathematical performance as my first experiment. Their results were convincing that they also gave participant other matching tasks (e.g., dot-number word matching and letter-speech sound matching tasks) and control tasks (e.g., Raven IQ test and a general processing speed task). A hierarchical regression analysis showed that only the digit-number word matching task (the same audiovisual matching paradigm in the current study), but not any other matching tasks nor control tasks, significantly contributed to the variance of mathematical performance. However, the current study failed to replicate the correlation. Future studies may need to carefully dissect the RT in an audiovisual matching task so that the exact element related to individual mathematical performance in a digit-number word matching task can be well identified.

## 2.5 Conclusion

Two main findings in the current study: First, the distance effect was discovered in my both experiments. Second, by the manipulation of SOA, one can observe that the largest distance effect was found when the auditory and visual stimuli were given simultaneously, and the distance effect became smaller when the SOA increased. These results clearly indicated that: Firstly, an automatic mapping happens when the bimodal numerals are given temporally proximate to each other; secondly, an abstract representation for auditory number words and Arabic digits exists.

From the comparisons between previous studies and current experiments, I can see that the SOA manipulation does give a lot more information about distance effect in an audiovisual matching paradigm. The current study offers a new way to look at distance effect, one of the most robust effects in numerical cognition. Future studies should focus more about how time factors existing in a paradigm can affect distance effect, making us know more about the nature of numerical representation.

From the next chapter I will introduce my EEG experiments to further investigate the correspondence between spoken number words and Arabic digits without the influence of responses.

# Chapter 3 – Establishing an EEG paradigm for studying the cross-format correspondence between audiovisual numerals

## 3.1 Introduction

In the previous chapter, in two behavioural experiments a clear numerical distance effect was found in the audiovisual matching paradigm. Participants were significantly faster to respond when the numeral was numerically more distant (e.g. much larger or much smaller) from the standard than when the two numbers were closer. The distance effect can be seen as evidence that both auditory and visual numerical symbols are processed semantically: Dehaene (1992) proposed that the distance effect is caused by the amount of overlap between the representations of two numbers on a mental number line. That is, the larger distance between two numbers, the less overlap there is between the two numerical representations, leading to less noisy, faster decision making when making a same/different (i.e., matching/not-matching) judgment. In the experiments in the previous chapter I used a same-different paradigm. That meant that different from a magnitude comparison task, participants were not explicitly instructed to compare the magnitudes (van Opstal et al., 2008; van Opstal & Verguts, 2011). Hence the presence of the distance effect indicates that although not strictly necessary, the participants nevertheless processed the auditory and visual stimuli semantically, i.e. their numerical value.

Furthermore, in both experiments the distance effect was modulated by SOA. The distance effect became smaller when the SOA increased. This data pattern has been reported in previous studies on letter-sound integration that the integration effect is modulated by SOA (e.g., Froyen et al., 2008; van Atteveldt, Formisano, Blomert, et al., 2007). The results from behavioural experiments therefore suggest that perhaps the correspondence between spoken number words and Arabic digits is similar to an integration, and this correspondence interacts with numerical distance.

The distance effect has been widely reported in the literature (e.g., Dehaene, Dupoux, & Mehler, 1990; Holloway & Ansari, 2009; Mitchell, Bull, & Cleland, 2012; Moyer & Bayer, 1976; Moyer & Landauer, 1967; van Opstal & Verguts, 2011; Verguts & van Opstal, 2005) and is considered as an indicator of magnitude representation specifically for the numerical stimuli. However, the origin of the distance effect is debated. Some researchers such as Dehaene (see above) propose that the overlap of the numerical representations is reflected as the distance effect. In contrast, some other studies suggested that the origin of distance effect is possibly, at least in part, related to domain-general factors, such as cognitive loading (Cohen Kadosh, Cohen Kadosh, et al., 2007) or response preparation, difficulty and selection (Göbel et al., 2004). For example, Göbel and colleagues (2004) showed that response selection and task difficulty explained a large amount of specific IPS activation during number comparison that in previous studies had been related to the distance effect (e.g., Pinel, Piazza, Le Bihan, & Dehaene, 2004). In order to differentiate whether the distance effect is originated from the semantic magnitude representation of numerical stimuli or is generated because of the response selection, the most straightforward way is to conduct an experiment without any response requirements.

Typical behavioural measures such as RT and accuracy necessitate a response. Electroencephalography (EEG), however, is a perfect method to investigate cognitive processing in the absence of a behavioural response and any response selection demands. With measuring EEG, one can look at the event-related potentials (ERPs) to understand how the human brain reacts in response to an event, for example, a word, a beep sound, or a picture, by collecting the brain electrical signal via electrodes placed on the scalp (Luck, 2012). I therefore can compare the amplitudes and latencies of the electrical signal of the brain from certain electrodes, which can replace RTs and accuracy rates as dependent variables so that no behavioural responses are required for an ERP experiment. Furthermore, brain activities can be recorded with high temporal resolution (e.g., 1 data point per 2 ms at 500 Hz sampling rate), which is extremely beneficial for what the current study aims to investigate: the timing of the integration process. It is also possible to trace back where the original signal comes from EEG data (e.g., Scherg, 1990), however, in the current study there were no strong predictions about the source localisation of brain activities.

In the previous chapter I introduced and discussed behavioural studies investigating the correspondence between spoken number words and Arabic digits, however, so far no studies have explored this audiovisual integration for numerical stimuli by conducting an EEG/ERP experiment. To search for a design specific for integration with EEG/ERP measurements, I turned to language studies because of the proximity between Arabic digits-number words and letters-speech sounds. Several studies focusing on letter-sound integration have been carried out and provided the main inspiration for my EEG experiments. I will introduce the paradigm previous researchers used in the following paragraphs.

Froyen and colleagues (2008) conducted an EEG experiment with an appropriate design in which participants did not respond to letters or sounds. There were two conditions in their study: an auditory-only condition with sounds only and an audiovisual condition with sounds and letters simultaneously displayed. The procedure in the two conditions was similar: several standard trials were always followed by a deviant trial. They used /a/ as the standard auditory sound, and /o/ as the deviant sound. For example, a sound sequence could be /a/-/a/-/a/-/a/-/o/. More importantly, in the audiovisual condition the visual stimulus was always the same, e.g., ‘a’, no matter whether the sound had been changed from /a/ to /o/. They purposefully designed their experiment in this way, because their analyses were based on difference waves. First, they looked at the difference between standard and deviant trials. With this design, they ensured that for the difference between standard and deviant trials of the two conditions represented the same physical difference while comparing a deviant trial and a standard trial, i.e. the visual letter component ('a') was 'subtracted out' in the audiovisual condition. Now in both conditions the remaining difference between the standard and the deviant trials is only the change of sounds (from /a/ to /o/). In a second step, they then compared the difference waves between the auditory-only and the audiovisual condition. Hence, if the underlying mechanisms between auditory and audiovisual conditions were the same, when comparing the two difference waves between standard trials and deviant trials, the brain responses in the auditory-only and the audiovisual conditions should be identical, and thus there should no difference in this difference wave. However, if there are significant differences between the auditory-only and the audiovisual difference wave, then it suggests that the mechanisms underlying the processing in these two conditions differ. The authors propose that if there is a larger difference in the audiovisual difference wave than the auditory only difference wave then this might be evidence for an additional process, for example the integration between auditory and visual stimuli.

As mentioned earlier, one of the advantages of an ERP study is that it does not necessitate a behavioural response. Instead, brain responses for an event are measured. Conventionally in an ERP study, researchers would decide to look into a component in advance according to the brain mechanism of interest. Previous studies have discovered numerous components which represent different underlying mechanisms and cognitive processing (for an introduction, see Luck, 2014). This procedure is essential for ERP data analyses, especially for a conventional ANOVA (see methods for more details), because it determines the time-window in which a peak in terms of amplitude in micro volts will be detected, and hence the peak amplitude and the latency of the peak amplitude can be used for further analyses.

In the study of Froyen et al. (2008; 2009), the mismatch negativity (MMN) was the component they investigated because they proposed that it reflects the early letter-speech sound integration. The MMN usually appears between 150 to 250 ms after stimulus onset, it is therefore an early component that represents some early, automatic brain reactions to stimuli. Moreover, the MMN has been widely observed when auditory stimuli are used and it has been suggested that the size of the MMN reflects the amount of conflict between a deviant and the memory representation of standards (Näätänen et al., 2007).

Using the aforementioned design with the auditory-only and the audiovisual condition, Froyen and colleagues (2008) found that the MMN amplitudes between two conditions were different. The MMN was larger for the condition with an extra mismatch between auditory sounds and visual letters than for change only of auditory sounds. In addition, the amplitude of MMN became smaller when there was a 100 or a 200 ms SOA between auditory sounds and visual letters (visual letters came first) in comparison to a simultaneous presentation. Froyen and colleagues therefore concluded that this larger amplitude of the MMN in the audiovisual condition indicates an integration process when both spoken number word and visual letter appeared simultaneously. Furthermore, Froyen and colleagues repeated this experiment with participants with different reading abilities and found that this MMN integration effect (i.e., a larger MMN in the audiovisual than the one in the auditory-only condition) was absent in the children who just started learning to read (Froyen et al., 2009) and in dyslexic children with four years of reading experience (Froyen et al., 2011). Mittag et al. (2013) replicated this finding by applying a similar auditory oddball paradigm on normal reading and dyslexic adults. They successfully found the MMN integration effect on normal reading adults and found this MMN integration effect was absent in the adults with dyslexia. As a result, this oddball paradigm, without any relevant tasks to speech stimuli, can potentially be used as an indicator for detecting people with reading difficulties.

Given that numerical symbols are of interest to current study, in addition to the MMN I decided to also investigate components related to numerals. Some components have been reported in a task when numerals were used. The exact latency of these components can be varied, depending on the paradigm, but mostly later than the MMN. For instance, a negativity usually appears at around 400 ms after stimulus onset (N400) in a multiplication verification task (e.g., Galfano, Penolazzi, Vervaeck, Angrilli, & Umiltà, 2009; Niedeggen & Rösler, 1999; Niedeggen, Rösler, & Jost, 1999). For example, '4' and '6' were given as a multiplier and a multiplicand, then after a period of time, '21', which is an incorrect answer, appeared on the screen. The incorrect answer, '21', comparing to the correct answer, '24', induces more negative brain responses. However, in a relatively simple task, for example, a matching task (a same-different task) in which participants were only required to answer whether two digits were the same or different by pressing key buttons, the negativity emerged earlier than 300 ms post-stimulus onset (He, Luo, He, Chen, & Zhang, 2011; Hsu & Szűcs, 2011; Zhou et al., 2006). Since the latencies of these components were varied, in a more recent study, Hsu and Szücs (2011) named all these components referring to a mismatch between numerical stimuli the 'arithmetic mismatch negativity' (AMN).

As the AMN has been found in different number tasks, such as matching tasks and arithmetic verification tasks, it has been suggested that this ERP component may reflect some extent of the semantic processing of numerals. However, Hsu and Szücs purposed that it is possible that the AMN only reflects a general mismatch between stimuli, but not specific to numerical information.

In an oddball paradigm for investigating the mismatch negativity, the standard trials are usually 'matched' whereas the deviants are mismatched. In order to study whether the AMN is specific to the mismatch of numerical information or only reflects the general change of the relationship between stimuli (i.e., from matched to mismatched), Hsu and Szücs (2011) manipulated the frequency of mismatched trials. In their oddball paradigm, the mismatched trials were more frequent (66%) than the matched trials (33%). Within this setting, they found that the matched, less frequent pairs eclited a more negative wave than the mismatched, more frequent pairs in the time-window from 240 ms to 300 ms after stimulus onset. They therefore interpreted this result as the AMN only reflects a general mismatch between previous, more frequent trials and the current, less frequent trial, but not the mismatch of the numerial information between numerals. However, this interpretation is difficult to apply on those experiments in which the matched and mismatched trials were equal in number (e.g., He et al., 2011; Zhou et al., 2006). Moreover, Hsu and Szücs used an active task in which participants responded whether the visual Arabic digits were same or different in meaning. As it has been shown that the response-selection processing can largely influence the brain activities in a numerical task (e.g., Göbel et al., 2004), it is possible that the ERP component was influenced by cognitive processing when selecting the different responses for Arabic-digit pairs.

Although it remains unclear to what extent the AMN reflects the mismatch of numerical information, the AMN has been observed in a wide range of numerical tasks. Hence, except for the MMN, the current study will also examine the performance of the AMN during a passive, auditory oddball paradigm.

The current thesis aims to investigate the integration between spoken number words and Arabic digits. This is the first one investigating the integration between these two numerical symbols with an EEG/ERP design. In order to make the results of current study comparable to previous studies, I decided to follow the experimental design from Froyen et al. (2008), given that their research group carried out a series of studies about the letter-speech sound integration (e.g., Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Froyen et al., 2009, 2008; van Atteveldt, Formisano, Blomert, et al., 2007; van Atteveldt, Formisano, Goebel, & Blomert, 2007; van Atteveldt, Murray, Thut, & Schroeder, 2014; Žarić et al., 2014). Three separate ERP experiments were conducted to explore the cross-format integration between numerals with an EEG measurement. Each ERP experiment is presented in a separate chapter. The purpose of the first ERP experiment (the current chapter) was to establish the passive, auditory oddball paradigm used by Froyen and colleagues (2008, 2009) but with spoken number words and Arabic digits instead of speech sounds and letters. Although the stimuli are replaced from letters and sounds to Arabic digits and spoken number words, a similar data pattern is expected in the current study. That is, if an automatic early integration does not exist between spoken number words and Arabic digits, the MMNs of the audiovisual and the auditory-only conditions should not be significantly different from each other. In contrast, if there is an early integration, then a larger MMN should be observed in the audiovisual condition than in the auditory-only condition.

In addition to the MMN, a relatively later component, the AMN, is also explored in the current study. Since the AMN was usually reported when there is a mismatch between numerical stimuli in visual format with an active task (e.g., He et al., 2011; Niedeggen & Rösler, 1999; Zhou et al., 2006, but see Hsu & Szűcs, 2011 for an alternative explanation), it would be interesting to see if the AMN is also sensitive to passive cross-modality semantic comparison. If it is, a difference between the AMN in the auditory-only and the audiovisual condition is expected. More specifically, the AMN in the audiovisual condition should be larger than the one in the auditory-only condition, because 'more mismatches' happen in the audiovisual condition.

In addition, it has been showed that the cross-modal letter-sound integration is related to reading ability, such as dyslexic adults

(Mittag et al., 2013), dyslexic children (Froyen et al., 2011), children with only one-year reading experience do not show an integration (Froyen et al., 2009). Hence, I also include the Math Computation test of WRAT-4 to investigate whether the strength of the spoken number word-Arabic digit integration is correlated with individual differences in arithmetic abilities.

## 3.2 Method

### 3.2.1 Participants

Sixty-five adults (*M* = 22.02 years, *SD* = 4.63 years, range from 18 – 41 years; 21 males) participated either for course credit (2 hrs) or monetary compensation (£12). All participants were British, except for an Australian. All participants spoke English as their first language. The study received ethical approval from the Department of Psychology Ethics committee. All participants gave written informed consent.

### 3.2.2 Stimuli and procedure

Participants completed a computerised oddball paradigm while wearing the EEG cap and two behavioural tests after the EEG recording, the mathematical computation subtest of the Wide Range Achievement Test 4 (WRAT4, Wilkinson & Robertson, 2006) and the matrix reasoning subtest of Wechsler Abbreviated Scale of Intelligence (WASI-II, Wechsler & Hsiao-pin, 2011). Including the setup of EEG, the whole experiment took around 2 hours to complete.

The computerized oddball paradigm had two conditions: an auditory and an audiovisual condition (Figure 3-1). Both the auditory and the audiovisual condition had 4 blocks with 544 trials each: 400 standard trials, 96 deviant trials, and 48 pictures trials. The ratio between standard and deviant trials were therefore close to 8:2, which had been widely used in previous research for the MMN investigation (Näätänen et al., 2007). The appearance of picture trials was randomly assigned as roughly once every eleven trials. Picture trials were designed for making sure that the participants were concentrated and looking at the screen. Participants were instructed to categorise these pictures in landscape or animal category by pressing 'F' or 'J' on keyboard when they saw one. The pictures lasted until participants made a response.

The natural speech sounds, /four/ (duration: 456 ms), /six/ (444 ms) and /eight/ (451 ms) were used as auditory stimuli, and the Arabic digits '4', '6', and '8' as visual stimuli. The sound stimuli were the same stimuli used in the previous behavioural experiments. The sounds were displayed binaurally through loudspeakers at a volume of around 45 dB. The digits were displayed in white on a black background in the centre of a screen for 450 ms, in Arial font at letter size 50. Participants sat on a chair roughly at 60 cm distance from the screen. There were 2-6 standard trials between two deviant trials, with an average of 3.73 trials. The only difference between the auditory and the audiovisual condition was that in the audiovisual condition, in addition to the speech sounds, the visual Arabic digits (always the standard) were displayed simultaneously with the speech sounds. For each participant, the numerals for the deviant or the standard were the same. Inter-trial intervals were randomly assigned from 1 to 1.6 seconds with the average ISI of around 1.3 s.

In order to avoid that the ERP results could be explained by the specific numerical stimuli I used, participants were assigned[4] into four groups in which different standard and deviant numbers were used. In group one, /four/ was presented as standard speech sound and /six/ was the deviant sound; whereas in group two, /six/ was the standard sound and /four/ was the deviant sound. In group three, /six/ was presented as standard speech sound and /eight/ was the

[4] The original plan was only used 6 and 8 as stimuli, thus only two groups, 6 and 8 as standards and deviants respectively in the two groups. After recruited 32 participants with random assignment, in order to generalise the current study to other numerals, I decided to collect one more group which used 4 as standards and 6 as deviants. Then I realised that it would be even better to include one last group in which 6 were standards and 4 as deviants. Therefore, only the first half participants (n = 32, group 1 and group2) were assigned randomly.

deviant sound; whereas the opposite, /eight/ as standards and /six/ as deviants for group four. Despite varying the numbers, in this experiment the numerical distance between standard and deviant was kept constant (at 2).

The task of interest, the oddball task, was purposely designed as a passive task without any response requirement relevant to numerals. Picture trials were inserted and required a response, they were introduced to make sure participants were attending the screen, i.e., keeping their eyes open. The overall accuracies for picture trials were close to ceiling across conditions (audiovisual condition: $M = .98$, $SD = .02$; auditory condition: $M = .97$, $SD = .04$; visual condition: $M = .97$, $SD = .09$).

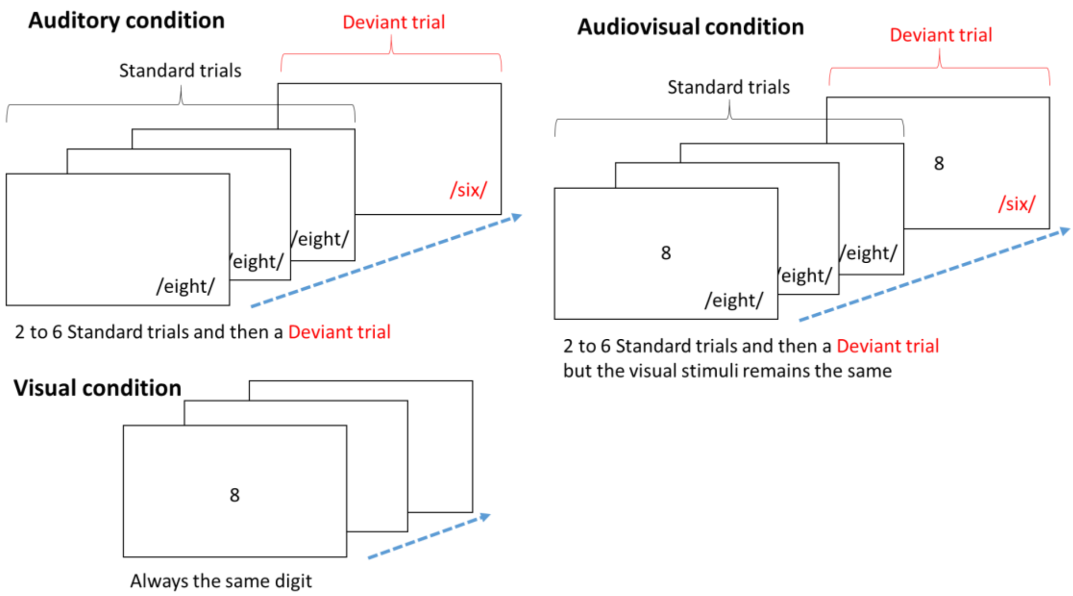


*Figure 3-1.* Experimental procedure for the computerized oddball paradigm.

The WRAT-4 math computation subtest (Wilkinson & Robertson, 2006) is the same test used in Chapter 2. Participants were asked to solve arithmetic questions from simple to more difficult questions in 15 minutes with pencil and paper. The standardised score of each participant was calculated from the raw score based on age norms.

WASI-II matrix reasoning test (Wechsler, 2011) is the same test used in Chapter 2. The matrix reasoning subtest is for measuring non-verbal intelligence. There was no time-limit for this test. Testing was stopped if participants made three consecutive errors. One point was given for each correct answer, the raw scores for each individual were then transferred to standardised T-scores based on age.

### 3.2.3 EEG acquisition

EEG waveforms were recorded with 32 Ag-AgCl electrodes in a Waveguard cap (ANTNeuro, The Netherlands). Data were acquired using ASAlab (AntNeuro, The Netherlands) and amplified by an ANT-Neuro amplifier with active shielding. All electrode impedance levels were kept below 5 kΩ. The sampling rate was at 500 Hz. Stimulus-dependent triggers were sent from the VIEWPixx device to the EEG amplifier by using a 25-pin parallel port. Eye-movements and blinks were measured with bipolar VEOG/HEOG channels. Participants were told to reduce eye movements and body movements while the EEG experiment was ongoing.

### 3.2.4 EEG pre-processing

The EEG data was analysed with BrainVision Analyzer 2 (Brain Products GmbH, Gilching, Germany). The data was bandpass filtered between 0.01 – 30 Hz off-line and was re-referenced with the average of mastoids. Epochs were defined from -200 to 600 ms relative to the stimulus onset, using the 200 ms pre-stimulus for baseline correction. Epochs containing voltage deviations exceeding +/- 100 µV at any of the recording electrodes were rejected. After artefact rejection, all epochs for each condition separately were averaged for each individual (remaining trials: *M* = 74%, *SD* = 16%). Twelve participants were excluded because they had less than 30 trials in at least one of the conditions (Luck, 2005). As a result, data from 50 participants were used in further analyses (*M* = 21.93 years, *SD* = 4.58 years, range from 18 – 41 years; 20 males; number of subjects for group 1 to 4 with different standards and deviants: 13, 13, 11, and 13). Averaged EEG responses were produced for each participant according to conditions and trial types. Namely, the average waves were auditory standard, auditory deviant, audiovisual standard, audiovisual deviant.

Since the numbers of standard (total N = 400) and deviant trials (total N = 96) was not equal in the design, only 96 of standard trials were randomly selected for data analyses. In addition, once the 96 standard trials were decided, the same 96 standard trials were chosen for each individual. The standards which were the first three trials of a block or followed immediately after a deviant or a picture were excluded from this selection.

### *3.2.5 ERP analysis*

The current study aimed to test whether there was a difference between the amplitude of the MMN in the auditory versus the audiovisual condition. The subtraction design (Figure 3-1) ensured that any brain activity related to the presentation of the Arabic digit in the audiovisual condition should be subtracted out when calculating the difference between standard and deviant trials. Thus, as a consequence for both the auditory and the audiovisual MMN, any remaining brain responses should only reflect the change of speech sounds. If there were any differences, the most plausible reason would be that the incongruity between the presented Arabic digit and the spoken number word automatically modulated the MMN in the audiovisual condition. This therefore could be interpreted as an evidence of the early integration between these Arabic digits and spoken number words.

To calculate the mismatch-negativity (MMN), I followed the procedure used by Froyen et al. (2008). Firstly, the difference wave between standard and deviant trials was calculated for each participant and each condition separately (brain waveform of deviant trials was subtracted from standard trials, i.e., standard - deviant). Secondly, the most positive peak was detected in each difference wave in a time-window from 50 to 250 ms after stimulus onset using the peak detection procedure in BrainVision analyzer. Instead of using the amplitude of peak solely, I used mean peak amplitudes in the current study as suggested by Luck (2014). The mean peak amplitude was defined as the mean of a 50 ms window (+/- 25 ms) around the individual maximal peak. This was done separately for each participant in each condition and at each electrode by using BrainVision Analyzer 2.0, and the data were then extracted for further statistical tests.

In order to explore the AMN in the current oddball paradigm, the method described in Hsu and Szucs (2011) was followed: first extracting the mean amplitude between 240 and 300 ms after stimulus onset for both auditory and audiovisual conditions, then comparing whether two difference waves had different amplitudes in this time-window.

The hypotheses were not specific to a certain electrode. However, using all electrodes in a parametric analysis is tricky because of potential collinearity issues (Slinker & Glantz, 1985). I therefore decided to average over groups of electrodes and use those as factors in further parametric analyses. Thirty electrodes (except for eye electrodes and mastoids) were used and divided into 6 groups, depending on caudality (anterior & posterior) and hemisphere (left, right, and midline) (Figure 3-2). Namely, six groups were: Left Anterior (red): Fp1, F7, F3, FC5, FC1, T7; Midline Anterior (yellow): FPz, Fz, Cz; Right Anterior (orange): Fp2, F4, F8, FC2, FC6, T8; Left Posterior (purple): C3, CP5, CP1, P7, P3, O1; Midline Posterior (green): Pz, POz, Oz; Right Posterior (blue): C4, CP2, CP6, P4, P8, O2. The mean peak amplitudes of the MMN from each electrode were averaged into six electrode groups for further ANOVA analyses. Four-way ANOVA (Condition: Auditory & Audiovisual; Caudality: Anterior & Posterior; Hemisphere: Left, Right, and Midline; Stimuli group[5]: 1 to 4) was conducted for amplitudes of MMN and AMN separately[6]. All the

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[5] Group 1: 6 as standard 8 as deviant; Group 2: 8 as standard 6 as deviant; Group 3: 4 as standard 6 as deviant; Group 4: 6 as standard 4 as deviant.

[6] The same ANOVA was conducted for latencies of MMN (the AMN was obtained as the average amplitude in a certain time-window, therefore no peak latencies were acquired), however, no significant effects were found.

statistics were reported as Greenhouse-Geisser corrected (Luck, 2012), and the post-hoc comparisons were adjusted by Bonferroni correction unless stated otherwise.

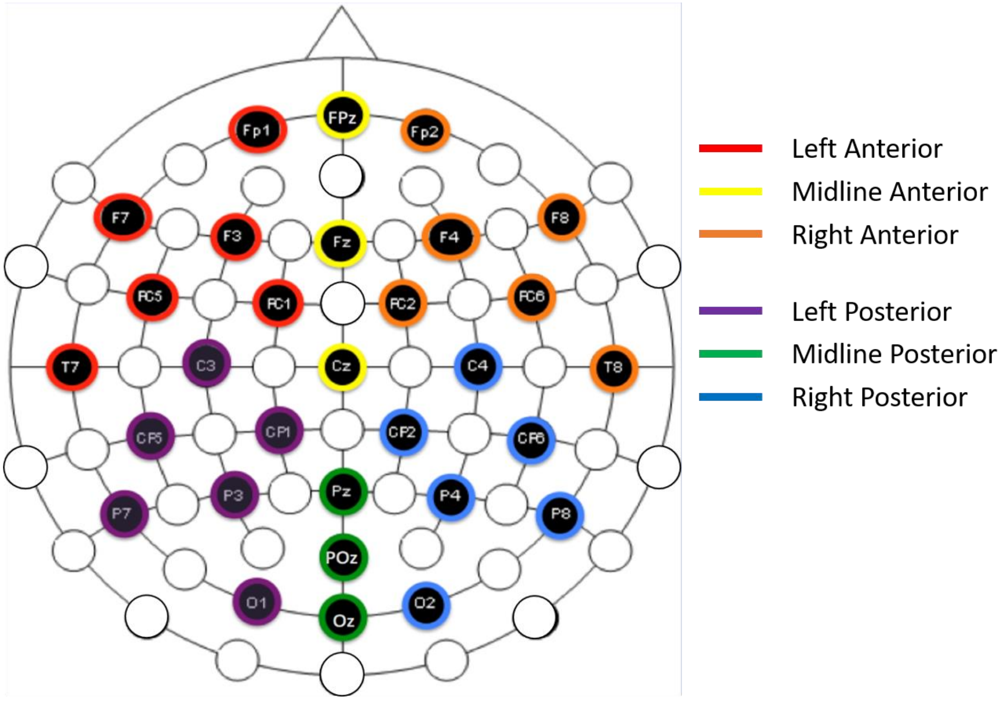


Figure 3-2. *The scalp map of 30 electrodes divided into six brain regions used in the EEG experiments.*

### *3.2.6 Non-parametric test – a permutation test*

The ANOVAs I introduced above have been commonly used in the most of previous ERP studies (Luck, 2012), however, some obvious shortcomings exist in an ANOVA when using electrophysiological data as dependent variable. In fact, most assumptions of an ANOVA, such as normality, homogeneity of variance and homogeneity of covariance are often violated in most of ERP studies (though these violations are manageable, see Luck, 2014). As a result, I also conducted a non-parametric test, a permutation test, as a complimentary analysis in the current study.

A permutation test is a statistical test which examines whether the observed data could be from the same probability distribution by comparing the observed data with the distribution generated from repetitive rearrangements of the labels on the observed data, that is, permutation (Galán, Biscay, Rodríguez, Pérez-Abalo, & Rodríguez, 1997; Maris & Oostenveld, 2007). Hence, unlike an ANOVA, a non-parametric test makes no assumptions about the data probability distribution. I will explain the permutation test, and why the permutation test nowadays is often considered a better method than an ANOVA for analysing EEG/ERP data in the following paragraphs.

Three disadvantages of ANOVAs were pointed out in a previous study (Groppe, Urbach, & Kutas, 2011): First, an ANOVA can only reveal the difference in a selected time-window. For example, the time-windows I examined in the current study for the MMN and the AMN in the ANOVAs were from 50 to 250 ms and 240 to 300 ms after stimulus onset respectively. However, a component cannot be found if it appeared outside of these time-windows. Some interesting EEG responses might therefore be ignored. Second, the time-windows for components have to be decided prior to conducting an ANOVA, but the latency of a component sometimes varies due to the paradigm (e.g., Fein & Turetsky, 1989), making this process fairly difficult. Third, an ANOVA cannot identify exactly which electrode(s) (unless the electrodes were not grouped) show a significant effect and exactly when an effect occurs (it can only reveal an effect within a given time-window).

The aforementioned problems do not exist in a permutation test. A permutation test offers precise temporal (the resolution depending on the sampling rate) and spatial information for a significant effect. Take the current study as an example, the result of a permutation test could show that the MMN amplitude in audiovisual condition becomes significantly more negative than auditory-only condition from 250 ms after stimulus onset, starting at CP1, CP2, C3, P3 and CPz electrodes.

Below are the basic procedures for the non-parametric test (Maris & Oostenveld, 2007), I will explain these procedures by taking the current study as an example:

1. For each time point (e.g., 100 ms after stimulus onset), each electrode (e.g., Cz), and each participant, there were two values within a participant, one was from the auditory-only condition, and the other one was from the audiovisual condition. Therefore, since fifty participants were included in the data analyses, there were 50 values in each condition, and the values were pair-wised.

2. Pretend that there were no different conditions, randomly draw one of the pair-wised values from each participant to form a new set. The remaining data becomes another set.

3. Conduct a test statistic (e.g., a *t*-test) between these two sets.

4. Repeat the procedure above for many times (e.g., 2500 times in the current study). Construct a histogram for the statistical results. The distribution acquired from this procedure is called a permutation distribution.

5. Compare the statistical result of the actually observed data set, i.e., the original data that has not been randomly selected, calculate how many of the *t*-scores of randomly selected permutations are equal to or smaller than the *t*-score of observed data set. This number is the *p*-value of the non-parametric test. For example, if the observed *t*- score is 99% larger than the t scores from permutations, then the *p*-value is 2% for a two-tailed test (Groppe et al., 2011).

A permutation test is based on the insight of exchangeability. That is, if data from different conditions are actually from the same probability distribution, then the data from two conditions should be 'exchangeable', which means that it makes no difference if one of two (or more) data points are randomly exchanged within a subject. The distribution of *t*-scores can be generated from permutations. The relative location of the observed *t*-scores on the distribution therefore can be used to decide whether the null hypothesis, that these data points from different conditions are exchangeable, should be accepted.

If it should not be accepted, it means that they are likely from different distributions, i.e. significantly different from each other.

The cluster-based permutation test was chosen in the current study because of its high sensitivity to detect more distributed components (Groppe et al., 2011; Maris & Oostenveld, 2007; for other methods of permutation test, see Groppe et al., 2011). In the cluster-based permutation test, the above-threshold *t*-scores are grouped together as clusters at adjacent time points and electrodes (i.e., a cluster is across electrodes and time points). Then the *t*-scores of each cluster are summed up to form the cluster-level *t*-score, which is called the 'mass' of the cluster (Bullmore et al., 1999). Only the most extreme *t*-score is used to derive a distribution, and the *p*-value of each cluster is derived from its ranking on the distribution. Last, each cluster *t*-score is given to all its members, it therefore shows an adjustment for multiple comparisons. That is, the *t*-score of a single time point is not from a single comparison, but from the comparisons with the whole data set. More specifically, since the *p*-values are derived from cluster-level comparisons, the cluster *p*-value may not represent any members within the cluster. Therefore, there is an uncertainty about whether the effect exists in a single time point within a cluster. For example, if the *p*-value of a cluster is 5%, one can only be 95% sure that some effects appear in that cluster, but not 95% confident that any single time point in that cluster is significant (Groppe et al., 2011).

From the description above, one can expect that the cluster-based permutation test gives a weak control of family-wise error rate (Groppe et al., 2011; Maris & Oostenveld, 2007). The concept about a 'strong' and a 'weak control' were commonly introduced in fMRI studies (e.g., Holmes, Blair, Watson, & Ford, 1996). According to Maris and Oostenveld (2007), a strong control refers to a voxel-specific null hypothesis, that is, for a given voxel, there is no difference across experimental conditions. On the other hand, a weak control refers to no difference between the experimental conditions for none of the voxels. They have also pointed out that a weak control of false alarm rate is better for an EEG study because it has a larger power for detecting an effect than a strong control. Meanwhile the brain signals are correlated among electrodes (the signals from source project to all electrodes in some degree), especially when electrodes are close to each other. In addition, with respect to temporal resolution, usually an ERP component lasts for a couple of tens, sometimes hundreds of milliseconds. Therefore, it is not very beneficial to lose the power for applying a strong control on EEG/ERP data. A cluster-based permutation test with a weak control is therefore recommended for EEG data sets (but see Groppe et al., 2011 for further instructions) and was used in the current study.

Although I have explained the advantages of a permutation test compared to a conventional ANOVA, most previous ERP studies employed ANOVAs only. This makes comparisons between current results and previous findings difficult if I only conduct permutation tests. Therefore, both ANOVAs and non-parametric tests were performed and are presented in the current study.

### *3.2.7 The setting of cluster-based permutation test used in the current study*

The 'Mass Univariate ERP Toolbox' (Groppe et al., 2011) was used within MATLAB for conducting the cluster-based permutation test for the brain responses. As indicated in the previous sections, the main interest of the current design was to test the difference between difference waves of auditory-only and audiovisual conditions. Two difference waves were therefore submitted to a repeated measures, two-tailed cluster-based permutation test based on the cluster mass statistic (Bullmore et al., 1999) using a family-wise alpha level of .05. The most extreme cluster mass in all sets of tests was recorded and used to estimate the distribution of the null hypothesis (i.e., no difference between conditions[7]). The permutation cluster mass percentile ranking of each cluster from the observed data was used to derive its *p*-value[8]. The time points from 100 to 550 ms at 30 scalp electrodes were included in the test, which made 6,780 comparisons in total[9].

### 3.2.8 Correlation analysis

Correlation analyses were conducted in order to investigate the relationship between brain responses of integration between spoken number words and Arabic digits. Three stages of correlation analyses were performed in which different types of brain responses were used.

First of all, the correlation between amplitudes of components (auditory-only MMN, audiovisual MMN, auditory-only AMN, & audiovisual AMN) and WRAT standardised scores were examined respectively by electrode group[10].

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[7] More specifically, the null hypothesis of the permutation test is that positive differences between conditions could have just as likely been negative differences and vice-versa. Thus, the distribution of the null hypothesis is symmetric around a difference of 0.

[8] The p-value of the cluster was assigned to each member of the cluster and t-scores that were not included in a cluster were given a p value of 1.

[9] It is worth noting that a few free parameters in the cluster-based permutation test were set following the suggestion of the toolbox. First of all, the electrodes within 5.44 cm were its neighbours, which means on average, 3.3 neighbours for each electrode (when the circumference of head size was 56 cm). Secondly, only the t-scores corresponding to p-values of .05 or less constructed the clusters. Any setting of p-value higher than .05 could possibly lead to mistakenly significant results (i.e., type I error). Last, the permutation was set to 2,500 times, which was over twice than suggested as minimum by previous research for family-wise alpha level of < .05 (Manly, 1997).

[10] There were six electrode groups, thus generating six Pearson coefficients for each component (MMN & AMN) in each condition (auditory-only or audiovisual).

In the second correlation analysis, instead of using auditory-only and audiovisual mismatch brain responses, a single value was calculated and used, that was, the amplitude of the auditory mismatch component (e.g., auditory-only MMN) was subtracted from the amplitude of the audiovisual mismatch component (e.g., audiovisual MMN). The correlation between this single value and individual mathematical ability was investigated. The reason to calculate the difference between audiovisual and auditory-only condition was: the audiovisual mismatch component contained two mismatch components, one was the mismatch between current and previous sounds, which was exactly the same as the one in the auditory-only condition, and the other one was the mismatch between the auditory sound and the visual digit. Therefore, by using this subtraction method, the later mismatch element, which likely corresponded the specific relationship (i.e., integration) between auditory and visual stimuli, could be isolated from the audiovisual mismatch brain responses. A similar method was used in the previous study investigating the relationship between the cross-modal integration of speech stimuli and reading abilities (Froyen et al., 2011).

The last one was a partial correlation analysis. The same single value was used with the standardised matrix reasoning score as a control variable. This was in order to observe whether the correlation between the single value of brain responses and mathematical ability could be explained by non-verbal IQ ability. If so, the significant correlation would disappear in this partial correlation analysis, otherwise the correlation should remain.

## 3.3 Results

At first, visual inspection of the data pattern of standard and deviant trials, showed similarities across conditions especially in the anterior sites (see Figure 3-3, upper panel). First of all, a clear negative deflection presents between 100 and 180 ms post-stimulus onset across most sites. Following this, the EEG responses rebound to a positive peak at around 200 to 250 ms. The brain waveforms go down again and produce another negative peak between 400 and 450 ms post-stimulus onset. Finally, the EEG responses are increasing in amplitude towards the end of the epoch. The similar difference waves for the auditory and the audiovisual condition also confirms this observation, and this pattern continues to the end of the epoch (Figure 3-4, upper panel).

The brain waveforms in the posterior sites (see Figure 3-3, lower panel) have a similar pattern of ups and downs as in the anterior sites, but the positive peak at around 200 – 250 ms is much larger than the one in the anterior sites. In addition, the audiovisual EEG difference waves start to be more negative than the auditory-only EEG difference waves at around 250 ms (Figure 3-4, upper panel).

Next, I will present the results of statistical tests.

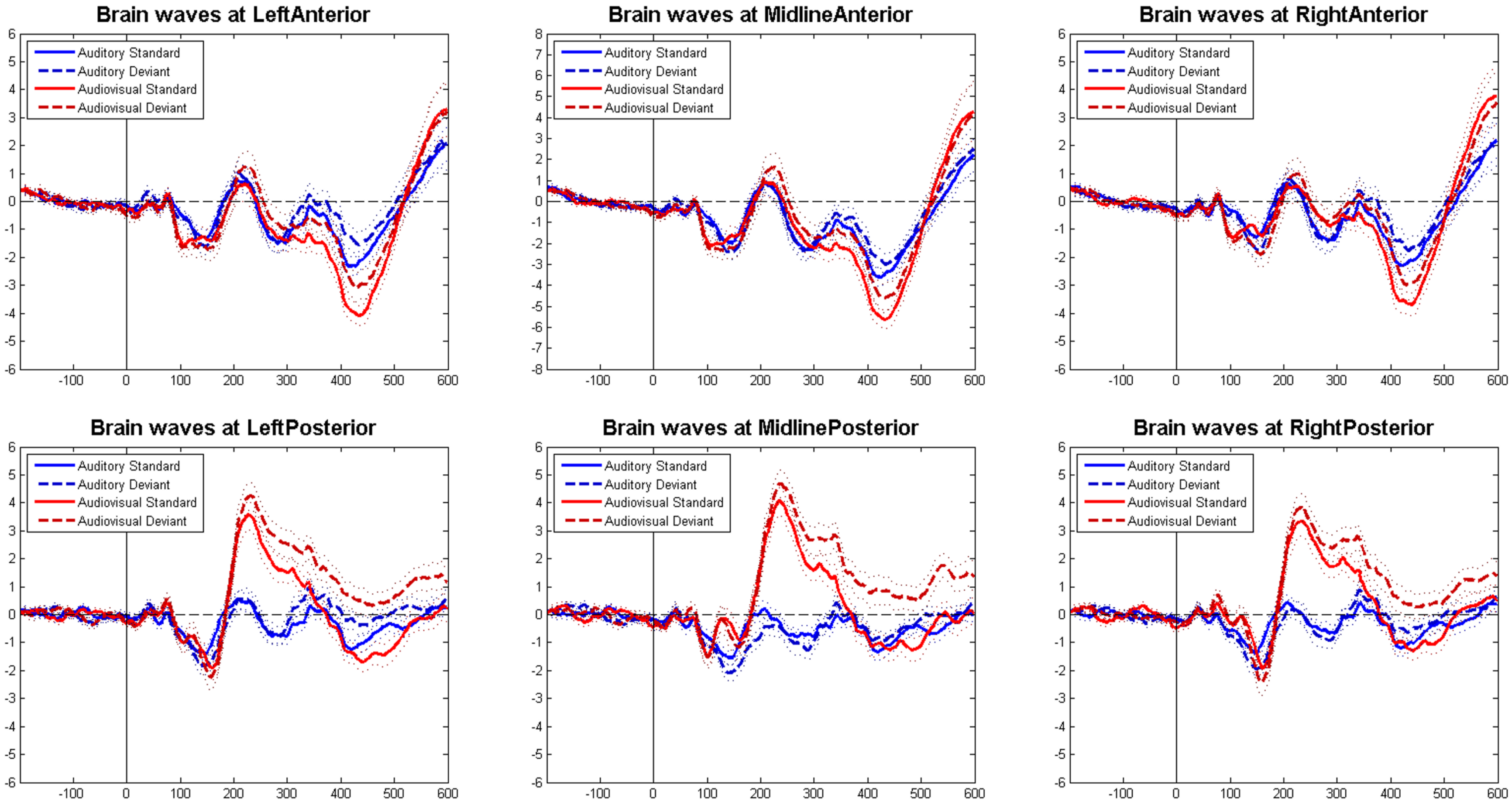


*Figure 3-3.* The averaged EEG responses of standard and deviant trials in the auditory-only & audiovisual conditions by electrode groups. The amplitudes of difference waves were acquired from standard minus deviant trials (±1 *SE*). See Figure 3-2 for the groups in detail.

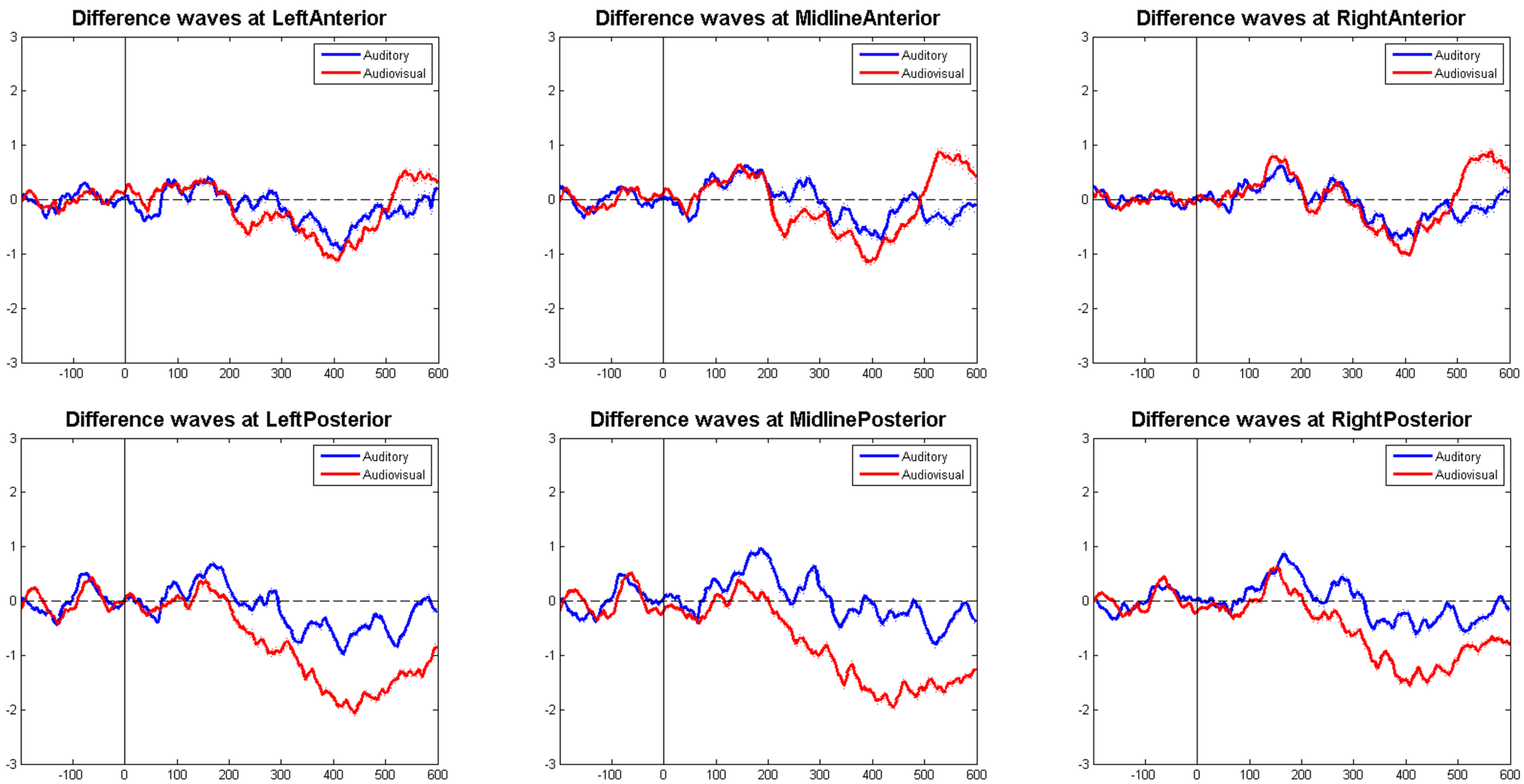


Figure 3-4. The averaged difference waves of in the auditory-only & audiovisual conditions by electrode groups (±1 *SE*). The amplitudes of difference waves were acquired from standard minus deviant trials (±1 *SE*). See Figure 3-2 for the groups in detail.

### *3.3.1 MMN*

To analyse the MMN, the difference waves must be calculated (Näätänen et al., 2007). In the current study, the averaged brain wave of deviant trials was subtracted from averaged standard trials, and then the amplitude peak was detected in the window of 50 to 250 ms after stimulus onset (same time-window was chosen in the study of Froyen et al., 2008). Because deviant stimuli were expected to induce more negative brain activity than standard stimuli, the most positive peak (but not negative) was detected. This procedure was done for both the auditory and the audiovisual condition.

Before testing for the differences between the MMN of the auditory and the audiovisual condition, I first examined whether in each condition separately there was actually a significant MMN. Twelve one sample t-tests were conducted for the mean peak amplitudes of each electrode group in both auditory and audiovisual conditions. The results showed that the MMNs of the six electrode groups were all significantly different from zero in both auditory and audiovisual conditions (all $t(49) > 3.57$, all $p <= .001$). The *p*-values were small enough to stay significant after Bonferroni correction, i.e. a significant MMN could be detected for all six electrode groups.

Subsequently, the main interest of the current study, whether the MMN is modulated by the presence of an Arabic digit, was tested firstly by an ANOVA. Because the current study is interested in the MMN difference by condition, I will only present the main effects of ANOVA and the significant interactions related to the condition factor in the following paragraphs (see the full results report in Appendix A from page 252).

A 4-way ANOVA (condition: auditory & audiovisual; caudality: anterior & posterior; hemisphere: left, right, and midline; stimuli group[11]: 1 to 4) was conducted for the examination of the difference

[11] Group 1: 4 as standard 6 as deviant; Group 2: 6 as standard 4 as deviant; Group 3: 6 as standard 8 as deviant; Group 4: 8 as standard 6 as deviant. The reason to use more than a pair of numerals was to avoid possible alternative

in the MMN between the auditory and the audiovisual condition. Stimuli group was a between-subject factor. The results showed that the main effect of hemisphere was significant ($F$(1.9, 87.7) = 4.51, $p$ = .01, $\eta^2$ = .09), as well as stimuli group ($F$(3, 46) = 3.12, $p$ = .04, $\eta^2$ = .17), but there was no significant main effect for condition ($F$(1, 46) = 0.44, $p$ = .51, $\eta^2$ = .01), or caudality ($F$(1, 46) = 1.90, $p$ = .18, $\eta^2$ = .04). Bonferroni post-hoc comparisons indicated that the amplitude in the left electrode group ($M$ = 1.14 μv) was significant smaller than the amplitude in the midline electrode group ($M$ = 1.34 μv, $p$ = .005). There were no other significant interactions related to the condition factor (see the full report on page 252).

The main factor of interest was condition but that there was neither a significant main effect nor any significant interactions with conditions. This suggested that while in both conditions there was a significant MMN, there was no significant different in the MMNs between the auditory-only and the audiovisual condition. In addition, though some interactions between stimulus group and other electrode factors were discovered, in the current chapter I only focused on the main interest of task, whether the MMN was modulated by condition.

### 3.3.2 AMN

A similar 4-way ANOVA (Condition: Auditory & Audiovisual; Caudality: Anterior & Posterior; Hemisphere: Left, Right, and Midline; Stimuli group: 1 to 4) was then conducted for the AMN mean amplitude. Here, a significant main effect was found for condition ($F$(1, 46) = 4.80, $p$ = .034, $\eta^2$ = .09), hemisphere ($F$(1.9, 88.2) = 7.80, $p$ = .001, $\eta^2$ = .45) and stimuli group ($F$(3, 46) = 30.66, $p$ <.001, $\eta^2$ = ,67), but not for caudality ($F$(1, 46) = 1.56, $p$ = .22, $\eta^2$ = .03). The two-way interaction was found significant between condition and hemisphere ($F$(1.7, 76.6) = 5.36, $p$ = .01, $\eta^2$ = .10). Post-hoc comparisons revealed that although all amplitudes were smaller in the audiovisual condition than in the auditory condition, these differences were only significant

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explanation that the observed effect only applied to a specific pair of numerals but not generalisable to other numerals.

on left ($p$ = .03) and midline ($p$ = .007) electrodes, but not on electrodes in the right hemisphere ($p$ = .22). There were no other significant interactions related to the condition factor (for the complete result report please see Appendix A on page 252).

### 3.3.3 Cluster-based permutation test

Only one widely-distributed cluster of significant differences was revealed by the cluster-based permutation test (see Figure 3-5). The results illustrated a significance difference between auditory-only and audiovisual difference waves from 250 ms after stimulus onset at central and posterior electrodes (starting at C3, CP1, CP2, P3, & POz), then at around 300 ms, the difference only remained significant at the POz electrode, and then the difference became extensively distributed at central and posterior electrodes (C3, Cp1, Cp5, P3, P7, O1, Pz, POz, Oz, Cp2, Cp6, P4 etc., see Figure 3-2 for more details) again from late 300 ms until early 500 ms after stimulus onset. The audiovisual difference wave was always more negative than the auditory-only difference wave throughout the whole cluster.

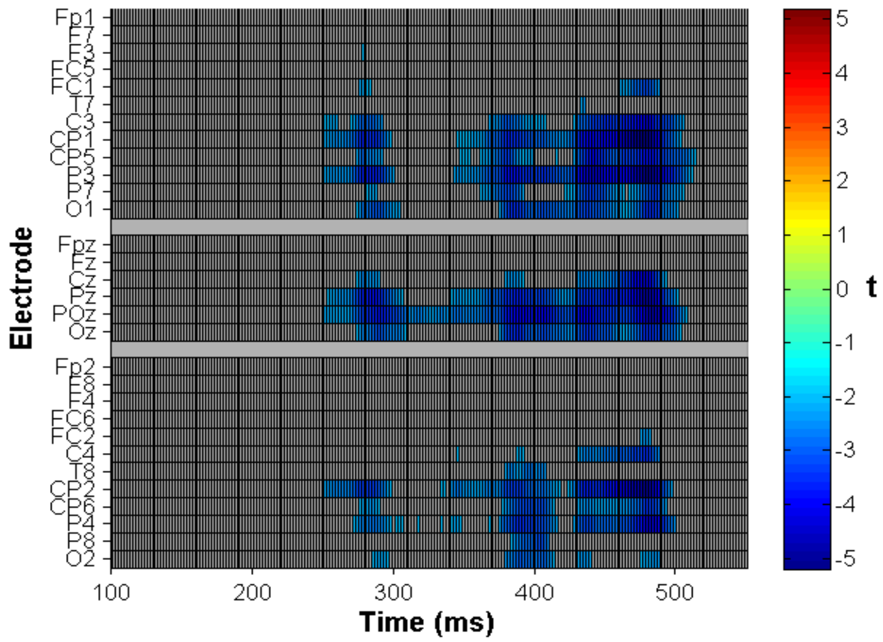


*Figure 3-5.* The result of non-parametric test when comparing difference waves of auditory-only and audiovisual condition. Only the significant *t*-scores were displayed (p < .05).

Comparing the results from the permutation test with the ones from the conventional ANOVAs, there is not much difference between these two analyses within the MMN and AMN's time-windows. More specifically, the permutation test also reported no difference between auditory-only and audiovisual conditions in the MMN's time-window (before 250 ms post-stimulus onset). Moreover, a significant effect, the amplitude of the audiovisual condition became more negative the one of auditory-only condition from 250 ms after stimulus onset, which was the same as the ANOVA found about the amplitudes within the time-window of the AMN. Interestingly, the permutation test also revealed the significant difference between two conditions after 300 ms until early 500 ms post-stimulus onset. As mentioned earlier in the method section, the conventional ANOVAs were not capable to reveal this effect because such a later effect was not expected beforehand.

### *3.3.4 Correlation between brain responses and mathematical ability*

The scores from the WRAT4 ($M$ = 104.1, $SD$ = 14.2, range from 76 to 143) and WASI-II ($M$ = 56.0, $SD$ = 8.7, range from 40 to 76) showed that participants' performance on both tests was slightly better than average for their age. To examine the relationship between individual mathematical ability and brain electrical activity, the brain responses of MMN and AMN were entered into correlation analyses with the standardised WRAT scores respectively (see Methods for details).

The results show that in the first correlational analysis, although no significant relationship was revealed neither between WRAT scores and MMN amplitude in each condition nor WRAT scores and AMN amplitude in each condition, the direction of the correlations across electrode groups were different between the auditory and audiovisual condition. That was, the MMN amplitudes of the auditory-only condition were positively correlated with WRAT scores ($r$ from .13 to .23) while the MMN amplitudes of the audiovisual condition were negatively correlated with WRAT scores (*r* from -.03 to -.20). The AMN amplitudes of the auditory condition were barely correlated with WRAT scores (*r* from -.01 to .02), whereas AMN amplitudes of audiovisual condition were negatively correlated (*r* from -.16 to -.27).

In the second correlational analysis, significant negative correlations were found for the right anterior ($r$ = -.34, $p$ = .02), anterior midline (r = -.30, $p$ = .04), and the left posterior electrode groups (r = -.31, $p$ = .03) between WRAT scores and MMN amplitude differences (Table 3-1). For the AMN amplitude differences, significant negative correlations were revealed with WRAT scores for the left anterior ($r$ = -.31, $p$ = .03), right anterior ($r$ = -.30, $p$ = .04), midline anterior ($r$ = -.31 $p$ = .03), left posterior ($r$ = -.29, $p$ = .05), and the right posterior electrode groups ($r$ = -.32, $p$ = .03) (Table 3-1). These negative correlations indicate that the more negative the amplitude difference was, i.e., the larger the difference between conditions, the better the participant performed on mathematical test. As a result, the relationship between WRAT scores and MMN amplitude difference seemed similar to the one between WRAT scores and AMN amplitude difference

To control the influence of non-verbal IQ on the correlations mentioned in the second correlational analyses, partial correlations were computed with the standardised matrix reasoning IQ score controlled. Results showed that for the MMN amplitude difference, only the correlation on right anterior electrode group remained significant ($r$ = -.29, $p$ = .04) (Table 3-1), whereas for the AMN amplitude difference, all the correlations disappeared (only marginally significant on left anterior electrode group: $r$ = -.28, $p$ = .057) (Table 3-2).

Table 3-1. *The Correlations between MMN and AMN Amplitude Difference and Standardised WRAT Score*

| Condition | Audiovisual minus Auditory-only | | | | | |
|---|---|---|---|---|---|---|
| Electrode group | Anterior | | | Posterior | | |
| | Left | Right | Midline | Left | Right | Midline |
| MMN | -.27 | -.34* | -.30* | -.31* | -.27 | -.15 |
| AMN[1] | -.31* | -.30* | -.31* | -.29* | -.32* | -.19 |

The amplitude differences were calculated as the amplitude of the audiovisual condition minus the amplitude of the auditory-only condition (N = 50). * $p < .05$.

Table 3-2. *The Partial Correlations between MMN and AMN Amplitude Difference and Standardised WRAT Score*

| Condition | Audiovisual minus Auditory-only | | | | | |
|---|---|---|---|---|---|---|
| Electrode group | Anterior | | | Posterior | | |
| | Left | Right | Midline | Left | Right | Midline |
| MMN | -.19 | -.29* | -.23 | -.18 | -.16 | -.03 |
| AMN[1] | -.28 | -.24 | -.21 | -.16 | -.18 | -.06 |

The amplitude differences were calculated as the amplitude of the audiovisual condition minus the amplitude of the auditory-only condition (N = 50). The values in the table are the partial correlations whilst controlling for standardised matrix reasoning IQ scores. * $p < .05$.

## 3.4 Discussion

To investigate the automatic integration between spoken number words and Arabic digits, in the current study I used a passive oddball paradigm in which participants were not required to respond to numerical stimuli. Firstly, in an early time-window (50 to 250 ms after stimulus onset), a significant MMN was found in both the auditory-only and the audiovisual condition. However, there was no significant difference between the MMN amplitudes in these two conditions. Secondly, in a later time-window (240 to 300 ms after stimulus onset), audiovisual stimuli elicited on average a significantly more negative amplitude than auditory-only stimuli did.

### *3.4.1 Modulation of MMN*

First of all, significant MMNs were revealed in both the auditory-only and the audiovisual condition. The MMN was robustly found in an auditory oddball paradigm (Näätänen et al., 2007), thus the existence of MMN in both conditions indicated a proper manipulation of the ratio between standard and deviant trials. This makes it clear, that while the current study failed to find a significant modulation of the MMN by condition, this was not due to not being able to elicits MMNs. Significant MMNs were present in both conditions, so the MMNs were induced successfully. In addition, the strongest MMN was found in the anterior midline electrodes (Fpz, Fz, & Cz), which is in line with previous findings (Luck, 2014). The MMN usually represents a conflict between current perceived deviant and the repetitive standards in the last few seconds (Näätänen et al., 2007). This therefore indicates that in both the auditory-only and the audiovisual condition, despite not having to perform a task, participants successfully formed a representation of the standards and detected a deviation.

However, the current study failed to find a significant difference between the auditory-only and audiovisual condition in terms of the peak amplitude of the MMN. This finding is in contrast to the results of previous studies investigating audiovisual integration between letters and letter-sounds (Froyen et al., 2008; Mittag et al., 2013). Froyen et al. (2008) found a significantly larger MMN in the audiovisual condition than in the auditory-only condition. More specifically, a deviant trial in the audiovisual condition (‘a’ letter with /o/ sound) caused significantly larger negative EEG responses than a standard trial (‘a’ letter with /a/ sound), thus leading to a larger MMN than in the auditory-only condition. In the current study, the results from the cluster-based permutation test confirmed the null effect between auditory-only and audiovisual difference wave in the time-window for the MMN (before 250 ms post-stimulus onset, see Figure 3-5)

Following the argument that a larger MMN for audiovisual stimuli suggests the occurrence of integration progress (Froyen et al., 2008; Mittag et al., 2013; Žarić et al., 2014), the current study has found no evidence for an early integration between spoken number words and Arabic digits. Thus, this study suggests that the relationship between these two kinds of numerical stimuli might not be the same as the one between letters and speech sounds shown in the previous research (e.g., Froyen et al., 2008).

### *3.4.2 Modulation of AMN*

First of all, it is worth noting again that the integration between spoken number words and Arabic digits has never been investigated under a passive, auditory oddball paradigm with an EEG/ERP experiment. Previous research investigating numerical cognition with EEG/ERP has used mostly visual numerical stimuli, and therefore only compared the brain responses between visually matched and non-matched trials (e.g., Hsu & Szücs, 2011; Kiefer & Dehaene, 1997; Zhou et al., 2006). This meant that: firstly, I can only compare the AMN within a condition, but not directly the AMN difference between two conditions, with previous findings. More importantly, different brain responses are expected because the current study employed auditory and audiovisual stimuli under a passive oddball paradigm.

The ANOVA of AMN amplitudes (mean amplitudes between 240 to 300 ms after stimulus onset) revealed a significant difference between auditory-only and audiovisual conditions. The cluster-based permutation test also revealed the same effect from 250 ms after stimulus onset (see Figure 3-5). Froyen et al. (2008), in their study of letter-sound integration, only investigated brain differences in a time-window from 50 to 250 ms, so I cannot compare my results for this later time-window to theirs.

The time-window for the AMN analysis was chosen based on the study of Hsu and Szücs (2011). They manipulated the regular setting of an oddball paradigm, making the occurrence of matching pairs of digits less frequent than the occurrence of non-matching pairs of digits (the ratio was 1:2). They found that the matching, less frequent pairs elicited a more negative wave than the non-matching, more frequent pairs in this time-window. In contrast, a reversed result was found in the current study. That was, in both the auditory-only and the audiovisual conditions, the less frequent pairs (deviants, i.e., non-matching) induced a more positive EEG response than the more frequent pairs (standards, i.e., matching) did within the AMN's time-window. This result may thus suggest that the AMN reflects only whether the numerical values were matching or not (more negative for matching and more postive for non-matching), but the AMN may not reflect the frequencies of trials. However, this finding is contradicted by most studies investigating numerical representation using visual digits (e.g., Niedeggen et al., 1999; Zhou et al., 2006) in which usually a more negative brain response was reported when the stimuli were not matched. As auditory number words have never been investigated in a matching (same-different) task with an EEG/ERP measurement, a replication is therefore needed for a further exploration to whether this reversed effect was due to an auditory number word.

Considering the finding that the AMN in the audiovisual condition was more negative than the one in the auditory-only condition, there are at least two possible explanations: First, the AMN found in the current study could have been a late MMN (Korpilahti, Salmela, Lang, Pörn, & Krause, 1997). For example, it has been shown that the MMN can be rather late with words, to around 450 ms after stimulus onset, compared to speech sounds (Korpilahti, Krause, Holopainen, & Lang, 2001). However, the direction of the AMN in the current study was reversed to a common MMN, making this explanation problematic. Second, the AMN could be a signal for a magnitude process. More specifically, in the auditory condition, only the sound changed from a standard trial to a deviant trial. In contrast, in the audiovisual condition, except for the change of spoken number words, the visual digit and the spoken number word were incongruent in magnitude as well. This 'extra' incongruency in magnitude could lead to a larger semantic conflict, and this might be related to a larger AMN component in the audiovisual condition. Previous studies have widely reported a negativity around 400 ms after stimulus onset (N400) when encountering an unexpected (i.e., incongruent) word in a certain context (Henderson, Baseler, Clarke, Watson, & Snowling, 2011; Kutas & Hillyard, 1980, 1984). The N400 component has also been widely reported during an arithmetic mismatch of a multiplication verification task (Galfano et al., 2009; Niedeggen & Rösler, 1999; Niedeggen et al., 1999). Similar negativities were also observed when there was a mismatch in congruent tasks, such as matching the number of objects with spoken number words (Pinhas et al., 2014), the congruity between size and meaning of digits (Szűcs & Soltész, 2012). Although in the current study the AMN difference began from around 250 ms post-stimulus onset, which was earlier than a common N400, it can be due to a faster cognitive processing for the mismatch between an Arabic digit and a spoken number word than a calculation or the detection of an incongruent word within a context. This interpretation can therefore support the idea that a fast-correspondence exists between spoken number words and Arabic digits – though not as fast as the one between letters and sounds. Furthermore, when taking a closer look at the brain responses in a standard and a deviant trial separately, one could notice that a standard trial elicited a more negative signal than a deviant trial, which is opposite to the aforementioned studies (e.g., Galfano et al., 2009; Kutas & Hillyard, 1980). Though this result is less common, a reversed N400 effect has been reported in a semantic priming task previously (Bermeitinger, Frings, & Wentura, 2008). In this semantic priming task, a related or an unrelated category word was given as a prime. Participants were told that the target words belonged to four possible categories but some of them were misspelled, so they were required to respond whether the target word was a member of those four categories, or whether it was a misspelled word by pressing corresponding key buttons. Bermeitinger and colleagues (2008) found that the RTs were longer in the congruent trials, i.e., participants needed more time to respond when the target word belonged to the prime category. Furthermore, a reverse N400 was detected, the congruent trials induced a more positive wave while the incongruent trials elicited a more negative brain activity. In the current oddball paradigm, the standard numeral is repetitively displayed, thus it may somewhat similar to a priming task as the representation of the standard number is also 'primed' before a deviant trial. This may thus lead to a reverse N400, but not a common N400, in the current oddball paradigm for the semantic mismatch between visual digits and auditory number words.

### *3.4.3 Correlation between brain activities and mathematical ability*

Another purpose of the current study was to explore the relationship between the spoken number word-Arabic digit integration and individual mathematical ability. This was inspired by previous studies investigating letter-speech sounds integration which have demonstrated a close relationship between letter-sound integration and reading ability (Froyen et al., 2009, 2008, 2011; Mittag et al., 2013). The correlation between two ERP components, the MMN and AMN, and WRAT scores were therefore analysed respectively.

#### *3.4.3.1 Correlation between MMN and mathematical ability*

First of all, neither the auditory-only MMN nor the audiovisual MMN, were significantly correlated with individual mathematical ability. Secondly, the differences of amplitudes (audiovisual minus auditory-only, i.e., MMN integration effect) were significantly negatively correlated with individual mathematical ability (*Table 3-1*). This correlation makes sense when considering the different directions of correlations between the raw MMN amplitude of each condition and mathematical ability. That is, either a larger (i.e., the more positive) raw MMN amplitude of the auditory-only condition or a smaller (i.e., the more negative) raw MMN amplitude of the audiovisual condition can generate a more negative MMN integration effect (i.e., audiovisual MMN minus auditory-only MMN). Therefore, although these correlations have different notations of correlations with mathematical performance, they all point to the same thing: the more negative the MMN integration effect is, the better the participant performs in math. Furthermore, this correlation remained significant after non-verbal IQ (standardised scores of the matrix reasoning test) was controlled (Table 3-2).

As I mentioned in earlier paragraphs, previous studies have demonstrated a close relationship between letter-speech sound integration and reading ability. That is, a larger MMN in the audiovisual condition than in the auditory-only condition was only found in adults with normal reading ability (Froyen et al., 2008; Mittag et al., 2013), but was absent on adults with dyslexia (Mittag et al., 2013) nor in children (Froyen et al., 2009). However, participants' reading ability was not measured in most of these studies, so a direct correlation between one's reading ability and letter-speech sound integration could not be examined.

Interestingly, the only research reported a correlation between the MMN integration effect (i.e., the audiovisual MMN amplitude minus the auditory-only MMN) and the performance of a reading task was conducted on dyslexic children, who did not show a significant

MMN integration effect (i.e., no significant difference between the MMN amplitude of audiovisual condition and the one of auditory-only condition) (Froyen et al., 2011). The findings of this study show certain similarities with the current correlation analyses. Firstly, an early, automatic Arabic digit-spoken number word integration was absent in the current study, on the other hand, no early, automatic integration between letters and speech sounds was found for children with dyslexia. Secondly, a negative correlation was found between the MMN integration effect (audiovisual minus auditory-only) and mathematical ability in both the current and their study. There are two possible directions to further explain the similar findings: First, people encounter less arithmetic than dialogues on a daily basis, it is therefore more difficult for people to form an automatic bond between spoken number words and Arabic digits than letters and speech sounds. This hypothesis can be examined by recruiting people with mathematical expertise, or who have much experience about dealing with numbers, and see if an early spoken number word-digits integration can be found on them. Second, since no early integration was found neither in the current study nor the study of Froyen et al. (2011), the correlations possibly only reflect some general cognitive abilities, e.g., the ability to detect the mismatch between visual and auditory stimuli, but nothing to do with an integration between stimuli of two modalities. The current study has already ruled out some impact of non-verbal intelligence and still found correlations between brain responses with mathematical ability; however, one can still argue that some other cognitive abilities, e.g., the verbal IQ, can possibly contribute to the observed correlation.

#### *3.4.3.2 Correlation between AMN and mathematical ability*

Similar to the MMN, the raw AMN amplitudes of neither the auditory-only nor the audiovisual conditions were correlated with WRAT scores, but the amplitude differences (audiovisual minus auditory-only) were negatively correlated with individual mathematical ability (Table 3-1). This significant correlation indicated that the more negative the AMN amplitude difference was, the better the participants performed in the mathematical test. However, after the non-verbal IQ score was controlled for there was no significant correlation remaining (Table 3-2).

As I discussed in the earlier section, the AMN is possibly related to the magnitude processing of numerical stimuli (e.g., Hsu & Szücs, 2012; Niedeggen et al., 1999; Zhou et al., 2006). The correlation between the AMN amplitude differences and mathematical ability therefore is an evidence which further supports this hypothesis. More specifically, assuming that the significant AMN difference between conditions is due to the 'extra' magnitude mismatch between the visual digit and the auditory number word in the audiovisual condition, people with better mathematical performance are also more sensitive, i.e., have a larger EEG response, to this extra semantic mismatch. A similar relation between the N400 amplitude and reading ability has been reported on first-grade children that the N400 is larger for the high reading-ability group than for the low reading-ability group (Coch & Holcomb, 2003). However, the current study did not manipulate the numerical distance between a standard and a deviant stimulus (the distance was always 2). Hence, the physical characteristics of different stimuli can always be an alternative explanation for the observed AMN, which means that the correlation could be due to some other cognitive abilities, such as the ability to detect a physical mismatch, but not related to mathematical ability. The disappearance of significant correlations after the non-verbal IQ was controlled might somewhat support this alternative explanation. Hence, in order to further examine the role of the AMN in the current paradigm, it is necessary to add the manipulation of distance in the following ERP experiments.

### *3.4.4 Compared with previous behavioural experiments*

Unlike in the audiovisual matching task used in the previous chapter, the participants in the current oddball paradigm were not required to make any responses to spoken number words nor Arabic digits. However, it is still interesting to compare the current finding with the results of the behavioural experiments described in the last chapter.

In the previous chapter, a negative correlation between RTs of audiovisual matching task and WRAT scores was revealed in the first behavioural experiment but not in the second experiment. As described earlier, a RT in a magnitude comparison task contains different elements, e.g., identification, comparison, and response (Dehaene, 1996), one therefore cannot know which part of the RT correlated with mathematical ability simply from the behavioural data of RTs. In contrast to the limited conclusion one can draw in a behavioural task, the current study did not involve any response selection, nor an intentional comparison as participants were instructed to only react to picture trials but not to the numerical stimuli. As a result, it is fairly certain that only processes involved in the identification of a numerical stimulus contributed to the correlation found between the brain response and the mathematical performance in the current study.

In addition, although the current study failed to find the evidence for an early integration between audiovisual numerals, the significant different AMNs between conditions suggests that the mismatch between bimodal numerals is processed in the time-window of the AMN. This finding may imply that the meaning of a numerical stimulus is processed involuntarily when the numerical symbol is identified, which will thus support the presence of an amodal, abstract magnitude representation (Dehaene, 1992; McCloskey, 1992), just like the suggestion from the results of the behavioural task in the last chapter.

## 3.5 Conclusion

In summary, the current study did not find evidence for an early automatic integration between spoken number words and Arabic digits. There was no significant difference between the MMNs in the auditory-only and audiovisual condition. However, significant differences between these two conditions emerged in a later time-window. This novel finding is probably related to semantic processing of numerical symbols and will be investigated further in the next two chapters.

As mentioned earlier, the current study is the first to use a passive oddball paradigm with auditory and audiovisual numerals, therefore the findings of the current study need to be replicated. In addition, the novel finding in the relatively later time-window was not reported between letters and speech sounds. This makes it possible that the novel finding is related to the specific characteristics of numerical stimuli, i.e. the difference between the numerical values of different numerals. However, one cannot know since the current study did not manipulate the value difference between a standard and a deviant trial (the distance was always 2).

My next aim thus is to replicate the findings of this study and to further explore the influence of numerical factors, more specifically, to manipulate the numerical distance between standard and deviant trials under a similar oddball paradigm.

# Chapter 4 – The modulation of distance on the cross-format correspondence in the passive, auditory oddball paradigm

## 4.1 Introduction

The results presented in the last chapter suggest an absence of an early integration between spoken number words and Arabic digits: the concurrent presentation of audio- and visual stimuli does not induce a larger MMN. Interestingly, the concurrent audiovisual stimuli elicited a more negative amplitude than the auditory-only stimuli during 240 to 300 ms after stimulus onset, which is the time-window for the AMN (Hsu & Szűcs, 2011). This suggests that the mismatch between the visual digit and the auditory number word is processed in the AMN. Moreover, the AMN amplitude was positively correlated with WRAT scores[12]. This may suggest that magnitude processing happen during the AMN's time-window. However, it is only an indirect inference because the distance between standard and deviant trials was not directly manipulated in the last experiment. Hence, there might be other explanation for the different EEG responses in the AMN by distance, for example, it could be only a mismatch detection, and was not related to magnitude processing. To further investigate how numerical distance affects the ERP responses in the current passive, auditory oddball paradigm with visuo-audio numerals, a direct manipulation of numerical distance was added in the current experiment.

As introduced in earlier chapters, the distance effect is a robust phenomenon: participants take longer to decide which of two numbers is larger when two numbers are close to each other in numerical distance than when two numbers are further away (e.g., Moyer &

[12] The significant correlation between the AMN amplitude at right anterior electrodes and math ability became only marginally correlated after the matrix reasoning scores were controlled ($r$ = .28, $p$ = .057).

Landauer, 1967). This is usually seen as evidence about how distinct or overlapping between numerical representations (De Smedt et al., 2009). That is, the smaller the distance between two numbers, the more difficult it is to discriminate between them. Hence, the appearance of a distance effect is usually interpreted as evidence that the meaning of the numerical stimuli is processed, i.e. that the numerical stimuli are processed at a semantic level.

The effect of symbolic distance on EEG responses has been widely investigated with various tasks and paradigms, such as a matching task (Hsu & Szűcs, 2011; Zhou et al., 2006), a magnitude comparison task (Cao et al., 2010; Dehaene, 1996; Dehaene, Naccache, et al., 1998; Jiang et al., 2010; Libertus et al., 2007; Núñez-Peña & Suárez-Pellicioni, 2014; Pinel et al., 2001; Szűcs & Csépe, 2004b, 2005b; Temple & Posner, 1998; Zhao et al., 2012), a parity judgment task (Plodowski, Swainson, Jackson, Rorden, & Jackson, 2003), a numerical Stroop paradigm in which participants were required to judge either physical or numerical size of two digits (Ben-Shalom, Berger, & Henik, 2013; Cohen Kadosh, Cohen Kadosh, et al., 2007; Pinhas et al., 2015; Szűcs & Soltész, 2007; Szűcs, Soltész, Jármi, & Csépe, 2007), a mental arithmetic task (Isabel & Luisa, 2005; Niedeggen & Rösler, 1999; Niedeggen et al., 1999; Szűcs & Csépe, 2004a, 2005a), and an adaptation paradigm (Hsu & Szűcs, 2012).

The distance effect is commonly reported in the N1-P2 transition and P2p if conducting a number comparison task with Arabic digits (e.g., Cao et al., 2010; Dehaene, 1996; Libertus et al., 2007; Temple & Posner, 1998). However, the time-windows and the ERPs showing distance effect are also largely influenced by paradigm. For example, the distance effect is shown in the negativities during 240 to 300 ms in a matching task (Hsu & Szűcs, 2011; Zhou et al., 2006), which is later than the P2 and the N1-P2 transition in the symbolic magnitude comparison task mentioned above.

So far no studies have explored the cross-format distance effect between spoken number words and Arabic digits with an ERP experiment (for behavioural experiments, see Chapter 2 and Sasanguie & Reynvoet, 2014). Furthermore, it is a surprise that very little EEG/ERP research has investigated the numerical distance effect with spoken number words considering the frequency with which we encounter the spoken number words every day.

To the best of my knowledge, only four EEG studies included spoken number words in their experimental design when looking into the numerical distance effect (Pinhas et al., 2014; Szűcs & Csépe, 2004a, 2004b, 2005b). Compared to visual digits and written number words (e.g., Cao et al., 2010; Dehaene, 1996), spoken number words induce very different EEG responses. For example, Szűcs and Csépe (2004a) designed a mental addition task in which three different stimuli were displayed sequentially in one trial. Participants were instructed to add the first and the second stimuli as fast as possible, and then decide whether the third stimuli was the correct answer when they saw it displaying on the screen. The first stimulus could be a spoken number word, a written number word, or an Arabic digit. The ERP response to the first stimulus showed a clear P1 component for both visual digits and written number words at the posterior electrodes, whereas there was no P1 in the posterior electrodes for spoken number words, instead a large N1 component was shown across all electrodes. In addition, the P2 component was less obvious for spoken number words than for visual digits at the bilateral parietal and occipital electrodes. These results suggest differences in early processing for numerical symbols in auditory compared to visual presentation.

Szűcs and Csépe (2004b) conducted another study to directly investigate the numerical distance effect in spoken number words with Hungarian participants. They asked participants to judge whether a Hungarian spoken number word was numerically larger or smaller than 5, and compared the brain responses of numerical stimuli to a letter task in which participants were instructed to classify whether an auditory Hungarian letter name was preceding or following the letter ‘e’ in the alphabet (‘e’ is the fifth letter). Only numbers 1, 4, 6, and 9, and letters a, d, f, and i were used. Both spoken number words and letter names induced a similar P2p, whereas a deviation was revealed on the N2 component at the right posterior electrodes (P8 and P10). The far-distance number words elicited a larger N2 than the close-distance number words, while the letters further from the letter ‘e’ induced a smaller N2 than the letters close to the letter ‘e’. They therefore concluded that there is a distance effect for spoken number words in the right posterior area, which is not only caused by ordinality. Szűcs and Csépe (2005b) also compared the numerical distance effect in congenitally blind participants to a gender-, age-, and education-matched group with the same Hungarian auditory number words. Both groups showed similar ERP responses, and both showed the same distance effect: number words with larger distance (distance of 4) elicited a larger N2p (at P7, P8, P9, and P10) than number words with smaller distance (distance of 1). This study shows that congenitally blind participants possess very similar numerical representation of auditory numerals to normal individuals. To summarise these two studies, a larger N2p was reported for the far-distance spoken number words in both studies. However, using the exact same stimuli and the same task in both studies, there were also inconsistent findings. For example, the distance effect on N2 in the frontal electrode (F3 and F4) was only reported in the first study (Szűcs & Csépe, 2004b), while a larger P2 in the frontal electrodes (F3, Fz, and F4) for far distance were only found in the later one (Szűcs & Csépe, 2005b). Comparing these findings for spoken number words to the research using visual digits, it is clear that the N1-P2p components reported for visual digits (e.g., Libertus et al., 2007) has not been reported in EEG experiments with spoken number words. However, both EEG studies with spoken number words originate from the same research group and there were some inconsistent results between these two studies, so any conclusions have to be preliminary. However, at least these findings showed that the N1-P2p component is not the only component which represent the semantic processing of numerical stimuli. Instead, they suggest that other components such as N2 and P2 in the frontal area, and N2 in the posterior electrodes are worthwhile to invetsigate when using auditory stimuli in a number comparison task.

A more recent ERP study with spoken number words was carried out with 3 to 5 years old children by Pinhas and colleagues (Pinhas et al., 2014). They used a passive task that required no responses during the task. In each trial, a few objects (e.g., 2 puppies) were displayed on the screen and a spoken number word was played simultaneously. The number of objects and the spoken number word could be congruent (e.g., 2 puppies and /two/) or incongruent (e.g., 6 basketballs and /three/), and the ratio between the number of objects and the spoken number word were manipulated as small (e.g., 1:2) and large (e.g., 1:6). The recruited children were only asked to attend the visual objects on the screen. The results showed that the incongruent trials elicited a significantly larger negativity than the congruent trials during 200 to 500 ms after stimulus onset and a significantly larger positivity during 700 to 1000 ms after stimulus onset in the posterior sites. More importantly, these effects were only found in children with better mathematical knowledge (i.e., in cardinal principle knowers and 3-5 knowers, but not in 1-2 knowers[13]). Furthermore, a ratio effect was only found for cardinal principle knowers. In those children, the large ratio condition elicited ERP responses with a more positive amplitude during 700 to 1000 ms than the small ratio condition.

Objects rather than numerical symbols were used in the study and this could possibly induce some very different components when compared to the studies using Arabic digits (e.g., Dehaene, 1996). However, the results clearly demonstrate the feasibility of detecting a different ERP response to mismatched audiovisual numerical stimuli

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[13] These terms are referred to as children who knows number 1 and 2 (1-2 knowers), up to 5 (3-5 knowers), and children who knows the cardinal principle within numbers. These show that children are in different developmental stages of numerical cognition.

compared to the congruent condition in a task without any response requirement. In addition, these differences in ERP responses were modulated by semantic processing and magnitude representation as they also reflected the ratio between spoken number words and the number of objects.

To summarise, previous ERP research showed that ERP responses are influenced by numerical distance. Moreover, the distance effect in ERPs are largely affected by task demand and modality.

The current study aims to explore the effect of numerical distance on cross-format integration between spoken number words and Arabic digits. Hence, two levels of the distance factor are added in the current study. Similar to the studies of Szűcs and Csépe (2004b, 2005b), spoken number words 1, 4, 6, and 9 are used. The standard number is always 5 in the current study so the distance between deviants and standards for close and far distance is 1 and 4 respectively. The MMN and the AMN are the pre-defined components for examining the integration and the distance effect according to previous studies (for the MMN: Froyen et al., 2008; for the AMN: Hsu & Szűcs, 2011). Based on the results from my last experiment, I predict no difference in MMN modulation by condition (a replication of Chapter 3). This would suggest a different relationship between spoken number words and Arabic digits from the relationship between letters and sounds. In the last chapter, a difference was found between the audiovisual AMN and the auditory-only AMN, which can be explained either by semantic numerical processing or merely mismatch detection. Hence, if magnitude processing does play a role in the current auditory oddball paradigm, the AMN differences between conditions should be influenced by distance, indicated by an interaction between condition and distance.

Due to limited research evidence on spoken number words and the correspondence between spoken number words and Arabic digits, it is difficult to precisely predict how the distance effect will be demonstrated in the current oddball paradigm with bimodal numerals. It is not clear whether a far-distance deviant will induce a larger or smaller EEG response than a close-distance deviant in the current paradigm. On the one hand, previous ERP research found a larger MMN when a deviant tone was more different from a standard tone (e.g., Sams, Paavilainen, Alho, & Näätänen, 1985). As the close-distance deviants are numerically more similar to the standards than far-distance deviants, a larger conflict should be induced for far-distance deviants. Some previous EEG studies using spoken number words in a magnitude comparison task also found a more negative EEG response for far-distance number words (Szűcs & Csépe, 2004b, 2005b). On the other hand, some other studies proposed that numbers close to each other lead to a larger overlap between representations, causing slower RTs and lower accuracy rates (e.g., Dehaene, 1992; Moyer & Landauer, 1967). In this case, close-distance deviants may induce a larger distance effect in ERPs because it is difficult to differentiate bimodal numerals when they are numerically close (e.g., Cao et al., 2010; Dehaene, 1996; Libertus et al., 2007).

There is no specific prediction about the location of the distance effect (i.e., the difference ERP responses by distance) because the distance effect was reported not only in the posterior sites but also in the anterior and frontal-central electrodes (e.g., Jiang et al., 2010; Szűcs & Csépe, 2005b; Zhou et al., 2006). The electrode groups are therefore included as factors of ANOVAs to explore the effect of distance on EEG responses in different locations on the scalp. In addition, as the current study is novel and exploratory, there is only a very limited number of previous studies to guide the choice of relevant components and time-windows for the analysis. Therefore, a non-parametric test will be employed to identify additional time-windows which show the distance effect.

The correlation between EEG responses and individual mathematical performance will also be examined. Previous behavioural studies have shown that a smaller distance effect is related to better mathematical achievement (De Smedt et al., 2009; Holloway & Ansari, 2009; Rousselle & Noël, 2007), however other studies suggest mathematical achievement is not related to the distance effect (Defever, Sasanguie, Vandewaetere, & Reynvoet, 2012; Sasanguie et al., 2012, 2013; Schneider, Grabner, & Paetsch, 2009). As controversial findings exist in the behavioural research, it would be worth to examine the relationship between mathematical performance and distance effect neurally.

## 4.2 Method

### 4.2.1 Participants

Forty-eight adults (*M* = 20.10 years, *SD* = 1.96 years, range from 18 – 30 years; 15 males) participated either for course credit (2 hrs) or monetary compensation (£12). All participants were British except a Gambian raised in the UK. All participants spoke English as their first language and were right-handed. The study received ethical approval from the Department of Psychology Ethics committee. All participants gave written informed consent. Fifteen of them also attended the previous EEG experiment in Chapter 3.

### 4.2.2 Stimuli and Procedure

The procedure of the current study was the same as for the experiment reported in Chapter 3. Participants performed a computerised oddball paradigm in a quiet room while wearing the EEG cap, and then completed two behavioural tests after the EEG recording, the math computation subtest of the WRAT-4 (Wilkinson & Robertson, 2006) and the matrix reasoning subtest of WASI-II (Wechsler & Hsiao-pin, 2011). Including the setup of the EEG cap, the whole experiment took around 2 hours to complete.

The computerised oddball paradigm used was identical to the one used in the previous experiment consisting of an auditory and an audiovisual condition. The only, but crucial change was the manipulation of the numerical distance between the standard and the deviants in the current study. In the current study, number 5 was always used as the standard (i.e., digit '5' and spoken number word /five/), while there were four auditory deviants, /one/, /four/, /six/, and /nine/ (the visual stimulus remained the same and was '5' throughout the audiovisual condition in the current study, as in the previous study there were only auditory but no visual deviants). There were two levels of numerical distance, close and far, manipulated in the current study. The deviants /four/ and /six/ accounted for the close-distance as the numerical distance between them and the standard was 1, whereas in the far distance, the deviants /one/ and /nine/ had a distance of 4 to the standard. All participants experienced the same stimuli in the same pseudorandom sequence.

The number of standard and total deviant trials was the same as in the last chapter, 400 and 96 respectively for the auditory and audiovisual condition. Each deviant was displayed 24 times (48 trials in total for each level, close and far, of distance). The same 48 picture trials as in previous experiments were used to ensure participants were attending to the task. The overall accuracies for picture trials were close to ceiling across conditions (audiovisual condition: $M = .97$, $SD = .01$; auditory condition: $M = .99$, $SD = .03$).

### 4.2.3 EEG acquisition and pre-processing

The details of EEG acquisition and pre-processing were identical to the previous experiment described in Chapter 3 (page 96 & 96). Since one of the main interest of the current task was to explore the modulation of EEG responses by numerical distance (the numerical distance between a deviant and a standard), the number of trials for the close and far distance should not be less than 30 after artefacts rejection (Luck, 2005). This is a stricter criterion for excluding a participant in the current experiment than in the last experiment because of the close-far distance conditions (with only 48 trials for each sub-condition). Following this criterion, 36 of 50 participants were entered into further data analyses ($M = 20.06$ years, *SD* = 1.29 years, range from 18 – 24 years; remaining trials: *M* = 86%, *SD* = 8%).

Just like the design of the experiment in Chapter 3, the numbers of standard (total N = 400) and deviant trials (total *N* = 96) were unequal. Hence, when comparing the brain responses between standard and overall deviant trials (a combination of deviants in a small and a far distance to a standard), only 96 of the 400 standard trials were averaged. On the other hand, when comparing the brain responses to standards and a specific type of deviants (small or far distance to a standard), another 48 of standard trials were randomly selected for data analyses[14]. Like in the last experiment, once these standard trials were decided, the same standard trials were chosen for each individual. Also, the standard trials which were the first three trials of a block or followed immediately after a deviant or a picture were excluded from the selection.

### 4.2.4 ERP analysis

The first aim of the current study was to replicate the findings of the previous experiment by examining the difference between the amplitude of the MMN and the AMN in the auditory versus the audiovisual condition. Therefore, the first part of data analyses followed mostly the same procedure as in Chapter 3 (page 97).

The same subtraction design (Figure 3-1, on page 95) ensured that any brain activity related to the presentation of the Arabic digit in the audiovisual condition is subtracted out when calculating the difference between standard and deviant trials. Thus, any remaining brain responses should only reflect the change of speech sounds. If there were any difference, the most plausible reason would be that the incongruence between the presented Arabic digit and the spoken

[14] Non-parametric permutation tests revealed no significant difference (i.e., no cluster *p*-values < .05) between the 96-trial average and 48-trial average in both the auditory-only and the audiovisual conditions.

number word automatically modulated the brain responses in the audiovisual condition.

The same method and time-windows to extract the MMN (50 to 250 ms after stimulus onset) and the AMN (240 to 300 ms after stimulus onset) as in the last experiment was used (see Method in Chapter 3 on page 97). The analyses were conducted separately for each participant in each time-window, and the data (e.g., amplitudes) were then used for further statistical tests.

Thirty electrodes were split into six groups as described in Chapter 3 (see Figure 3-2 on page 99). In order to compare the current results to the last experiment, I used exactly the same analyses as in Chapter 3 except I added one extra factor: distance. Thus, 4-way ANOVAs (distance: close & far distance; condition: auditory & audiovisual; caudality: anterior & posterior; hemisphere: left, right, and midline) were conducted for the peak amplitudes and latencies of the MMN and the averaged amplitudes of the AMN[15].

However, having changed the focus of interest to the effect of distance in the current study, it will be important to assess whether the time-windows used in the previous chapter, selected for detecting MMN and AMN are still appropriate. The latency of a component can vary substantially across studies (Segalowitz & Barnes, 1993). Besides, to the best of my knowledge, no one had used the current auditory oddball design with numerical symbols to investigate the distance effect, so there were no a-priori time-windows for the detection of the distance effect could be specified. After preliminary analyses, it was obvious that the previous time-windows were not suitable for examining the distance effect in the current data (see results section). Therefore, when analysing the effect of numerical distance on brain responses, as well as applying the time-windows that were used in the previous chapter for the MMN and the AMN mentioned above, I selected additional time-windows based on the

[15] As for chapter 3, there were no latencies for the AMN as the amplitudes were averaged in that time-window.

results from the non-parametric tests. All the statistics are reported Greenhouse-Geisser corrected (Luck, 2014), and the post-hoc comparisons were adjusted by Bonferroni correction unless stated otherwise.

### *4.2.5 Permutation test*

The same cluster-based permutation test as described in the last chapter (see page 99 in Chapter 3) was conducted in the current study by employing the 'Mass Univariate ERP Toolbox' (Groppe et al., 2011) within MATLAB. The time points from 0 to 450 ms at 30 scalp electrodes were included in the test, which made 6,750 comparisons in total. Other parameters were also the same as the ones in Chapter 3. This permutation test was used for: firstly, directly comparing the close and far deviants (close minus far) in the auditory and the audiovisual condition, respectively; secondly, the time-windows showing differences were then used for further ANOVAs to examine the interaction effect between condition and distance.

### *4.2.6 Correlation analyses*

The correlation analyses in the current study were performed to examine the relationship between brain responses and mathematical performance. The same analyses as in Chapter 3 (see page 104 in Chapter 3) were conducted but separately for close and far distance. That was, the amplitude differences between conditions (audiovisual minus auditory-only) by distance were used as the dependent variable for brain responses. In addition, the amplitude differences between distances (close minus far) by condition were also examined in the current chapter.

## 4.3 **Results**

This section is split into two main parts: First, the results from the difference waves. Second, the results from the raw waves. The analyses related to the MMN and the AMN are reported in the first part. The results of the non-parametric tests and of some further

ANOVAs based on the results of the non-parametric tests, are presented in the second section.

### 4.3.1 Difference waves

The difference waves (standard minus deviant) were examined first as the MMN and the AMN were the pre-selected components to investigate the integration effect between spoken number words and Arabic digits.

Firstly, in Figure 4-1 the overall waves combining the close- and far-distance deviants are displayed. Based on visual inspection, a positivity at around 200 ms after stimulus onset was shown for both auditory and audiovisual stimuli. Only the EEG responses at the anterior midline electrode group are shown here because previous research indicated that the MMN is usually found at the frontocentral electrodes (Näätänen et al., 2007), also the EEG responses were similar in three levels of hemisphere (left, right, and midline). The brain responses of all six electrode groups are shown in Figure B1 on page 254.

The difference waves were calculated by standard minus deviant trials, thus the positivity indicated a more negative brain response when the deviants were displayed, i.e., when the stimuli were mismatched. The auditory-only stimuli elicited a more positive peak at around 100 ms compared to the audiovisual stimuli. Overall though, the two conditions basically showed a very similar data pattern across the whole epoch.

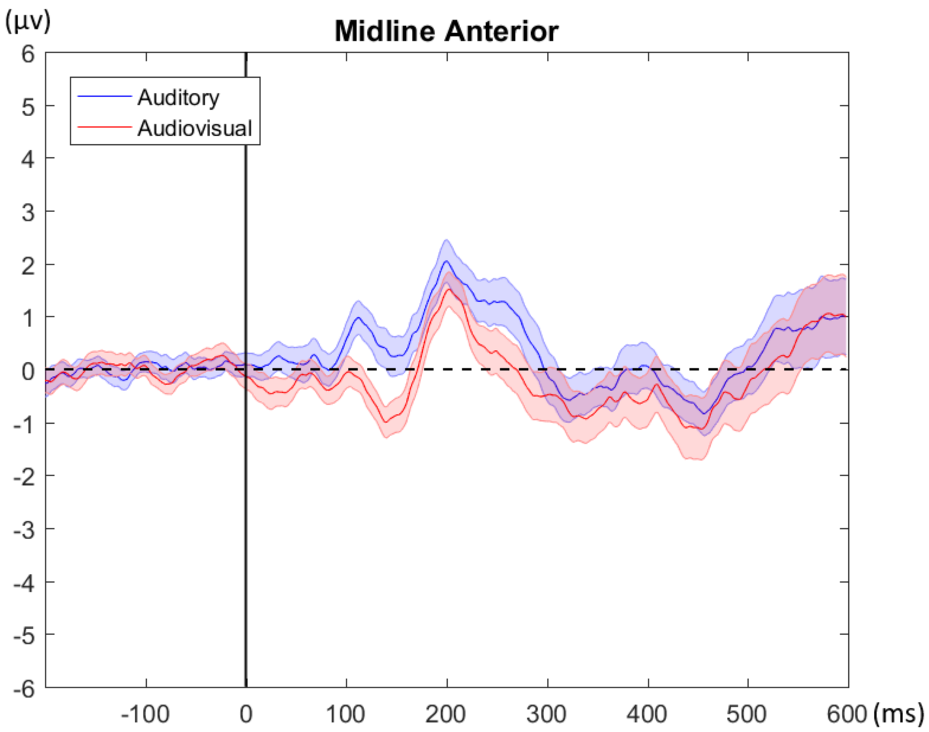


*Figure 4-1.* Difference waves of overall deviants (standard minus the average of close and far-distance deviants) at the anterior midline electrode group (±1 *SE*).

Because the new variable of interest in this chapter was distance, the average waves by distance are presented in Figure 4-2. The data pattern of close-distance deviants was similar to the overall waves (Figure 4-2A). That was, a large positivity for both conditions as well as an earlier and smaller positive peak for the auditory condition only were found. However, the large positivity peaked at nearly 300 ms post-stimulus onset, i.e., it was later than the one observed in the overall difference wave. In addition, although both conditions induced a similar data pattern, generally the audiovisual stimuli elicited a more negative wave than the auditory-only stimuli in the whole epoch across all electrode groups (for the brain responses to far-distance deviants in all six electrode groups, see Figure B2 on page 255).

Compared to the close-distance deviants, the brain responses to far-distance deviants were very similar between the audiovisual and auditory-only condition, especially after the first 150 ms (Figure 4-2B). A large positivity peaked at around 200 ms post-stimulus onset across all electrode groups, and was followed by a big negativity peaking at around 300 ms. This pattern was also observed in the close-distance deviants but with a longer latency (for the brain responses to far-distance deviants in all six electrode groups, see Figure B3 on page 256).

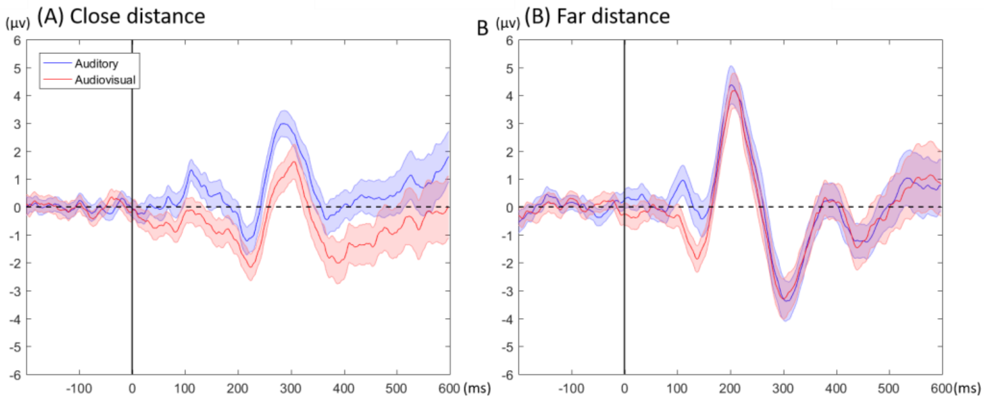


*Figure 4-2.* Difference waves of (A) close-distance deviants and (B) far-distance deviants (standard minus deviant) at the anterior midline electrode group (±1 *SE*).

#### 4.3.1.1 MMN

The first analysis was to test whether the MMN was present under the current paradigm. That was, the MMN amplitudes (standard minus deviant trials) should be significantly larger than zero. Twelve one sample t-tests were conducted for the mean peak amplitudes during 50 – 250 ms after stimulus onset in both the auditory and the audiovisual condition for all six electrode groups (for the means and *SD*s in details, see Table B1 on page 261). The results showed that the MMNs of the six electrode groups were all significantly different from zero in both the auditory and the audiovisual. The *p*-values of auditory-only condition were small enough to stay significant after Bonferroni correction (all *t*-scores > 4.6 and all *p*-values < .001). On the other hand, the *p*-values of audiovisual condition at the left anterior ($p$ = .013) and the right anterior ($p$ = .007) electrode groups were not significant after Bonferroni correction condition (for the details of the $t$-tests, see Table B2 on page 262). In summary, a significant auditory MMN could be detected for all six electrode groups. In contrast, a significant audiovisual MMN only existed in four out of six electrode groups.

After the presence of MMN were confirmed, 4-way ANOVAs (distance: small & large: condition: auditory & audiovisual; caudality: anterior & posterior; hemisphere: left, right, and midline) of MMN amplitudes and latencies were conducted to investigate: (1) if there was a significant difference in MMN between the two conditions; (2) whether the MMN was modulated by distance.

To make the results section as succinct as possible, only the main effects, and the highest-order interactions[16] related to the main interest of the current study, i.e., the distance or the condition factor, will be reported in detail in the main text. See Appendix B from page 254 for the complete ANOVA tables**.**

The results of the 4-way ANOVA of MMN amplitudes showed a significant main effect of distance ($F$(1, 35) = 64.85, $p$ < .001, $\eta^2$ = .65). The far-distance numerals elicited a larger MMN amplitude ($M$ = 1.86 µv, $SD$ = 1.49 µv) than the close-distance numerals ($M$ = 0.32 µv, $SD$ = 1.02 µv). There was no significant main effect of condition ($F$(1, 35) = 2.17, $p$ = .15, $\eta^2$ = .06). A significant interaction was found between distance and condition ($F$(1, 35) = 6.40, $p$ = .02, $\eta^2$ = .16). Post-hoc comparisons showed that the auditory-only stimuli induced a more positive MMN ($M$ = 0.80 µv, $SD$ = 1.28 µv) than the audiovisual stimuli ($M$ = -0.15 µv, $SD$ = 1.49 µv, $p$ = .01) in the close-distance deviants, whereas no difference of the MMN amplitudes was found between auditory-only ($M$ = 1.86 µv, $SD$ = 1.86 µv) and audiovisual stimuli ($M$

[16] For example, if the 3-way interaction between distance, condition, and hemisphere and the 2-way interaction between distance and condition were both significant, only the 3-way interaction and the further post-hoc comparisons based on the 3-way significant interaction will be reported in the main text.

= 1.87 μv, *SD* = 2.06 μv) for far distance. There was no other effect related to distance or condition. Other effects are reported in Table B3 on page 263 (also see Table B1 on page 261 for the mean and *SD* for each cell).

A similar 4-way ANOVA (distance: small & large: condition: auditory & audiovisual; caudality: anterior & posterior; hemisphere: left, right, and midline) was conducted for the MMN latencies. A significant main effect was found on distance ($F$(1, 35) = 134.62, $p$ < .001, $\eta^2$ = .79). The peak MMN latency of close-distance deviants (*M* = 136 ms, *SD* = 19 ms) was faster than the far-distance deviants (*M* = 188 ms, *SD* = 18 ms). The main effects of condition ($F$(1, 35) < 0.01, $p$ = .99, $\eta^2$ < .01), caudality ($F$(1, 35) = 0.88, $p$ = .36, $\eta^2$ = .03), or hemisphere ($F$(1.7, 58.0) = 0.61, $p$ = .55, $\eta^2$ = .02) were not significant. There was no significant interaction with condition or distance (for the ANOVA table, see Table B5 on page 266; for the means and *SD*s, see Table B4 on page 265).

#### 4.3.1.2 AMN

A 4-way ANOVA (distance: small & large: condition: auditory & audiovisual; caudality: anterior & posterior; hemisphere: left, right, and midline) was conducted for the AMN amplitudes[17] to investigate the effect of the manipulation of distance. A significant main effect of distance was found ($F$(1, 35) = 8.64, $p$ = .006, $\eta^2$ = .20). A more positive AMN amplitude was found for close distances (*M* = 0.79 μv, *SD* = 1.50 μv) than for far-distance (*M* = -0.26 μv, *SD* = 2.23 μv). The main effect of condition was not significant ($F$(1, 35) = 1.34, $p$ = .25, $\eta^2$ = .04). A significant interaction was found between condition and distance ($F$(1, 35) = 6.17, $p$ = .02, $\eta^2$ = .15). Post-hoc comparisons showed that the auditory-only condition elicited a significantly more positive AMN amplitude (*M* = 1.31 μv, *SD* = 1.81 μv) than the audiovisual stimuli (*M* = 0.27 μv, *SD* = 2.35 μv, $p$ = .04) only when the close-distance deviants

[17] The latencies of the AMN were not analysed here because in line with previous papers the AMN amplitudes were calculated as the mean average of the amplitude, instead of the peak, in the time-window from 240 to 300 ms after stimulus onset.

were displayed, but there was no significant difference between AMN amplitudes in the two conditions (auditory: $M$ = -0.24 μv, $SD$ = 2.48 μv; audiovisual: $M$ = -0.28 μv, $SD$ = 2.98 μv) for far-distance deviants. A significant interaction was found between distance and caudality ($F(1, 35) = 16.63$, $p < .001$, $\eta^2 = .32$). Post-hoc comparisons showed that close-distance deviants provoked a more positive AMN amplitude ($M$ = 0.72 μv, $SD$ = 1.67 μv) than far-distance deviants ($M$ = -0.96 μv, $SD$ = 2.63 μv, $p < .001$) in the anterior site, but not in the posterior sites (close: $M$ = 0.86 μv, $SD$ = 1.59 μv; far: $M$ = 0.44 μv, $SD$ = 2.17 μv, $p = .22$).

A 3-way significant interaction was found between condition, caudality, and hemisphere ($F(1.9, 67.2) = 3.65$, $p = .03$, $\eta^2 = .09$). Post-hoc comparisons showed that the auditory-only stimuli elicited a significant more positive AMN amplitude ($M$ = 0.51 μv, $SD$ = 2.70 μv) than the audiovisual stimuli ($M$ = -0.66 μv, $SD$ = 2.81 μv, $p = .047$) in the midline anterior electrode group only (for the ANOVA table, see Table B7 on page 269; for the means and *SD*s, see Table B6 on page 268).

### 4.3.2 Raw waves

The ANOVAs above were all conducted on the difference waves (standard minus deviant). However, a component present in difference waves could indicate multiple possibilities about the components in the raw waves of standard and deviant trials. For example, when a difference wave shows that the audiovisual MMN is more negative than the auditory MMN, the two original components could both be negativities or positivities, or one is a positivity while another one is a negativity. These different EEG performances can essentially influence the interpretation of the data. Besides, some interesting effects fell outside of the pre-selected time-windows. For example, there is a large positive peak at around 300 ms after stimulus onset within the close-distance deviant (see Figure 4-2A). As the peak only starts to rise at around 250 ms, it cannot be captured in the pre-defined time-window for the MMN, which was 50 to 250 ms after stimulus onset. More importantly, from visual inspection the raw waves show remarkable differences between close and far-distance trials from early on (< 100 ms) until late (> 400 ms; see Figure 4-3).

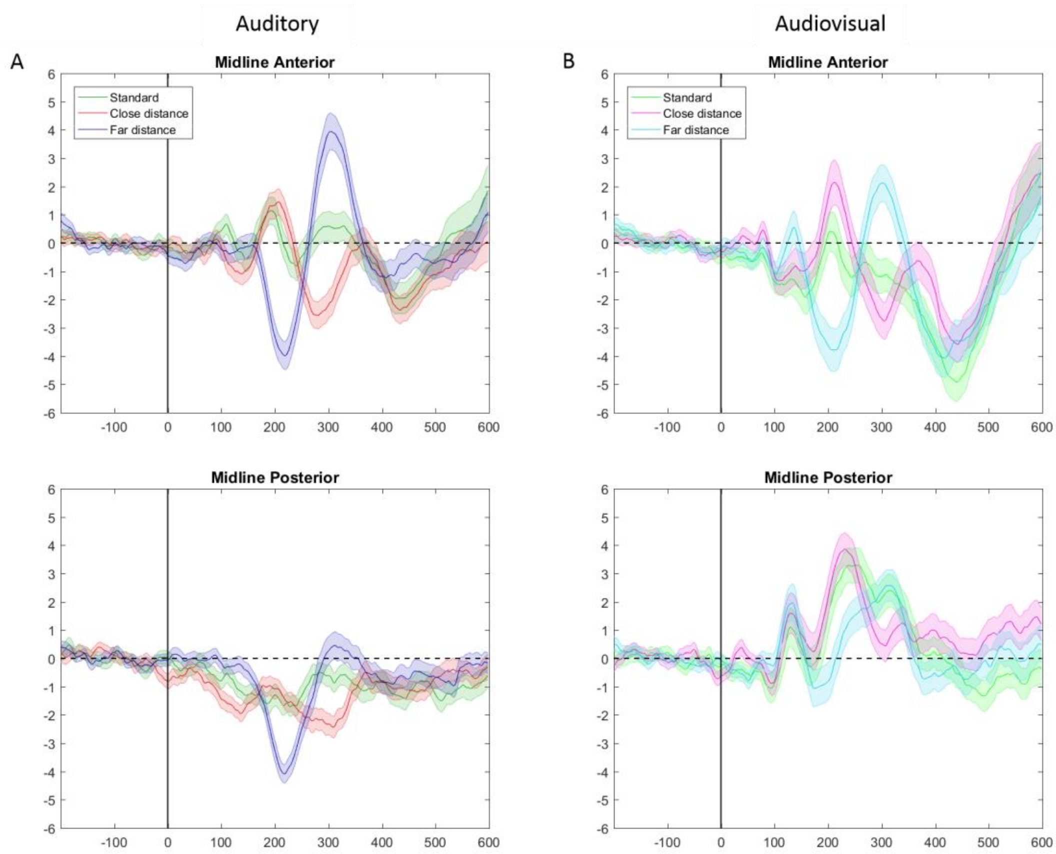


*Figure 4-3*. Raw waves of different stimuli at midline electrode groups in the (A) auditory-only and the (B) audiovisual condition (±1 *SE*).

The raw waves of standard, close-distance, and far-distance numerals by condition are displayed in Figure 4-3. Only midline electrodes are illustrated here because the ERP components are more salient in the midline electrodes, and the data patterns of brain responses are not markedly different between three levels of hemisphere groups (left, right, and midline).

In the auditory condition, the brain responses to standard trials (i.e., spoken number word, /five/) elicited the first positive peak at around 100 ms in the anterior electrodes (Figure 4-3A, top), whereas similar positive peaks could not be observed for the close- and far-distance deviants. In contrast, both the close- and far-distance deviants induced a more negative amplitude at that time point. The second positive peak induced by standard trials was at around 200 ms post-stimulus onset. The brain responses to close-distance deviants performed very similar to standard trials at 200 ms. However, a totally different pattern was observed for the far-distance deviants: here a big negative peak was observed at around 200 ms. The brain responses to standard, close and far deviants also differed markedly at around 300 ms after stimulus onset. The standard trials induced a positive peak, and the far-distance deviants induced an even larger positive peak, whereas the close-distance deviants elicited a negative peak. The brain responses to all three kinds of stimuli became more similar after 450 ms post-stimulus onset.

In the audiovisual condition, the brain responses in the anterior and the posterior electrode groups look more different from each other compared to the auditory-only condition. Hence, I will describe the brain data pattern by caudality separately.

First, comparing the audiovisual with the auditory-only condition, there are large differences at the posterior electrodes (Figure 4-3, bottom). All three kinds of stimuli (close, far and standard trials) induced a positivity (P1) at around 100 to 150 ms after stimulus onset in the audiovisual condition which was not observed in the auditory-only condition. Previous research has shown that the P1 is related to early visual stimulus processing (e.g., Hillyard & Anllo-Vento, 1998). Since the visual stimulus was always the digit ‘5’ no matter which spoken number word was presented, it was not a surprise that the amplitudes and the latencies of P1 were similar. The ERP responses to close, far and standard trials started to diverge from about 200 ms post-stimulus onset. All three kinds of stimuli elicited a P2 (the second salient positivity), but the P2 only reached its peak at around 300 ms for far-distance deviants, while both standards and close-distance deviants had the peak earlier, at around 250 ms after stimulus onset.

From visual inspection of EEG responses in the anterior midline electrodes, there is no large difference between the data patterns of the three types of stimuli in the auditory-only versus audiovisual conditions (Figure 4-3, upper panel). The only remarkable difference between three types of stimuli is that in the earliest component (before 150 ms) the standard trials now show a negative wave, whereas the far-distance deviants show a positive peak, which are both different to their performance in the auditory-only condition.

In general, from visual inspection it is clear that there are large differences in brain responses to close- versus far-distance deviants. These outstanding data patterns related to the distance manipulation could not have been discovered by the just described ANOVAs of difference waves. Therefore, apart from the pre-selected time-windows for examining the MMN and the AMN, I conducted a non-parametric test to identify and explore other time-windows which showed significant differences between close and far distances.

#### *4.3.2.1 Results of non-parametric test*

The non-parametric permutation test conducted in the current study followed the same procedure as reported in the previous experiment. The only difference was that the non-parametric test in the current study was used for an exploratory purpose, that was, to demonstrate the distance effect and to find the time-windows for further analyses. As mentioned earlier, although there are some advantages for looking at difference waves (Luck, 2014), some information is also lost during the calculation of difference waves. To directly show the difference between close- and far-distance, i.e., the distance effect, the brain responses for close and far-distance deviants were therefore compared to each other in the auditory-only and the audiovisual condition separately with non-parametric tests.

The results of the non-parametric test showed large differences between the brain responses to the close and far-distance deviants in both the auditory-only (Figure 4-4) and the audiovisual condition (Figure 4-5).

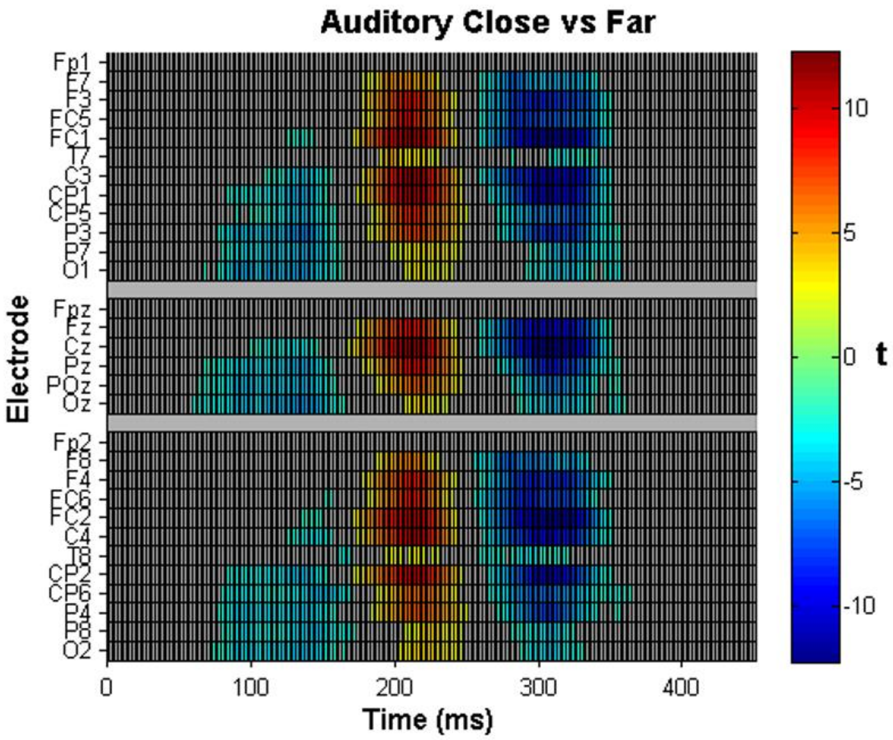


*Figure 4-4.* The differences between close and far distance (close minus far) revealed by a permutation test in the auditory condition ($p < .05$).

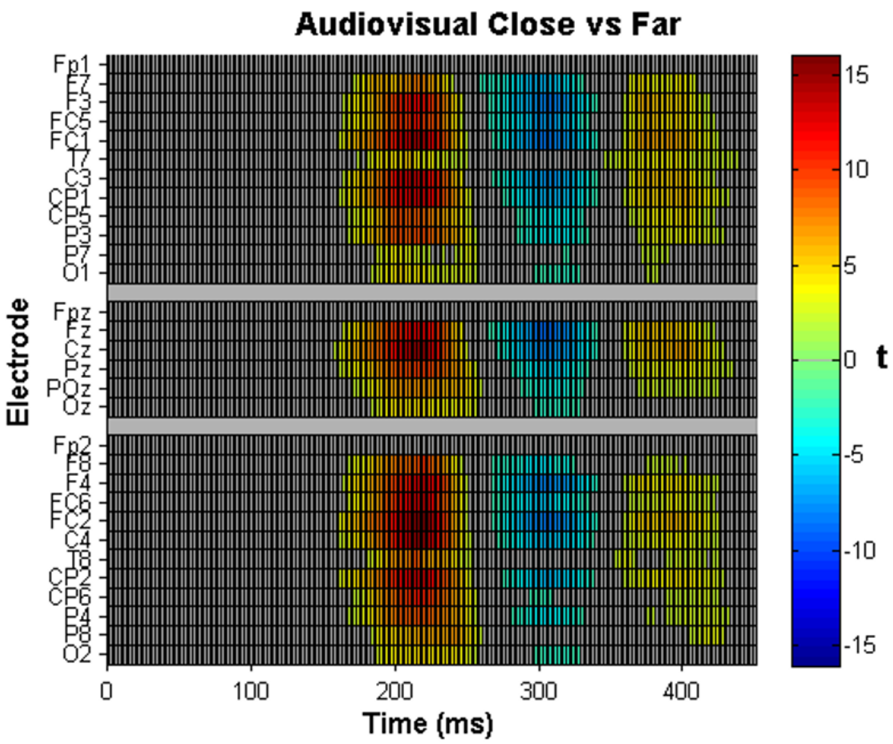


*Figure 4-5.* The differences between close and far distance (close minus far) revealed by a permutation test in the audiovisual condition ($p < .05$).

In the auditory condition, two negative clusters and one positive cluster of significant differences were revealed by the non-parametric permutation test (family-wise error rate < .05). The results showed that the brain responses were significantly more negative for the close-distance than far-distance deviants during 60 to 170 ms and 254 to 364 ms, while they were more positive during 170 to 250 ms after stimulus onset. Furthermore, in the time-window of 60 to 170 ms, the difference appeared more strongly in the posterior electrodes, while the differences were more spread across the whole scalp in the other two clusters (see Figure 4-4 for the electrodes showing the differences in detail).

In the audiovisual condition, two significant positive clusters and one negative cluster were found (family-wise error rate < .05). The brain responses were more positive for the deviants with a close distance toward the standard (i.e., /four/ and /six/) than the ones with a far distance (i.e., /one/ and /nine/) during 158 to 258 ms and 346 to 438 ms, whereas more negative during 258 to 342 ms after stimulus onset. All clusters were distributed over the whole scalp (see Figure 4-5 for the electrodes showing the differences in detail).

In summary, Figure 4-4 and Figure 4-5 clearly demonstrate the differences between close- and far-distance deviants in several time-windows, in between 60 to 438 ms after stimulus onset. In addition, there were two similar time-windows, in between approximate 160 ms to 346 ms, reported in both the auditory-only and audiovisual conditions.

Although the amplitude difference between close- and far-distance deviants was clearly shown by the results of non-parametric tests, the direct comparison between deviants with close and far distance might include not only semantic-related but also some other processing of stimuli. For example, part of the differences could be reflecting the acoustic features among close and far-distance spoken number words. Hence, a better way to investigate the distance effect was to also consider the effect of condition in the analyses. By calculating the amplitude difference between the audiovisual and the auditory-only condition (VA - A) within distance, the acoustic differences among spoken number words were subtracted out. In addition, when examining the close- and far-distance deviants only, a significant effect between distances can only demonstrate that the close- and far-distance numerals behave differently, but cannot tell which distance of numerals performs a stronger semantic processing. Therefore, to better understand the influence of distance, the standard trials were also included in as a level of distance in the conventional ANOVAs. Given that there is no semantic conflict between the audiovisual stimuli in the standard trials, it shows that which distance of numerals cause more semantic processing by comparing the close and far distance to the standard respectively.

#### *4.3.2.2 ANOVA for raw waves*

As mentioned earlier, to further examine the interaction between condition and distance, the conventional ANOVAs were conducted for the mean peak amplitudes[18] with the time-windows discovered by non-parametric tests. Those time-windows were: 60 to 170 ms, 170 to 250 ms, 250 to 346 ms, and 346 to 438 ms after stimulus onset. The durations of time-windows were slightly adjusted to avoid overlaps. Based on visual inspection on grand-average waveforms, either a positive or a negative peak was chosen depending on which direction could best denote the brain responses in each time-window. This was done separately for close, far and standard trials. As a result, After the peaks were selected, the EEG amplitudes in a time-window of 25 ms before each peak to 25 ms after each peak latency were then averaged, to acquire the mean peak amplitudes for the further ANOVAs.

As mentioned earlier, in order to get rid of the acoustic differences within auditory number words, the dependent variable in

[18] The peak latencies were not reported because there was no precise prediction about how the peak latencies of components would be influenced by an interaction between distance and condition in raw waves.

the ANOVAs reported below are amplitude differences between the audiovisual and the auditory-only condition (VA - A).

Four 3-way (distance: close, far, & standard; caudality: anterior & posterior; hemisphere: left, right, and midline) ANOVAs were conducted separately for the four different time-windows on the mean peak amplitude differences. As mentioned earlier, only the effects which were related to distance will be reported in the main text. Other effects in are reported in Appendix B (for means and *SD*s, see Table B8 on page 271).

In the time-window of 60 – 170 ms, a significant main effect was found on distance ($F(1.8, 64.0) = 16.37$, $p = < .001$, $\eta^2 = .32$). Pair-wise comparisons showed that the amplitude difference was significantly more positive for close-distance deviants ($M = 1.48$ µv, $SD = 1.18$ µv) than for standards ($M = -0.15$ µv, $SD = 1.64$ µv, $p < .001$) and for far-distance deviants ($M = 0.18$ µv, $SD = 1.43$ µv, $p < .001$) whereas the amplitude differences were not different between standards and far-distance deviants ($p > .999$). There were no other effects related to the distance factor (see other effects in Table B9 on page 273).

In the time-window of 170 – 250 ms, the main effect of distance was not significant ($F(1.7, 59.1) = 1.81$, $p = .18$, $\eta^2 = .05$) and there were no other effects related to the distance factor (see other effects in Table B10 on page 274).

In the time-window of 250 – 346 ms, the main effect of distance was not significant ($F(1.7, 59.8) = 2.35$, $p = .11$, $\eta^2 = .06$). The interaction between distance and caudality was significant ($F(1.6, 55.1) = 3.59$, $p = .045$, $\eta^2 = .09$). Further post-hoc comparisons showed that there was no any significant simple main effect (all *p*-values > .05). However, while looking into the details of the comparisons between close distances and standard trials, the amplitude difference of close distance was descriptively more positive than the amplitude difference standard trials in the anterior electrode group (close: mean = 0.20 μv, *SD* = 3.29 μv; standard: *M* = -0.66 μv, *SD* = 2.82 μv), whereas it became descriptively more negative than standard in the posterior electrode group (close: mean = 2.79 μv, *SD* = 2.08 μv; standard: *M* = 2.98 μv, *SD* = 2.16 μv). Though there was no significant difference between close-distance and standard trials in each caudality ($p$ = .23 in the anterior, $p$ = .15 in the posterior), this cross-over data pattern (one difference was positive while the other difference was negative) in two caudalities perhaps led to the significant interaction (see Figure B7 on page 260). There were no other effects related to the distance factor (see other effects in Table B11 on page 275).

In the time-window of 346 – 438 ms, a significant main effect was found on distance ($F$(1.7, 58.4) = 7.45, $p$ = .002, $\eta^2$ = .18). Pair-wise comparisons showed that the amplitude difference was significantly more positive for close-distance deviants (*M* = 0.64 μv, *SD* = 2.12 μv) than for standards (*M* = -.91 μv, *SD* = 2.31 μv, $p$ < .001) and for far-distance deviants (*M* = -1.00 μv, *SD* = 2.19 μv, $p$ < .001), while far-distance deviants was not significant different from standards ($p$ > .999). A significant 3-way interaction was found between distance, caudality and hemisphere ($F$(3.2, 110.8) = 7.23, $p$ = .008, $\eta^2$ = .11). Follow-up analyses showed a significant simple interaction was only found in the midline electrodes ($F$(1.9, 66.6) = 5.38, $p$ = .008, $\eta^2$ = .13), but not in the left $F$(1.9, 66.3) = 2.57, $p$ = .09, $\eta^2$ = .07) nor in the right electrode groups $F$(1.8, 61.8) = 2.51, $p$ = .10, $\eta^2$ = .07). Further post-hoc analyses showed that the amplitude of standard trials (*M* = -3.00 μv, *SD* = 3.76 μv) was more negative than close-distance deviants (*M* = -0.50 μv, *SD* = 3.32 μv, $p$ = .005) in the midline anterior electrodes, but the amplitudes were similar between standard and close distance in the midline posterior electrodes (close: *M* = 1.87 μv, *SD* = 2.64 μv; standard: *M* = 1.25 μv, *SD* = 2.38 μv, $p$ = .78; for the full ANOVA table, see Table B12 on page 276).

A clearer picture about the EEG responses for three types of stimuli in each time-window is shown in

Figure 4-6. When compared the close- or far-distance deviant to the standard trial, it is clear that the close-distance deviant is the one which is more different from standards, whereas the EEG responses for far distances are more similar to the standard trial, especially in the first and the last time-window.

In summary, the ANOVAs in four time-windows showed that except for the time-window of 170 – 250 ms post-stimulus onset[19], the amplitude difference of close-distance deviants was more positive than standard trials in general, whereas the far-distance deviants behaved more similar to standard trials in all time-windows from 60 to 438 ms after stimulus onset (see

Figure 4-6; for the data by caudality, see Figure B7 on page 260).

[19] A 4-way ANOVA (distance: close, far, & standard; time-window: 60-170, 170-250, 250-346, & 246-438 ms; caudailty: anterior & posterior; hemisphere: left, right, midline) showed a significant interaction between distance and time-window ($F(4.5, 34.0) = 3.68$, $p = .005$, $\eta^2 = .10$). This result supported that the relationship between close, far, and standard trials were different across time-windows.

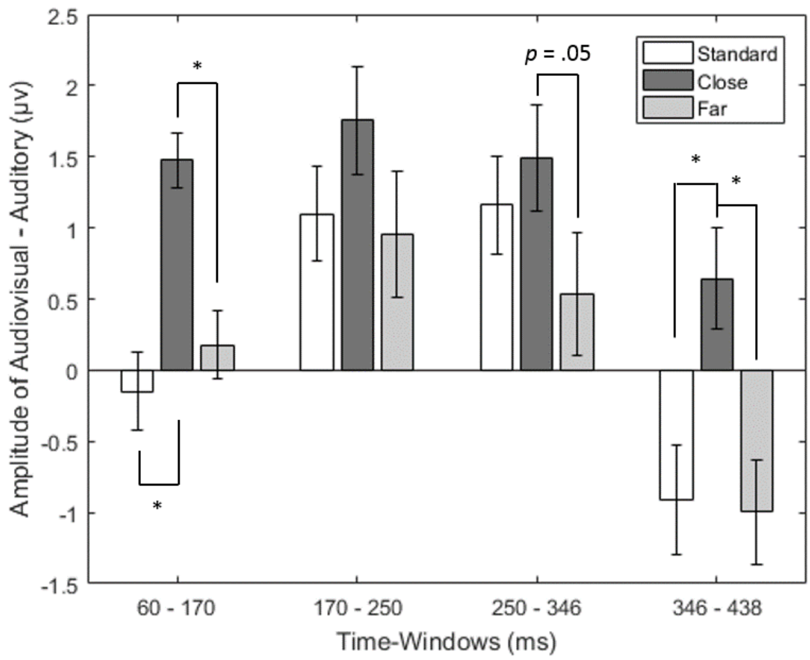


Figure 4-6. *The amplitude difference between conditions (VA - A) by distance in different time-windows (±1* SE*).*

### 4.3.3 Correlational analyses

Similar correlational analyses as in Chapter 3 (page 104) were conducted. The correlations between the MMN and the AMN amplitude difference across conditions and individual WRAT scores were investigated by close and far distance respectively. The correlations between the amplitude difference across conditions and individual WRAT scores were examined by close and far distance respectively. In addition, as clear differences were shown between distances in the previous non-parametric tests, the correlations between the amplitude difference across distances and WRAT scores were also examined by the audiovisual and the auditory condition separately.

Participants' performance on the WRAT-4 test and the WASI-II test was slightly better than average for their age (*M* = 104.3, *SD* = 12.0, range from 81 to 129) and WASI-II (*M* = 58.7, *SD* = 8.7, range from 38 to 79).

#### *4.3.3.1 MMN and AMN*

The results showed that there was no significant relationship neither between individuals' WRAT scores and their MMN amplitude differences (VA minus A) by close and far distance (all *r*s < .25, *p*-values > .15), nor between their WRAT scores and their AMN amplitude differences by distance (all *r*s < .31, *p*-values > .07). Though none of these correlations were significant, both the MMN and AMN amplitudes showed positive correlations with WRAT scores across all electrode groups, indicating that descriptively the more positive the amplitude difference (VA minus A) was, the better the participant performed on the mathematical test. In addition, the AMN amplitude showed descriptively stronger correlations (*r*s from .18 to .31) than the MMN amplitudes (*r*s from .06 to .25), which was the same tendency as it showed in Chapter 3. The correlations did not show much difference by distance in both the MMN (close: *r*s from .11 to .25; far: *r*s from .06 to .23) and the AMN amplitudes (close: *r*s from .18 to .26; far: *r*s from .13 to .31). For more details about the correlations between WRAT scores and the amplitude of each component in each electrode group, see Table B13 in Appendix B.

Like the null results mentioned above, there were no significant correlations between individuals' WRAT scores and their MMN amplitude differences (close versus far) by condition, nor between their WRAT scores and their AMN amplitude differences by condition. For more details about the correlations between WRAT scores and the amplitude of each component in each electrode group, see Table B14 on page 278.

#### *4.3.3.2 Raw waves*

The results showed that there were no significant correlations between amplitude differences (VA minus A) and WRAT scores in the time-window of 60 to 170 and 170 to 250 ms after stimulus onset (all $p$-values > .11). In contrast, in the time-window of 250 to 346 ms and 346 to 438 ms, significant negative correlations were found in the right anterior electrode groups for close-distance deviant (250 – 346 ms: $r$ = -.38, $p$ = .02; 346 – 438 ms: $r$ = -.39, $p$ = .02), and both the right (250 – 346 ms: $r$ = -.35, $p$ = .04; 346 – 438 ms: $r$ = -.38, $p$ = .03) and midline anterior electrode groups (250 – 346 ms: $r$ = -.35, $p$ = .04; 346 – 438 ms: $r$ = -.34, $p$ = .048) for far-distance deviants. These negative correlations indicated that the more negative the difference between the peak amplitudes of two conditions (VA minus A), the better the performance in the mathematical test. For more details, see Table B15 in Appendix B (page 279).

The correlation analyses for the amplitude difference between distances by condition showed that there were no significant correlations with mathematical performance in the first two time-windows (all $p$-values > .26), nor in the last time-window (all $p$-values > .08). The only significant correlation was revealed at the left posterior electrode group ($r$ = -.36, $p$ = .034) in the time-window of 250 – 346 ms, only in the auditory condition. For more details, see Table B16 in Appendix B (page 280). Because the direct comparison between close and far distances may include more 'noise' which is irrelevant to semantic-related processing, such as different acoustic features between number words. It will make the interpretation of correlations difficult to explain, thus I will not further discuss the correlations based on amplitude difference between distances for each condition.

## 4.4 Discussion

In the current study, I employed a similar oddball paradigm as in Chapter 3 with an additional manipulation of numerical distance between standard and deviant trials. I added distance to further investigate the involvement of magnitude processing in the current auditory oddball paradigm with numerical symbols as stimuli.

A number of findings reported in Chapter 3 were successfully replicated in the current experiment: First, I found a significant MMN effect both in the auditory-only and the audiovisual condition. Second, there was no main effect of condition in terms of the MMN amplitude (however, an interaction was found between distance and condition which will be discussed later). Third, the AMN amplitude was significantly more negative in the audiovisual condition than in the auditory-only condition when close-distance deviants were used. A more negative audiovisual AMN was also reported in Chapter 3. Though distance was not manipulated in Chapter 3, the constant distance of 2 in the previous experiment is normally considered as a close distance. This makes the current experiment with close-distance numerals directly comparable to the previous experiment. Because the current series of experiments are, to my best knowledge, the first to investigate the integration between spoken number words and Arabic digits with EEG, it is crucial to find consistent results, i.e., replications, across experiments. Therefore, these similar discoveries in Chapter 3 and Chapter 4 indicate that the findings of the MMN and the AMN in terms of the condition effect are reliable.

Furthermore, adding the factor of distance led to several new findings in the current experiment. First, an interaction was found between distance and condition as predicted in terms of the AMN amplitudes. The significant difference between conditions was only revealed within close-distance deviants but not with far-distance deviants. The interaction between distance and condition was also significant in the MMN amplitudes. In addition to those findings for the MMN and the AMN components, further ANOVAs based on the time-windows identified by non-parametric tests also uncovered significant interactions between distance and condition on the raw waves in the time-windows after 250 ms post-stimulus onset.

In addition, on raw EEG responses, the close-distance deviants started to induce a more positive amplitude as early as 60 ms after stimulus onset. There was no modulation by distance in the second time-window, 170 – 250 ms, then the modulation by distance was shown again during 250 – 346 ms. During 250 to 346 ms, an interaction between distance and caudality was found.

In the following sections, I will in turn focus on the distance effect, and the interaction between distance and condition, on difference waves and raw waves.

### 4.4.1 Distance effect

Compared to the last experiment, distance has been added as factor in the current experiment in order to observe the semantic processing within the numerical symbols. Different from letters and speech sounds, both spoken number words and Arabic digits contain precise quantity representation. Therefore, by observing the differences induced by numerical symbols carrying different distances, i.e., the distance effect, it can provide more understanding about the correspondence, if not integration, between these two kinds of numerical symbols.

#### 4.4.1.1 MMN

The current experiment found that the far-distance deviants induced a larger, but later MMN than the close-distance deviants. It has been suggested that the MMN refers to a short-term memory trace back to the standard sounds (Näätänen et al., 2007). Thus, a larger MMN for far-distance deviants could indicate that the far-distance spoken number words are seen as more incongruent with the standard spoken number words compared to the incongruence between standard and close-distance spoken number words. This stronger brain response for the far-distance spoken number words is line with previous studies using Hungarian number words as stimuli. That is, with a similar latency as of the MMN found in the current study, a larger N2f have been reported for far-distance auditory number words than close-distance auditory number words (Szűcs & Csépe, 2004b, 2005b). As there was no number-related task in the current experimental design, this difference by distance found in the MMN likely indicates an early and automatic semantic processing of auditory number words.

However, I did not predict the later MMN for far-distance spoken number words and the onset difference is considered as large (around 50 ms) between close and far distance compared to previous research. Whereas a few ERP studies using visual stimulus have also described longer latencies of early components for far-distance numerical symbols (Cao et al., 2010; Zhou et al., 2006), most behavioural studies have reported a shorter RT for the far-distance numerals compared to the close-distance numerals, which leads to the distance effect (e.g., Moyer & Landauer, 1967). Previous research has indicated that the latencies of ERP components can be related to behavioural responses (e.g., Gajewski, Stoerig, & Falkenstein, 2008; Verleger & Jaśkowski, 2005). As the RT for the far-distance numerals has been found shorter in most of previous research, a shorter latency for ERP components was expected for the far-distance numerals as well.

In line with this expectation, but in contrary to the current finding, Szűcs and Csépe (2004b) found that the latencies of N2f and the N2p were both significantly earlier for the far-distance auditory number words (numerical distance of 4) than the close-distance auditory number words (numerical distance of 1). Two possible factors may account for the different findings between the current experiment and the previous research: the duration of the auditory stimuli and the task demands.

It has been shown that the duration of auditory stimuli can affect the latency of ERP components (Korpilahti et al., 2001; see also Tervaniemi, Lehtokoski, & Sinkkonen, 1999). That is, a shorter duration of an auditory stimuli can lead to an earlier latency of a component. In the current research, the durations of all auditory number words were well-controlled to be around 450 ms (mean = 451.6 ms, *SD* = 2.7 ms), whereas the durations of Hungarian number words used in the study of Szűcs and Csépe (2004b, 2005b) varied within a wide range. The duration of the Hungarian 'one' ('egy') was 200 ms, 'four' ('négy') and 'six' ('hat') were both 350 ms, and 'nine' ('kilenc') was 500 ms. This made the average durations of close and far-distance spoken number words were both 350 ms. However, 'kilenc' contains two syllables (pronounced as /ki-lenc/). When there is a task demand asking participants to make a judgement as fast and accurate as they can, it is likely that the task encourages participants to make a judgement when they have just heard the first syllable 'ki' of 'kilenc'. This may lead to a shorter 'actual duration' for the far-distance number words. Consequently, the shorter duration of far-distance number words then possibly causes shorter latencies of N2 components. As a result, if the 'actual duration' of auditory stimuli have been controlled, the far-distance Hungarian number words may not induce shorter latencies of components.

Latency differences, compared to amplitude differences, are rarely discussed in previous studies focusing on the distance effect with visual digits (e.g., Cohen Kadosh et al., 2007; Libertus et al., 2007; Pinel et al., 2001; Temple & Posner, 1998; Turconi, Jemel, Rossion, & Seron, 2004). One reason for this was because previous researchers often calculated the mean amplitudes (as the analysis of the AMN in the current study), but not mean peak amplitudes in a selected time-window (e.g., Libertus et al., 2007; Temple & Posner, 1998; Turconi et al., 2004). Also, the latency difference by distance might be very subtle for visual stimuli so that previous research rather focused on the amplitude difference. For example, Dehaene (1996) conducted a number comparison task in which participants were asked to judge whether the displayed numeral (an Arabic digit or a written number word) was numerically larger or smaller than 5. He did not find any latency differences on N1 nor on P2p between close- and far-distance numerals. Cao et al. (2010) conducted the same number comparison task and found a significant, but only 3 ms earlier N1 for close-distance Arabic digits than far-distance Arabic digits.

Furthermore, in the studies reporting latency differences there were no consensus results about latency differences by numerical distance. Some studies have reported a faster latency of a component, such as N1 (Cao et al., 2010) and N2 (Zhou et al., 2006), for close-distance numerals; whereas some other studies have found a faster latency for far-distance numerals on N3 (Szűcs & Csépe, 2005a) and P3 (Pinhas et al., 2015). Previous research has shown that some later components, such as P3b, have a close relationship to the response (e.g., Szűcs et al., 2007; Verleger & Jaśkowski, 2005). Hence, it is not a surprise that far-distance numerals induce a faster latency of a late component when a response is required. In contrast, it is not clear why the latency of an early component would be significantly shorter for close-distance numerals. A hypothesis to explain a shorter latency of early components whereas a longer RT for close-distance numerals, is that the processing of close-distance numerals starts earlier, but also lasts longer than far-distance numerals. For example, Cao et al. (2010) found a shorter latency of N1 for both close-distance Arabic digits and simplified Chinese number words compared to far-distance ones, whereas the RT of close-distance numerals was longer than far-distance numerals. However, as there is no response requirement for numerals in the current passive oddball paradigm, it is not possible to test this explanation in the current data.

Although a shorter latency for close-distance number words was not expected beforehand, this finding is in line with previous research on the priming numerical distance effect. It has been shown that when the numerical distance between a prime numeral and a target numeral is closer, the RTs of a later response (e.g., naming the target numeral) to the target becomes shorter (Reynvoet & Brysbaert, 2004; Reynvoet, Brysbaert, et al., 2002). This priming distance effect is found when cross-format numerals are used (including Arabic digits, written number words, and spoken number words), which supports that there is an amodal, shared magnitude representation for all number formats (Kouider & Dehaene, 2009; Reynvoet & Brysbaert, 2004). The common explanation of priming distance effect is that the number prime activates not only the representation of the number itself, but also triggers the representations which are numerically close to the number prime on a continuum, e.g., the mental number line.

In the current paradigm, the representation of the standard number, i.e., 5, is constantly activated. Thus, this may lead to a constant activation of neighbouring numbers, i.e. 4 and 6 – the number used in the close condition. This possibly makes the representations of close-distance numerals easier to be activated above a certain threshold than the far-distance numerals which are not pre-activated by the number prime. Therefore, making the latency of MMN shorter for the close distances than for the far distances.

In summary, a clear distance effect has been found in terms of MMN amplitude as well as latency: the MMN peak was larger but later for far-distance spoken number words than close-distance ones. The larger MMN is probably due to more incongruity for the far-distance spoken number words than for the close-distance spoken number words, compared to the standard number word. The latency difference between close and far-distance spoken number words is unexpected, has never been reported in the previous research and needs to be replicated. However, it could possibly indicate that the close-distance deviants are processed earlier than the far-distance deviants. This finding is novel, so clearly more research needs to be done to further understand the underlying mechanism of the MMN latency difference between distances in the current paradigm.

#### *4.4.1.2 AMN*

A more positive AMN amplitude was found for close-distance than far-distance numerals. This indicates a more negative amplitude for raw waves of close-distance deviants than far-distance deviants. Close-distance numerals inducing a more negative ERP response than far-distance numerals around 240 – 300 ms after stimulus onset was also reported in previous studies with a matching task (Hsu & Szűcs, 2011; Zhou et al., 2006). This may indicate that the mismatch in distance between visual digits and auditory number words in the visuo-audio condition is processed at a semantic level in the AMN's time-window, i.e., the magnitude representations of bimodal numerals are activated. However, this more negative ERP response for close-distance numerals is in contrast to the distance effect of spoken number words in previous ERP research (Szűcs & Csépe, 2004b, 2005b). In previous research, a larger (i.e., more negative) N2 was found in the posterior electrodes for far-distance spoken number words, which is opposite to the current result. This contradictory finding can be due to the latency difference by distance discussed earlier for the onset of the MMN. That is, because the time-window of the AMN is pre-defined and fixed across condition and distance, it is possible that the time-window of the AMN (240 to 300 ms after stimulus onset) actually captures different cognitive processes especially given the latency difference between close and far distance in the preceding MMN. For example, because the latency of the MMN was earlier for close distances than for far distances, which shows that close-distance numerals are processed faster than far distance. Hence, it is possible that the magnitude processing has already been engaged for a close-distance deviant during 240 – 300 ms after stimulus onset, but not yet for a far-distance deviant in the same time-window.

#### 4.4.1.3 Raw waves

Other than the analyses and discussion for the components based on difference waves above, the non-parametric test also demonstrated the differences by distance on raw waves in the audiovisual and the auditory-only condition separately.

An early cluster found in the auditory-only condition shows a more negative EEG response for close-distance deviants than standard trials and far-distance deviants which starts from 60 ms after stimulus onset in the posterior electrodes. Interestingly, the same early cluster was not found in the audiovisual condition. This can be interpreted as the simultaneously presented visual digit attracts the attention from the mismatched spoken number words. A dominance of visual stimuli has been suggested in previous research (e.g., Posner, Nissen, & Klein, 1976), which suggests that the concurrent visual digit may cause less awareness to the auditory mismatch (the sound change from the previous standard to the current deviant) at the beginning of stimulus onset in the audiovisual condition. This explanation is contradicted to my prediction that the mismatch should be larger in the audiovisual condition than in the auditory-only condition, which then would indicate an integration between the bimodal numerals. However, it fits the current MMN results as there was no evidence showing an early integration for bimodal numerals. Instead, the auditory-only MMN was larger than the audiovisual MMN, which may suggest a larger surprise in the auditory-only condition than in the audiovisual condition. Hence, this less awareness to the auditory mismatch due to a concurrent visual stimulus may also explain why the auditory MMN was larger than the audiovisual MMN in the current experiment.

Following the earliest cluster, the next two clusters were found in both the audiovisual and the auditory condition. One is from 170 to 250 ms, the other one is from 250 to 346 ms post-stimulus onset. These two clusters show clear differences of EEG responses between close- and far-distance deviants. In the time-window of 170 to 250 ms, the far-distance deviant induces a negativity whereas the close-distance deviant induces a positivity. In contrast, in the time-window of 250 to 346 ms, the far-distance deviant induces a positivity whereas the close-distance deviant induces a negativity. These data patterns apply to both the audiovisual and the auditory condition. Because the EEG responses are similar across both unimodal and bimodal conditions, it may mainly reflect the processing of the auditory number word rather than the visual digit. Previous ERP studies also show distance effect in similar latencies when using auditory number words in a symbolic number comparison task (Szűcs & Csépe, 2004b, 2005b). Hence, the magnitude processing of the auditory number words in the current experiment likely falls in these time-windows as well.

The last cluster of significant difference between close and far deviants is only found for the audiovisual condition, from 346 to 438 ms after stimulus onset. In this time-window, the EEG responses to far-distance deviants are more negative than close-distance deviants. The larger negativity for the far-distance deviants in this time-window could be an N400 effect.

The N400 is a component which reflects the semantic congruency in a sentence. That is, a more negative EEG response in the posterior electrodes appears approximate 400 ms post-stimulus onset when a word is semantically unrelated, or strongly incongruent to the context in a sentence (e.g., He took a sip from the *transmitter*). Moreover, the amplitude of the N400 is modulated by the extent of congruency to the context. A moderate incongruent word can still induce a N400 (e.g., He took a sip from the *waterfall*), but not as strong as an unrelated word (Kutas & Hillyard, 1984). The N400 is also revealed in number-related tasks. For example, Niedeggen and Rösler (1999) conducted a multiplication verification task in which two operands were displayed sequentially first (e.g., '5' then '8') and then participants required to judge whether the following answer (e.g., '40') shown on the screen is correct or incorrect. The incorrect answers were either with a close or a far numerical distance to the true answers. The authors found that the N400 was small for a correct solution. An intermediate size of N400 was found for the incorrect answers which were close to the real answer, whereas a large N400 was found for the answers with a far distance to the real answer. This result not only shows that the N400 can reflect the numerical distance, but also implies that the numerical distance between numerals can be seen as a dimension of semantic congruency. Therefore, as a more negative EEG response for far-distance deviants is found in the current experiment, and only for the audiovisual condition, it may reflect the degree of congruency (in numerical distance) between the visual digit and the auditory number word.

To summarise, the results of non-parametric tests show the changes of distance effect over time. An early distance effect in the auditory condition starts from 60 ms may reflect the early mismatch detection about the sound change. Interestingly, it is interrupted or attenuated by concurrent visual digit in the audiovisual condition. After that, a distance effect shows in both conditions during 170 to 346 ms, which possibly reflects the magnitude processing of spoken number words. This also suggests that the early influence of visual digit has already disappeared after 170 ms. In the last time-window from 346 to 438 ms, a distance effect in the audiovisual condition suggests the magnitude processing of the mismatch in numerical distance between visual digits and spoken number words.

### 4.4.2 Modulation of distance on condition effect

#### *4.4.2.1 MMN and AMN*

Both the MMN and the AMN amplitudes showed a significant, and similar interaction between condition and distance. That was, only for the close-distance deviant, the amplitude of the auditory-only condition was more positive than the amplitude of the audiovisual condition. In contrast, there was no significant amplitude difference between the auditory-only and the audiovisual condition for the far-distance deviants. As indicated earlier, any difference between conditions denotes a deviation between the auditory and the visual stimuli in the audiovisual condition. Thus, the non-significant result for far-distance deviants suggests that the mismatch in distance between the visual digit and the spoken number word does not induce any further EEG responses in the latency of the MMN (the mean peak latency for far distance is 188 ms) and the AMN (240 - 300 ms).

A larger auditory-only MMN was unexpected beforehand. The experimental setting of the close-distance condition in the current study is somewhat similar to the experiment reported in Chapter 3. Compared to the distance of 1 used in the current study as a close distance, the constant distance of 2 between standard and deviant trials in the last experiment is also commonly considered as a small distance. Therefore, since there was no significant difference between the auditory MMN and the audiovisual MMN in the last experiment, the same no-difference result was expected for the MMN amplitude by condition in the current experiment.

From the definition of the integration (Froyen et al., 2008), the evidence of an integration is that the auditory-only MMN is smaller than the audiovisual MMN. Thus, the current result cannot be explained by Froyen et al.'s definition. Priming studies may be able to help to explain the current unexpected result in the MMN (Kouider & Dehaene, 2009; Reynvoet & Brysbaert, 2004; Reynvoet, Brysbaert, et al., 2002): Firstly, the representations of close-distance numerals have been somewhat 'primed' by repetitive standard numbers because they are numerically close on the mental number line. Hence, this effect is only shown for close distances, but not for far distances. Secondly, the cross-modal numerals in the audiovisual condition 'double primed' the magnitude representations of numbers close by, thus making a less surprise when seeing a close-distance deviant in the audiovisual condition in comparison with seeing the same deviant in the auditory-only condition. This explanation also implies the presence of an automatic (not intentional), amodal (at least for both auditory and visual) magnitude representation for numbers.

The early MMN amplitude difference between conditions suggests that the magnitude processing for the mismatch in numerical distance between bimodal numerals is triggered earlier by the current paradigm. Compared to the previous experiment, the current experimental settings were similar in most parts except for two changes. First, the diversity of the deviants is larger in the current design. There are four different deviants in the current study (i.e., 1, 4, 6, and 9), instead of a constant deviant in the last experiment for each participant. More importantly, the distance between the spoken number word and the visual digit varies (i.e., either 1 or 4) in the current study, instead of staying constant as in the last experiment. Previous research has pointed out that it is difficult for people to attend to repetitive stimuli or unchallenging task (Robertson & O'Connell, 2010). Therefore, these modifications of experimental settings in the current study could possibly attract participants' attention more in an early stage, causing an earlier involvement of the magnitude processing for the mismatch between visual and auditory stimuli. In other words, a variety of deviants is important for the MMN result in the current study. Hence, one can expect that the current MMN amplitude difference between conditions for close distances would disappear (as it was in Chapter 3) if there is only one constant close-distance deviant (e.g., 6) and without far-distance deviants in the current paradigm.

In contrast to the discrepant results with respect to the MMN, the results of the AMN amplitude were similar across the previous and the current experiment. That is, the auditory AMN was more positive than the audiovisual AMN in the previous experiment, and the same data pattern was also found in the current experiment for the close-distance condition. The findings from the AMN suggest that the mismatch between visual digits and auditory number words in the audiovisual condition happens during 240 to 300 ms after stimulus onset in both experiments when the numerical distance between the visual digit and the auditory spoken number word is equal to or smaller than 2.

However, although the AMN did not show any difference between conditions for far-distance numerals, it did not guarantee that the mismatch between a far-distance spoken number word was not processed at all. As mentioned earlier, there was an around 50 ms difference between the MMN latencies of close and far distances. Since I calculated the mean amplitude in a fixed time-window (240 – 300 ms) for the AMN, it might capture different stages of processing for close and far distances. For example, it was possible that the numerical mismatch between bimodal numerals for far distances was reflected in an EEG response in a time-window which was later than 300 ms after stimulus onset. Hence, some exploratory analyses may be necessary to further understand the EEG responses in the current experimental setting.

In summary, the interaction between condition and distance found in the MMN and the AMN suggests that an automatic, and perhaps magnitude processing of numerals is involved in the current passive paradigm. More importantly, there is only evidence for the magnitude processing is for the close-distance numerals, but not for the far-distance numerals. This indicates that an automatic processing of the mismatch between visual and auditory stimuli only happens when there is a larger overlap between numerical representations.

In the next section, I will further discuss and compare the EEG responses of close, far-distance deviants, with standard trials.

#### *4.4.2.2 Raw waves*

With using the voltage difference of audiovisual and auditory deviants as dependent variable (but not a difference wave as it was for the MMN and the AMN) for ANOVAs in all four time-windows, the distance effect was found in the first and the last time-window, that was, during 60-170 ms and 346 – 438 ms after stimulus onset. In addition, although the main effect of distance was not significant during 250 – 346 ms, the direct comparison between close- and far-distance deviants showed a marginally difference (*p* = .05; see

Figure 4-6).

Moreover, the amplitude differences between conditions (VA minus A) of close-distance deviants are in general more positive than far-distance deviants (see

Figure 4-6; for more details by caudality, see Figure B7 on page 260). This is also in line with the inference from the results of the difference waves earlier, that is, the close-distance spoken number words, but not the far-distance spoken number words, should induce a more positive amplitude for the cross-modal condition than for the unimodal condition. However, as the distance effect happens in an early time-window as well as in a later time-window separately, the same relationship between EEG responses of close and far distances (close > far) may represent different cognitive activities in different time-windows.

In the early time-window during 60 – 170 ms, the more positive amplitude differences for close distances than for far distances might be related an earlier initiation for the processing of close-distance spoken number words. This could be due to the representations of close-distance numerals have been somewhat activated by recurring standard number, which is similar to a priming paradigm (Reynvoet & Brysbaert, 2004; Reynvoet, Brysbaert, et al., 2002). This probably makes a lower mismatch detection threshold for close-distance numerals than for far-distance numerals, and thus leading to an earlier EEG response for close distances. The faster MMN latency for close distances than for far distances also supports this argument. The more negative EEG response in the auditory-only condition than in the audiovisual condition for close distances also fits the priming explanation. That is, the cross-modal condition 'double primed' the representation of close distances compared with the unimodal condition. Thus, a 'smaller surprise' for the mismatch in the audiovisual condition leads to a smaller negativity compared to the auditory condition. In addition, this explanation may suggest that the magnitude representation has been at least partially involved at this early stage, so that the different spoken number words can be differentiated, then leading to different initiative processing for close- and far-distance number words.

In the last time-window, 346 – 438 ms post-stimulus onset, the close-distance deviants again elicit more positive amplitude differences than far distances as well as standard trials, whereas the amplitude difference of far-distance deviants is not different from standard trials, just like the data pattern in the first time-window during 60 – 170 ms. However, as this time-window is relatively late for a mismatch detection (late for a usual MMN), it is likely that this similar EEG response represents at least partially different cognitive activities other than detection, such as magnitude processing of the semantic mismatch between visual digits and auditory number words in the audiovisual condition. As mentioned earlier, the N400 reflects the semantic congruency in an arithmetic verification task. A more negative N400 appears when there is a larger numerical distance between the displaying number and the correct answer (Niedeggen & Rösler, 1999). In the current time-window, the relationship between close and far distances in terms of EEG amplitude difference is consistent with a classic N400 performance. That is, a far distance elicits a more negative EEG responses than a close distance. However, the far distances behave similarly to the standard trials without any semantic incongruency; hence, the N400 may not be able to fully explain the EEG responses between all three trial types in the current time-window. Some studies have suggested a late MMN that can appear in an auditory oddball paradigm after 400 ms post-stimulus onset (Cheour, Korpilahti, Martynova, & Lang, 2001). The late MMN only appears in auditory words but not in pseudo-words or complex tones. Thus, it has been suggested that the early MMN may reflect more about acoustic differences between a standard and a deviant sound, whereas the late MMN reflects more about the lexical mismatch between auditory stimuli, which is at a semantic level (Korpilahti et al., 2001). However, although the late MMN can explain the more negative EEG responses for far distances than for close distances, it still cannot explain the similar performance in terms of EEG amplitude difference between standard trials and far-distance deviants.

Considering the relationship between close and far distances in all time-windows, it shows that except for the time-window during 170 – 250 ms, close distances always elicit a more positive amplitude difference than far distances. Interestingly, a recurring distance effect in EEG responses has also been observed in an adaptation paradigm with visual Arabic digits (Hsu & Szűcs, 2012). In Hsu and Szűcs's adaptation paradigm, a numerically deviant Arabic digit followed several (either 6 or 8) to-be-adapted Arabic digits. The deviant digit was either numerically close, or numerically far to the standard digit. Participants did not require to do any responses to either the to-be-adapted digits or the deviant digits. The authors discovered a recurring distance effect that the visual digits with a far distance elicited a more negative EEG response in three separate time-windows during 204 – 438 ms after stimulus onset. They thus suggest this recurring distance effect is "related to the implicit nature of semantic analysis" (Hsu & Szűcs, 2012). Their adaptation paradigm is fairly similar to the current oddball paradigm as no responses are required and the number of deviants are few compared to total trials, perhaps a recurring distance effect is an EEG performance specifically related to this kind of passive tasks. However, although Hsu and Szűcs (2012) further investigated their EEG data with a frequency analysis, they only pointed out that there are two separate mental events, but without giving an explicit explanation about what exactly the function of the mental events, and how these separate mental events induce the recurring distance effect in ERPs.

In summary, the investigation of the relationship between close-, far-distance deviants and standard trials across time-windows shows a distance effect in EEG amplitude differences in both the early and the late time-window. Considering the latencies of time-windwos, the early distance effect may be more related to an early mismatch detection for close-distance number words because of a pre-activated representation by standard numbers, whereas the late distance effect may be more related to magnitude processing of the semantic mismatch between visual digits and auditory number words. Since no responses are required in the current experiment, these results suggest that there is an automatic, abstract magnitude representation for at least audiovisual numerals. However, either the N400, or the late MMN cannot fully explain the EEG responses in the late time-window. In addition, the similarities between the current experiment and an adaptation paradigm suggest more EEG research without an active task is needed for further clarifying the processing of numerals without a response.

### 4.4.3 Correlations

The correlational results are not conclusive in the current experiment. In Chapter 3, significant correlations were found between the MMN and the AMN amplitude difference (i.e., audiovisual minus auditory-only) and individual WRAT scores. That was, the more negative the amplitude differences were, the better participants performed in the standardised mathematical test. However, in the current study, the correlation between the MMN, AMN and the WRAT scores were non-significant. Furthermore, descriptively opposite, positive correlations, though not significant, were found between the AMN amplitude and the individual WRAT scores.

Similar correlational analyses will be conducted again in the next chapter. It will provide another chance to investigate the relationship between individual mathematical performance and EEG responses to the current experimental paradigm. The correlational results across all experiments will be further discussed in the general discussion.

### 4.4.4 Conclusion

In Chapter 4, I failed to find a larger audiovisual MMN compared to an auditory MMN, which is consistent with Chapter 3. This result thus again shows that there is no electrophysiological evidence supporting an early integration between spoken number words and Arabic digits as the integration between letters and speech sounds (Froyen et al., 2008). However, different EEG responses between the close and far distance are shown in the MMN (50 – 250 ms) and the AMN (240 – 300 ms). The shorter MMN latency for the close distances indicates that the close-distance numerals are initially processed earlier than the far distances. Moreover, the significant effect of condition in both the MMN and the AMN amplitudes which only appeared for close distances but not for far distances suggests that the mismatch between the visual digit and the spoken number word triggers specific brain processing only when the numerical distance between the simultaneous displayed audiovisual stimuli is small enough.

Furthermore, when investigating the raw waves by using the time-windows showing the differences between close and far-distance deviants acquired from non-parametric tests, I found that the EEG responses of close and far distances start to diverge as early as 60 ms after stimulus onset: the close distances induce a more positive amplitude difference between conditions compared to the standards whereas the amplitude of far distances is the same as the standards. These different EEG performances for close and far distances show in both the early and the late time-window, indicating that: Firstly, there is an early detection for the close-distance auditory number word. In addition, this early distance effect shows that the auditory number words are at least partially recognised or differentiated at an early stage. Second, perhaps the distance effect in the late time-window indicates the magnitude processing for the semantic mismatch between visual digits and auditory number words. Although the interpretations of some EEG performances remain unclear, some similar EEG responses are reported in a previous adaptation paradigm in which no responses are required (Hsu & Szűcs, 2012). This suggests that the EEG responses may largely depend on task demands, and thus using a passive task in an EEG study is important to investigate the 'pure' brain activities of stimuli.

In the next chapter I will further manipulate the SOA with the current paradigm. It has been widely suggested that the SOA is important for an integration (Spence, 2011; Stevenson et al., 2010; Stevenson & Wallace, 2013; van Wassenhove et al., 2007), and different stimuli may have different binding time-window for the integration in different tasks (Stevenson & Wallace, 2013). There are both acoustic and semantic differences between the speech stimuli used in Froyen et al. (2008) and the numerals used in the current study. Thus, adding more SOAs to investigate whether the SOA would influence the current results, such as the distance effect, would possibly help to further understand the correspondence, if not the integration, between Arabic digits and spoken number words.

# Chapter 5 – The influence of timing on cross-format integration

## 5.1 Introduction

In Chapter 4, again I failed to find a larger audiovisual MMN in comparison with an auditory MMN. According to previous reading studies (e.g., Froyen et al., 2008), this indicates that there is no evidence for an early integration between Arabic digits and spoken number words. However, an unexpected, opposite direction of effect in the MMN is revealed for close distances. That is, the auditory MMN is larger than the audiovisual MMN. This opposite effect may be because the magnitude representations of close-distance numerals have been triggered by repetitive standard trials due to closeness of representation on the mental number line (Reynvoet, Brysbaert, et al., 2002). This unexpected result also points out the semantic differences between speech stimuli and numerals. Hence, I decided to further investigate the correspondence, if not the integration, between spoken number words and Arabic digits by adding SOAs in the current oddball paradigm.

It has been suggested that the multi-sensory integration depends strongly on the context, e.g., the tasks and the stimuli (e.g., Stevenson & Wallace, 2013; van Atteveldt et al., 2014; van Wassenhove et al., 2007). Stevenson and Wallace (2013) found that when participants are requested to judge the simultaneity of audiovisual stimuli presented with an SOA, the SOA range that participants would perceive the stimuli are displayed simultaneously is narrower for simple tones and flash light than for letters and speech sounds. This specific SOA range for the multi-sensory stimuli to trigger the integration processing is sometimes called the temporal binding window of integration.

The SOA design has been widely used for investigating the temporal binding window of audiovisual integration in previous research (Stevenson et al., 2010; Stevenson & Wallace, 2013; Ten Oever, Sack, Wheat, Bien, & van Atteveldt, 2013; van Wassenhove et al., 2007). The temporal proximity between audiovisual stimuli has been shown critical for the integration. For example, the well-known McGurk illusion (McGurk & MacDonald, 1976), which refers to a fusion between the auditory speech sound and the visual clip of lip movements, only happens within the time-window from -34 ms audio lead to +173 ms audio lag (van Wassenhove et al., 2007). Froyen and colleagues (2008) have indicated that the cross-format integration between letters and sounds is the strongest, i.e., the audiovisual MMN amplitude is the largest, when the audiovisual stimuli are displayed simultaneously. With the increase of SOAs, this integration effect becomes smaller linearly (but see Žarić, González, Tijms, & Molen, 2014). A similar modulation effect of SOA was also found in an fMRI study, that was, the brain activity in the anterior and posterior auditory association cortex, the anterior superior temporal plane and the planum temporale, declined rapidly with temporal asynchrony (van Atteveldt, Formisano, Blomert, et al., 2007). However, other research indicates a maximal integration should happen when the visual information is presented before the auditory information due to visual information naturally precedes the sounds (Zampini et al., 2003). Nevertheless, all these studies agree that the audiovisual integration only happens when stimuli are displayed temporally close to each other, and this integration effect should decline with the increase of the SOA.

To the best of my knowledge, the distance effect between audiovisual numerals had not been systematically investigated with an SOA design before my behavioural experiments in Chapter 2 (for my behavioural design, see

Figure 2-1 on page 66). By conducting a matching task, a clear SOA influence on distance effect was revealed in experiments reported in Chapter 2 with different ranges and intervals of the SOAs. Also, the largest distance effect was found when the audiovisual numerals were displayed simultaneously in both experiments (but see Sasanguie & Reynvoet, 2014), and the distance effect declined with the increase of the SOA. Now I will further investigate whether I can get a similar pattern in EEG responses without any required responses.

As multi-sensory integration highly depends on the context, there are still debates about when the integration should take place after the multi-sensory stimuli are displayed (Koelewijn et al., 2010). However, early ERP responses (< 200 ms) are widely shown and interpreted as reflecting the audiovisual integration processing in previous research (e.g., Talsma, Doty, & Woldorff, 2007; Talsma & Woldorff, 2005), including the studies using speech sounds (Colin et al., 2002; Froyen et al., 2008; Möttönen, Schürmann, & Sams, 2004). As early processing was also observed in the last experiment, it can possibly be related to a fast, over-learned correspondence which behaves differently from the integration discovered between letters and speech sounds. As explained earlier, the magnitude representation of close-distance numerals may be already triggered by repetitive standard trials via a 'priming-like' spread out effect on the mental number line (Reynvoet, Brysbaert, et al., 2002). Unlike the comparison distance effect which has been also reported when using letters in a comparison task (e.g., judging whether 'a' is before or after 'e' in an alphabetic order), the priming distance effect has been restricted to numerals but is absent for letters (van Opstal et al., 2008). Hence, as previous studies have indicated that the temporal asynchrony between audiovisual stimuli essentially influences the integration effect (Froyen et al., 2008; Stevenson et al., 2010; Stevenson & Wallace, 2013; van Atteveldt, Formisano, Goebel, et al., 2007; van Wassenhove et al., 2007), an SOA manipulation can help to further understand whether the early processing found in the last experiment was reflecting a fast, special correspondence, if not an integration, between Arabic digits and spoken number words.

More specifically, according to Froyen and colleagues' hypothesis (2008; 2009), a larger audiovisual MMN reflects an integration, while no difference between auditory and audiovisual MMNs shows no integration. Hence, the unexpected result in Chapter 4, a larger auditory MMN, could not be explained by this definition. This novel finding thus does not rule out the possibility that the integration happened between spoken number words and Arabic digits. Instead, it may suggest a different correspondence between spoken number words and Arabic digits compared with the correspondence between letters and speech sounds, and is reflected by an unexpected relationship between the auditory and audiovisual MMN amplitudes.

In the current experiment, one main purpose is to examine whether the larger auditory MMN than the audiovisual MMN is modulated by SOA. As indicated earlier, it has been known that the multi-sensory integration only happens when stimuli are displayed simultaneously or within a short SOA (usually no more than 300 ms), and the integration is usually stronger when the SOA is shorter. Hence, if the auditory MMN remains larger than the audiovisual MMN regardless of SOA, this may suggest the unexpected result did not reflect the integration between spoken number words and Arabic digits. In contrast, if the relationship between the auditory MMN and the audiovisual MMN changes with the increase of the SOA, then it may suggest the unexpected ERP activities, the larger auditory MMN than the audiovisual MMN, indicated a special semantic correspondence between bimodal numerals which is different from the correspondence between letters and speech sounds.

To examine the SOA influence of the MMN amplitudes, two extra SOA manipulations were used in the current study. Namely, visual digits presented 100 ms (VA100) or 200 ms (VA200) before the onset of spoken number words. There is no auditory-precedes-visual condition since previous research has indicated that the temporal binding window of integration is often asymmetric, tending to be more tolerant to the audio lag than audio lead conditions (e.g., Stevenson & Wallace, 2013; van Wassenhove et al., 2007).

Another idea is to investigate whether the different EEG responses by distances, i.e., the distance effect, found in Chapter 4 are modulated by SOA. A modulation of SOA on the distance effect has been shown in Chapter 2 (see Figure 2-4 on page 69 and Figure 2-8 on page 78). If the size of the distance effect varies in different SOAs, it may indicate that the distance effect, even the behavioural distance effect in a matching task, can be seen as an index of the cross-format integration between spoken number words and Arabic digits.

In addition, as in Chapter 4, the correlation between EEG responses and individual mathematical performance will be also examined in the current study. It has been shown that the integration between letters and speech sounds, i.e., a larger audiovisual MMN, only exists in normal reading adults (Froyen et al., 2009, 2008; Mittag et al., 2013), but not in dyslexic adults (Mittag et al., 2013) nor for children with less than 4 years reading experience (Froyen et al., 2009). Hence, if the integration between Arabic digits and spoken number words is revealed in the current study, a positive correlation would be expected between the MMN amplitude and the mathematical performance.

## 5.2 Method

### *5.2.1 Participants*

Thirty adults (*M* = 20.07 years, *SD* = 1.44 years, range from 18 – 24 years; 17 males) participated either for course credit (1.5 hrs) or monetary compensation (£9). All participants also attended the previous ERP experiment[20] (the experiment in Chapter 4). Hence, participants in chapter 5 are a subset of participants of Chapter 4. All

[20] This was on purpose because the experiment in Chapter 4 was also one of the SOA conditions in the current experiment (VA0, bimodal numerals were displayed simultaneously), so that I could compare the ERP activities between 0, 100, and 200 ms SOA conditions. Since ERP activities are usually more consistent within a subject, I decided to use a within-subject design to maximize the power for detecting the experimental effect, even though this setting might lose some external validity.

participants were British except a Gambian raised in the UK. All participants spoke English as their first language and were right-handed. The study received ethical approval from the Department of Psychology Ethics committee. All participants gave written informed consent.

### *5.2.2 Stimuli and Procedure*

The procedure of the current study was the same as the experiment in Chapter 4, except they had completed the WRAT-4 math test (Wilkinson & Robertson, 2006) and the WASI-II matrix reasoning test (Wechsler & Hsiao-pin, 2011) when they were attending the ERP experiment described in the last chapter. Hence, participants only performed a computerised oddball paradigm in a quiet room while wearing the EEG cap. Including the setting up, the whole experiment took around 1.5 hours to complete.

The computerized oddball paradigm was basically the same as the audiovisual condition (VA) in the last experiment, except that the visual digits and the spoken number words were displayed with different SOAs. As all participants in the current study had attended the previous experiment in Chapter 4, the condition that visual digits and auditory number words were displayed simultaneously (VA0; was named as VA condition in Chapter 4) had been conducted already. Thus, there were two audiovisual conditions for the current experiment, namely, the VA100 and the VA200 condition. The stimuli were the same as the last experiment, number five was always the standard, and the spoken number words, /four/ and /six/, were the close-distance deviants while /one/ and /nine/ were the far-distance deviants. The visual digit was always displayed first in both standard and deviant trials. In a trial, the visual digit, ‘5’, was displayed first in the middle of screen, and then, for a standard trial, the spoken number word, /five/ was played, or for a deviant trial, one of the other spoken number words (i.e., /one/, /four/, /six/, or /nine/), was played through loud speakers after either 100 ms or 200 ms, depending on the SOA condition.

The experiment was composed of two blocks. One contained only the VA100 condition, and the other one was the VA200 condition. This block design was based on Froyen and colleagues' research (2008, 2009), which was the same as my previous experiments in Chapter 3 and 4. Participants were not told about the manipulation of audiovisual asynchronies prior to the task [21]. All participants completed both conditions with a counter-balanced order. The number of standard and total deviant trials was the same as in the last experiment, 400 and 96 respectively. Each deviant trial was displayed 24 times (this made 48 trials in total for each level, close and far, of distance). The same 48 picture trials as in previous experiments were used to make participants attend to the task. The overall accuracies for picture trials were close to ceiling across conditions (VA100 condition: $M$ = .98, $SD$ = .03; VA200 condition: $M$ = .98, $SD$ = .03).

### *5.2.3 EEG acquisition and pre-processing*

For the VA100 and the VA200 condition, the details of EEG acquisition and pre-processing were very similar to the previous experiment described in Chapter 3 (page 96) and Chapter 4 (page 133). Although there were asynchronies between auditory and visual stimulus onset time, the length of each epoch was still 800 ms, from -200 to 600 ms referencing to visual stimulus onset time. The baseline correction was also -200 to 0 ms referencing to visual stimulus onset time for each SOA condition. Same criteria for the artefact rejection as in Chapter 4 applied to the current data. Participants were excluded for further analyses if the close or far distance condition had less than 30 trials (Luck, 2005). Following this criterion, only the data from 21 of 30 participants was entered further data analyses (Mean age = 20.19 years, $SD$ = 1.44 years, range from 18 – 24 years; remaining trials: $M$ = 85.5%, $SD$ = 9.2%). The selection criteria for compensating the standard trials to the unequal number of trials

[21] None of my participants could tell that the SOA was different in two blocks after they completed the experiment nor did they notice that the spoken number words and Arabic digits were not displayed simultaneously.

between standard and deviant trials were the same as in the last experiment (page 133).

### 5.2.4 ERP analysis

At the beginning of this section, I would like to emphasise again that the current study did not re-conduct the auditory-only nor the VA0 condition (was named as audiovisual condition in Chapter 4). Instead, as all participants in the current study had attended the EEG experiment in Chapter 4, it allows me to directly include the data of these two conditions into the analyses and compare the SOA influences on the distance effect on different ERP components.

#### 5.2.4.1 Difference waves

The MMN and AMN amplitudes were examined as in the previous two experiments. The same method and time-windows to extract the MMN (50 – 250 ms after stimulus onset) and the AMN (240 – 300 ms after stimulus onset) was conducted separately for each participant in each time-window, and the data was then used for further statistical tests. The current study focused on the brain responses after both visual and auditory stimuli were presented, thus the brain activities before the auditory stimulus onset were not analysed. Also, to make the comparisons among SOAs easier to comprehend, the stimulus onset time mentioned in the text from now on was all referenced to the auditory stimulus onset in each SOA condition, but not the visual onset time, unless stated otherwise.

Like the analyses in Chapter 3 and Chapter 4, first I checked whether there were significant MMNs. Twelve one-sample *t*-tests were thus conducted separately for each electrode group in the VA100 and the VA200 condition. Then, to examine how the SOA can influence the EEG responses to the deviation between visual digits and auditory number words, four-way ANOVAs (distance: close & far distance; SOA: VA0, VA100, and VA200; caudality: anterior & posterior; hemisphere: left, right, and midline) were conducted separately for the MMN amplitudes and latencies as well as the AMN amplitudes.

For the ANOVAs of the MMN and the AMN amplitudes, instead of using the amplitude of each SOA condition (VA0, VA100, and VA200), the amplitude difference between each SOA and the auditory-only condition was calculated and used as dependent variable. The condition effect in each SOA was then examined by separate one-sample *t*-tests. This was designed to avoid too many separate ANOVAs, as well as to directly observe the influence of SOA on the condition effect (audiovisual[22] minus auditory[23]). In other words, whether the condition effect changed across SOAs.

#### *5.2.4.2 Raw waves*

Other than the analyses for the difference waves, the similar analyses as in Chapter 4 were conducted as well for the raw waves in the current study. This was because the pre-defined AMN's time-window looked not appropriate any more for the current study. As it was shown in the last chapter that the close distances might be processed earlier than the far distances, the AMN's time-window might capture different cognitive stages for close and far distances. Although the time-windows generated from a non-parametric test could not guarantee to completely capture all interesting EEG responses, at least they would be more fit to the current data in comparison with a pre-defined, fixed time-window.

Four-way ANOVAs (distance: standard, close, and far distance; condition: VA0, VA100, and VA200; caudality: anterior & posterior; hemisphere: left, right, and midline) were performed to investigate the interaction between SOA and distance in different time-windows acquired from the results of non-parametric tests (the details of non-parametric tests will be introduced in the next section). In the last chapter, the amplitude difference between the audiovisual and the auditory deviants on raw waves interacted with distance[24]. Therefore, in the current study the same amplitude difference (each audiovisual

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[22] All the SOA conditions were also audiovisual conditions.
[23] The data of the auditory-only condition had been collected in Chapter 4.
[24] Please note that this is not the condition effect as the difference of visual stimuli in two kinds of deviants was not considered here.

deviant[25] minus the auditory deviant) was also used as the dependent variable for the ANOVAs. The standard trials were also included in the analyses as in Chapter 4, in order to better observe which distance of deviant induced a different response compared to the standard.

All the statistics were reported as Greenhouse-Geisser corrected (Luck, 2014), and the post-hoc comparisons were adjusted by Bonferroni correction unless stated otherwise.

### 5.2.5 Permutation test

Like the data analyses in Chapter 4, the pre-selected MMN and AMN components are based on the difference waves. Information in raw waves can be lost when looking at difference waves, thus the cluster-based permutation was again introduced in the current study to explore the raw waves. The cluster-based permutation test was conducted by using the 'Mass Univariate ERP Toolbox' (Groppe et al., 2011) within MATLAB as in Chapter 3 and Chapter 4.

I ran 4 separate non-parametric tests for VA0, VA100, VA200, as well as auditory-only condition (VA0 and auditory-only condition were not re-collected but was run from a sub-dataset of Chapter 4 with 21 subjects).

To compare the brain responses, the brain data of the VA0, VA100, and VA200 were aligned referencing to the auditory stimuli onset. The duration for an epoch was 800 ms, from -200 to 600 ms for the VA0 condition, from -300 to 500 ms for the VA100 condition, and from -400 to 400 ms for the VA200 condition with a reference to the auditory stimuli onset.

[25] Namely, they were VA0 minus Auditory, VA100 minus Auditory, and VA200 minus Auditory.

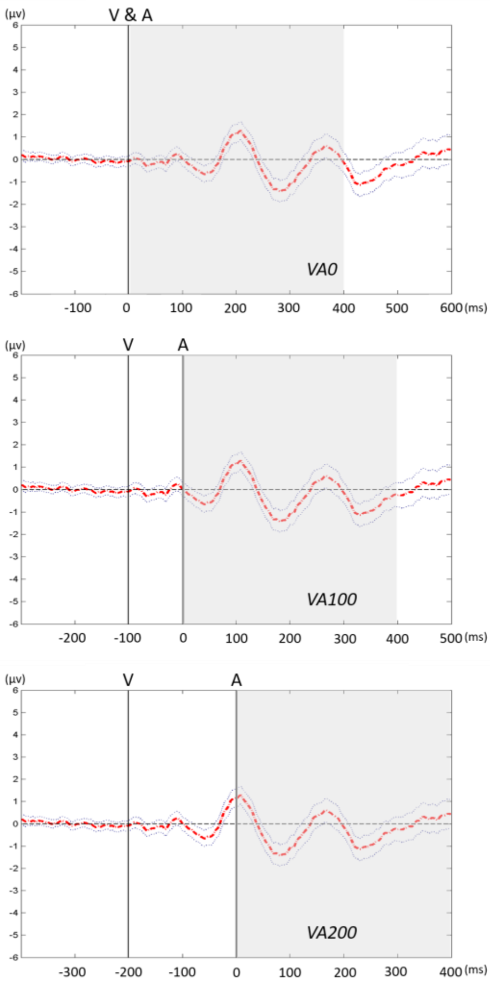


*Figure 5-1.* The illustration for the alignment across SOA conditions. The grey area are the time-windows used for the comparisons. V = Visual stimulus onset; A = Auditory stimulus onset. The brain wave is only an example but not the real data from the current result.

The meaningful comparison was between 0 to 400 ms[26] after auditory stimulus onset across SOA conditions (see Figure 5-1, the grey areas). The EEG responses before the auditory stimulus onset were not investigated because in the VA100 and the VA200 condition they exclusively reflected the preceding visual digit but was not related to the auditory number word.

[26] 400 ms is the maximum for the VA200 condition since the length of an epoch was the same and the visual digit was shown 200 ms earlier than the VA0 condition.

The time points from 0 to 400 ms at 30 scalp electrodes were included in the test, which made 6,000 comparisons in total. Other parameters were also the same as the ones in the previous chapters (see from page 99 in Chapter 3). Similar to Chapter 4, the non-parametric test here helped to identify the difference between close versus far distance in each SOA condition. The time-windows showing the significant differences then used for extracting the mean amplitudes for the further ANOVAs.

### *5.2.6 Correlation analyses*

The correlation analyses in the current study were performed to examine the relationship between EEG responses and mathematical performance in each SOA condition. The analyses were conducted separately for close and far distance. More specifically, the amplitude differences between conditions (audiovisual minus auditory-only) by distance were used as the dependent variable for brain responses. In addition, the amplitude differences between distances (close minus far) by condition were also examined in the current chapter.

## 5.3 **Results**

### *5.3.1 Difference waves*

Similar to Chapter 3 and 4, the difference waves (standard minus deviant) were examined first for the MMN and the AMN.

Firstly, in Figure 5-2 the overall waves combining the close- and far-distance deviants of all SOA conditions are displayed. Similar to Chapter 4, only the EEG responses at the anterior midline electrode group are shown here as previous research indicated that the MMN is usually found at the frontocentral electrodes (Näätänen et al., 2007), also the brain data is similar in three levels of hemisphere (left, right, and midline). The EEG responses of all six electrode groups were shown in Figure C1 on page 281.

Based on visual inspection, the difference wave of VA100 is slightly more positive than VA0 and VA200 within the first 100 ms after auditory stimulus onset. A positivity at around 200 ms is shown for all SOA conditions. After the positivity at 200 ms, the difference wave of VA0 decreases with time until the end of the epoch, whereas another positive peak can be observed for the VA100 and VA200 in the late 200 ms.

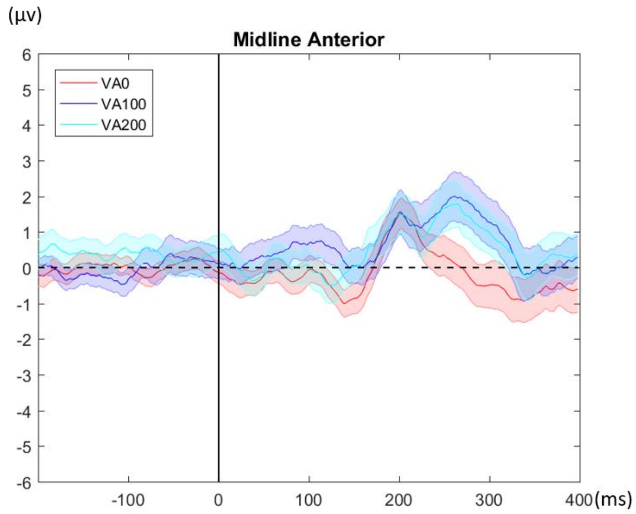


*Figure 5-2.* Difference waves of overall deviants (standard minus the average of close and far-distance deviants) at the anterior midline electrode group across all SOA conditions (±1 *SE*).

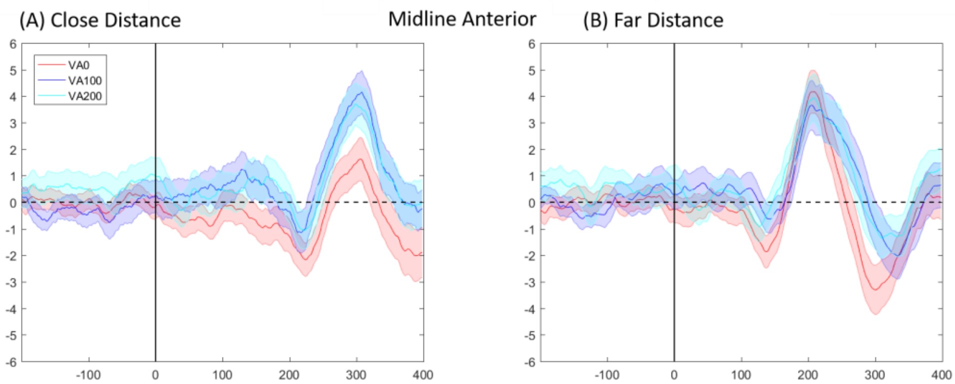


*Figure 5-3.* Difference waves of (A) close distance and (B) far distance (standard minus deviant) at the midline anterior electrode group (±1 *SE*).

Inspecting the difference waves in more details by looking into the data of close and far distance separately, the data patterns are similar in general but there are some differences among SOA conditions (see Figure 5-3). In close distance, in general the difference wave of VA0 is more negative compared to the VA100 and the VA200 condition. It becomes more obvious at the positive peak at around 300 ms after auditory stimulus onset. In far distance, the difference waves among all three SOA conditions are very similar, except that the VA0 has a more negative peak at around 300 ms compared to the other two SOA conditions (for the difference waves at all the six electrode groups, see Figure C2 on page 282 for close distance and Figure C3 for far distance on page 283).

Furthermore, the similar patterns across all SOA conditions also indicated that the different latencies of the largest positive peak between close and far distance were shown again when audiovisual stimuli were displayed asynchronously. That was, the largest positive peak was at around 300 ms for close distance, while the largest positive peak was at around 200 ms after auditory stimulus onset for far distance.

In summary, from the visual inspection on difference waves, there was no striking difference among SOA conditions particularly within 200 ms after auditory stimulus onset. Also, the performance of the VA100 and the VA200 condition look very similar to each other. In close distance, the VA0 condition behaved somewhat differently from the other two SOA conditions in two time-windows. One is before 200 ms, the other one is at around 300 ms. In contrast, in far distance, the VA0 condition was very similar to the other two conditions, except that there was a more negative peak for the V0 condition at around 300 ms after auditory stimulus onset.

#### 5.3.1.1 MMN

Like the analyses in Chapter 4, the first analysis was to test if the MMN existed in the current paradigm with SOA manipulation. Twelve one sample *t*-tests were therefore conducted for the mean peak amplitudes of each electrode group in both the VA100 and the VA200 condition. In addition, to make sure that the VA0 and auditory-only dataset with 21 subjects was not fundamentally different from the original dataset, the same *t*-tests were conducted again for the audiovisual MMN and the auditory MMN on the current participants. The results showed that the MMNs of the six electrode groups were all significantly different from zero in both the VA100 and VA200 condition (all *p*-values ≤ .002, see Table C1 on page 287). All but one *t*-test (Auditory at left anterior: $p = .052$) were significant for the audiovisual (VA0) and the auditory MMN (see Table C2 on page 288). These results firstly show that there is a significant MMN also in the VA100 and the VA200 condition. Also, the MMNs in the audiovisual and the auditory condition were similar to MMNs shown in Chapter 4 (see Table B2 on page 262 for the *t*-tests results of the MMN), indicating that the current data of 21 subjects did not have major differences compared to the data of 36 subjects in the last experiment.

After the presence of MMN was confirmed, the next step was to examine how the distance effect interacted with the SOA. Similar to previous chapters, only the main effects, and the highest level of interactions related to the main interest of the current study, i.e., the distance or the SOA factor, will be reported in detail in the main text. The whole ANOVA tables and the means and *SD*s of each condition are reported in Appendix C.

A 4-way (SOA: VA0, VA100, and VA200; distance: close & far distance; caudality: anterior & posterior; hemisphere: left, right, and midline) ANOVA of the MMN amplitude differences (audiovisual minus auditory) was conducted first. There was no significant main effect of SOA ($F(1.4, 28.0) = 1.70$, $p = .21$, $\eta^2 = .08$). A marginally significant main effect was found on distance ($F(1, 20) = 3.88$, $p = .063$, $\eta^2 = .17$), showing that the amplitude difference of close distance ($M = -0.02$ μv, $SD = 1.96$ μv) was marginally smaller than far distance ($M = 0.84$ μv, $SD = 1.36$ μv). In addition, the interaction between distance and SOA was marginally significant ($F(1.8, 35.1) = 3.01$, $p = .068$, $\eta^2 = .13$).

Post-hoc comparisons showed that the amplitude difference was more negative for the close distance (*M* = -0.77 μv, *SD* = 1.78 μv) than the far distance (*M* = 0.75 μv, *SD* = 2.23 μv; *p* = .01) only when the audiovisual stimuli were displayed at the same time (see Figure 5-4), but there was no significant difference between two distances when the audiovisual stimuli were displayed asynchronously (VA100: *p* = .65; VA200: *p* = .15). There was no other significant effect related to the SOA or distance factor (see the means and *SD*s for each cell in Table C1 on page 294 and other effects of ANOVA in Table C2 on page 295).

According to the definition of integration from previous reading research (e.g., Froyen et al., 2008), integration exists when the audiovisual MMN is larger than the auditory-only MMN. Hence, I did a one-sample test for the amplitude difference between the visuo-audio and the auditory-only condition at each SOA condition.

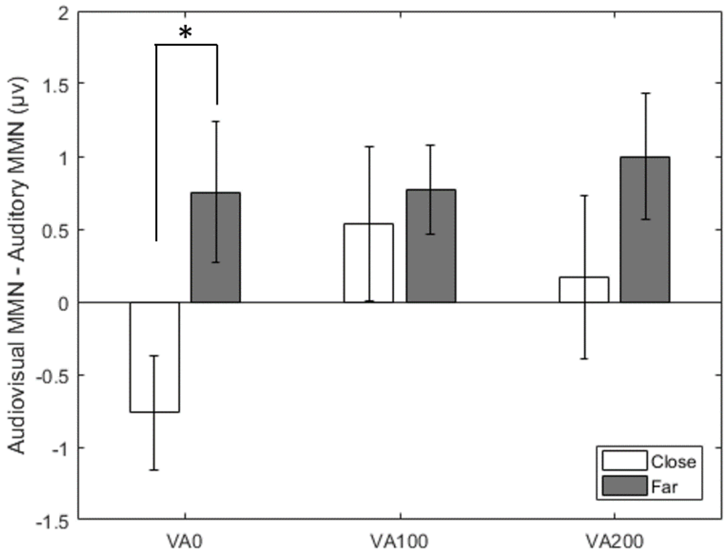


*Figure 5-4.* Amplitude difference of MMN by distance in each SOA condition. * shows its significance at 0.05 level.

The one-sample t-tests for the condition difference in each SOA by distance showed that: for the close distance, the audiovisual MMN was marginally more negative in comparison with the auditory-only MMN at VA0 ($t$(20) = -1.97, *p* = .063), whereas the MMNs were the same at VA100 ($t(20) = 1.01$, $p = .32$) and VA200 ($t(20) = 0.30$, $p = .77$). For the far distance, the audiovisual MMN was the same as the auditory-only MMN at VA0 ($t(20) = 1.54$, $p = .14$), whereas the audiovisual MMN was significantly larger (more positive) than the auditory-only MMN at VA100 ($t(20) = 2.53$, $p = .02$), and VA200 ($t(20) = 2.32$, $p = .03$).

Another 4-way ANOVA with same factors was conducted for the MMN latencies[27]. There was no significant effect of ($F(1.6, 31.8) = 1.16$, $p = .32$, $\eta^2 = .06$). A significant main effect was found on distance ($F(1, 20) = 114.16$, $p = < .001$, $\eta^2 = .85$), showing that the MMN latency was shorter for close distance ($M$ = 136 ms, $SD$ = 18 ms) than for far distance ($M$ = 190 ms, $SD$ = 18 ms). Other effects related to distance or SOA were not significant. See the full details of the current ANOVA in Table C4 on page 298.

After done the preliminary analysis of the AMN, the AMN's time-window again looked inappropriate for studying the modulation of SOA on condition or distance effect. Hence, I will not report the AMN's results in the main text. Please see page 289 in Appendix C for the results of the AMN in detail.

### 5.3.2 Other time-windows from raw waves

#### 5.3.2.1 Results of non-parametric test

The procedure of the non-parametric permutation test conducted in the current study was the same as in the previous experiment. Like in Chapter 4, the current non-parametric test was introduced for an exploratory purpose, to demonstrate the distance effect and to find the time-windows for further analyses (for the raw ERP waves, see Figure C1 on page 291 and Figure C2 on page 293)

[27] The reason not to use VA – A for the analysis of MMN latency was to make the current analysis comparable to the last experiment. The results from Chapter 4 showed that there were no latency differences between the audiovisual and the auditory condition, thus the current ANOVA only compared the audiovisual conditions of different SOAs. The means and *SD*s for the auditory condition was also reported in Table C3 on page 299, but they were not included in the current ANOVA of the MMN latency.

The brain responses for close and far-distance deviants were compared to each other in the VA100 and the VA200 condition separately with non-parametric tests. Similar to the distance difference found between the audiovisual and the auditory-only condition in Chapter 4, the results of non-parametric test showed large differences between the close and far-distance deviants in both the VA100 and the VA200 condition (Figure 5-5). In the VA100 condition, one negative cluster and one positive cluster of significant differences were revealed (family-wise error rate < .05). The results showed that the brain responses were more positive for the close-distance deviants than the far distances during 178 to 264 ms, while they were more negative during 264 to 358 ms after stimulus onset. In the VA200 condition, very similar time-windows were found. A negative cluster and a positive cluster of significant differences were revealed (family-wise error rate < .05). The results showed that the brain responses were more positive for the close-distance deviants than the far distances during 170 to 262 ms, while they were more negative during 264 to 352 ms after stimulus onset.

In order to compare the current study with Chapter 4, I also re-conducted the non-parametric tests for the VA0 condition and the auditory-only condition with the reduced number of participants of the current experiment (see Figure 5-6). The purpose was to find some similar time-windows as in Chapter 4. In the auditory-only condition, two negative clusters and one positive cluster of significant differences were revealed (family-wise error rate < .05). The results showed that the brain responses were more negative for the close-distance deviants than the far ones during 58 to 164 ms and 258 to 364 ms, while they were more positive during 176 to 254 ms after stimulus onset. In the VA0 condition, also two significant positive clusters and one negative cluster were found. The brain responses were more positive for the close-distance deviants than far-distance deviants during 156 to 264 ms and 350 to 398 ms, whereas more negative during 274 to 344 ms after stimulus onset. These clusters from the auditory-only and the VA0 condition were very similar to the ones reported in the Chapter 4.

Like the analyses in Chapter 4, these time-windows with slightly adjustment to avoid overlaps, 58 – 164 ms, 164 – 264 ms, 264 – 350 ms, 350 – 398 ms, were then used for the further ANOVAs to study the interaction effect between distance and condition. If the interaction effect found in Chapter 4 was an integration-like effect, then a decrease of the interaction should be revealed with the increase of SOA.

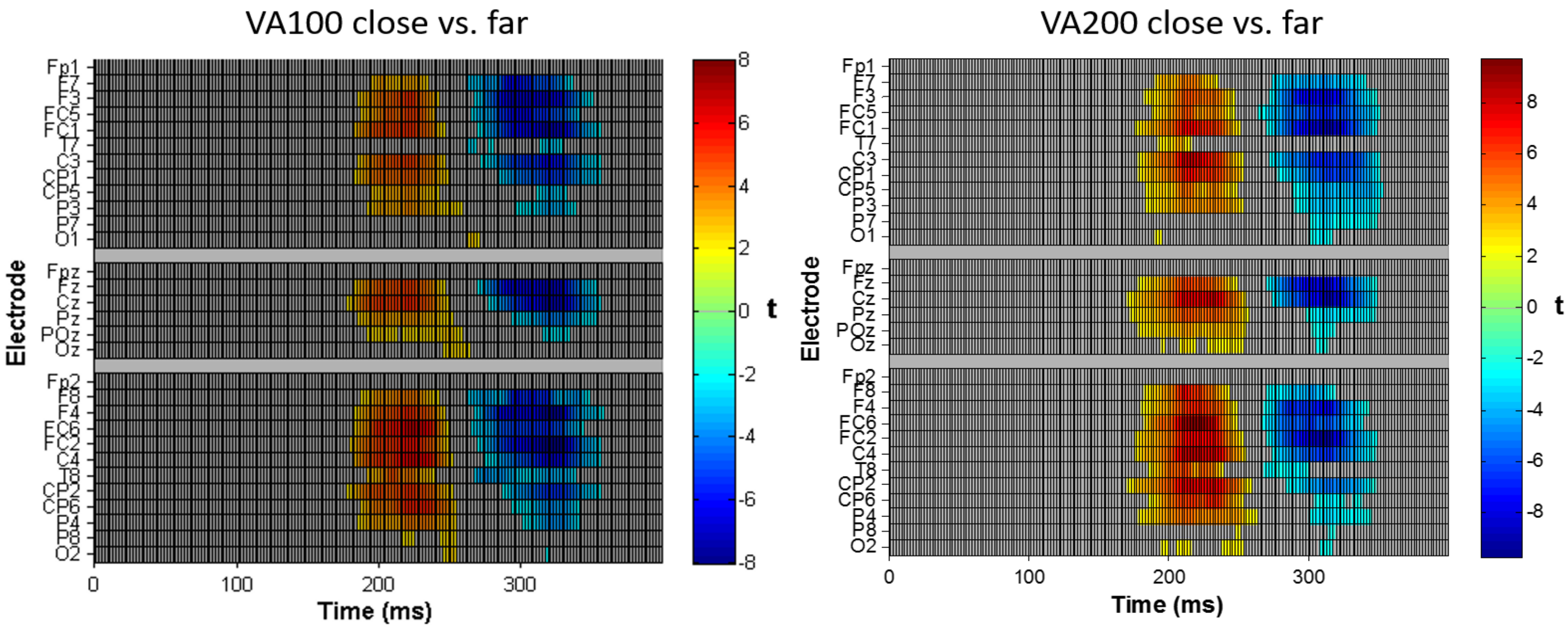


*Figure 5-5. The differences between close- and far-distance deviants (close minus far) revealed by a permutation test in the VA100 and the VA200 condition (p < .05).*

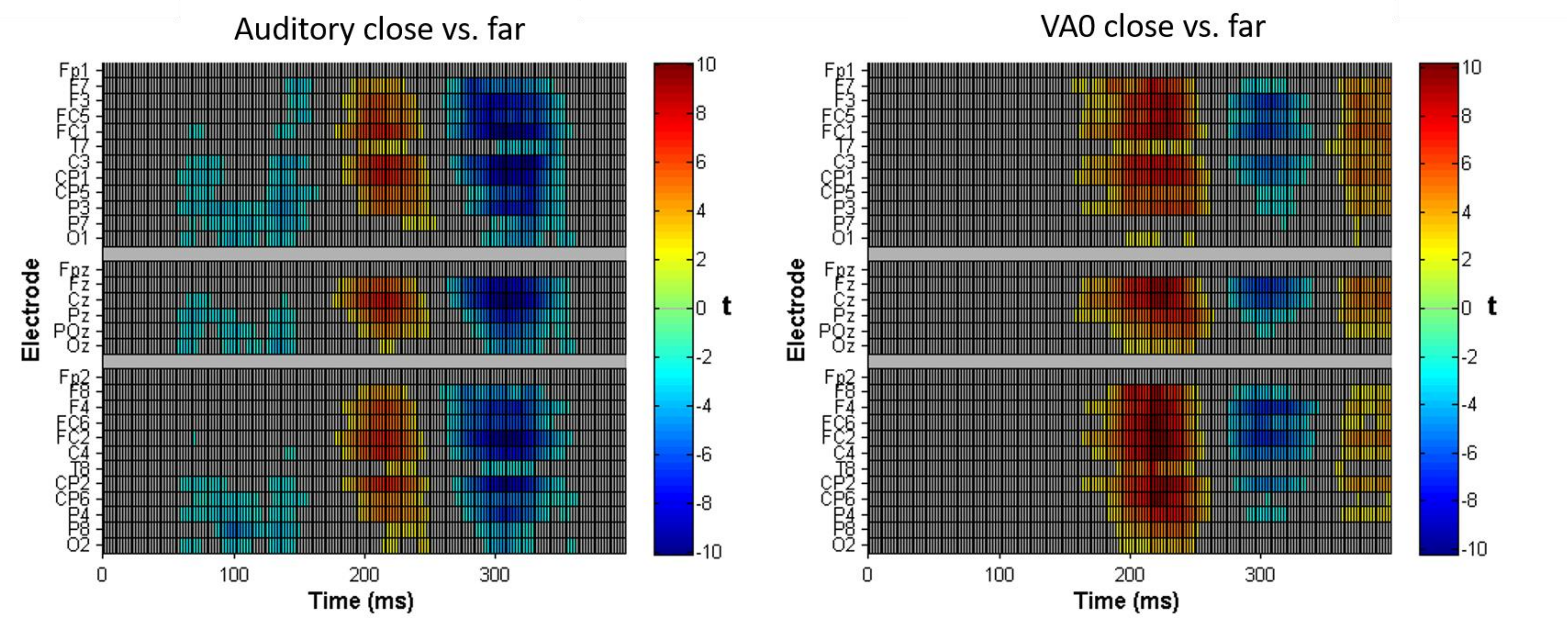


*Figure 5-6.* The differences between close- and far-distance deviants (close minus far) revealed by a permutation test in the auditory-only and the VA0 condition ($p < .05$).

#### *5.3.2.2 ANOVA in the other time-windows*

In order to further examine the interaction between SOA and distance, conventional ANOVAs were conducted for the mean amplitudes with the time-windows discovered by non-parametric tests. The durations of time-windows were slightly adjusted to avoid overlaps, they were: 58 – 164 ms, 164 – 264 ms, 264 – 350 ms, and 350 – 398 ms after stimulus onset. The mean amplitudes, but not mean peak amplitudes, were used because the EEG responses were gradually decreases or increase in some time-windows in the VA100 and the VA200 condition, especially in the posterior electrodes. This means that there was no clear peak which could represent the EEG response within a time-window. This made peak detection inappropriate as the peaks will be selected either at the starting or the ending point in a time-window. Hence, the mean amplitudes were calculated for the dependent variable of the ANOVAs described below.

Four 4-way (SOA; VA0, VA100, & VA200; distance: standard, close, far; caudality: anterior & posterior; hemisphere: left, right, and midline) ANOVAs were conducted separately for the four different time-windows with the mean amplitudes. Only the effects which were related to the interaction between distance and SOA will be reported in the main text. Other effects will be reported in Appendix C.

In the time-window of 58 – 164 ms, there was no significant main effect of SOA ($F(2.0, 39.5) = 2.67$, $p = .08$, $\eta^2 = .11$), nor of distance ($F(1.4, 28.5) = 1.91$, $p = .18$, $\eta^2 = .09$). The interaction between distance and SOA was significant ($F(3.0, 59.6) = 2.85$, $p = .045$, $\eta^2 = .13$). Further pairwise comparisons showed that in the VA0 condition, the amplitude difference of close distance was marginally more positive ($M$ = 1.07 μv, $SD$ = 1.34 μv) than standard trials ($M$ = 0.18 μv, $SD$ = 1.11 μv, $p = .053$) while the amplitude difference of far distance was no different ($M$ = 0.12 μv, $SD$ = 1.21 μv, $p > .99$) from standard trials. This data pattern was gone in the VA100 condition, on the contrary, the amplitude difference of close distance ($M$ = 0.93 μv, $SD$ = 2.16 μv) was not different from standard trials ($M$

= 1.40 μv, *SD* = 1.90 μv, $p$ = .99) while the amplitude difference of far distance ($M$ = 0.74 μv, *SD* = 1.43 μv) was significantly more negative than standard trials ($p$ = .032). In the VA200 condition, the amplitude difference of standard trials ($M$ = 1.32 μv, *SD* = 1.65 μv) were not different from close distance ($M$ = 1.51 μv, *SD* = 2.23 μv, $p$ > .99) or far distance ($M$ = 0.97 μv, *SD* = 1.68 μv, $p$ = .53). There were no other significant effects related to the interaction between distance and SOA (see the means and *SD*s in Table C7 on page 303 and other effects of ANOVA in Table C8 on page 304).

In the time-window of 164 – 264 ms, a significant main effect was found on SOA ($F$(1.7, 33.1) = 6.38, $p$ = .007, $\eta^2$ = .24). Pairwise comparisons showed that the amplitude difference between Visual-audio deviants and auditory deviants in VA100 ($M$ = 1.25 μv, *SD* = 1.60 μv) was significantly more positive than in VA200 ($M$ = -0.30 μv, *SD* = 2.03 μv, $p$ = .005), while there was no significant difference between the VA0 ($M$ = 0.98 μv, *SD* = 1.50 μv) and the VA200 condition ($p$ = .10). The main effect of distance was not significant ($F$(1.6, 31.9) = 1.04, $p$ = .35, $\eta^2$ = .05). There were no other significant effects related to the interaction between distance and SOA (see the means and *SD*s in Table C9 on page 306 and other effects of ANOVA in Table C10 on page 307). The linear trend was significant for the close distance ($F$(1, 20) = 8.90, $p$ = .007, $\eta^2$ = .31), but was not significant for both the far distance ($F$(1, 20) = 2.52, $p$ = .13, $\eta^2$ = .11) and the standard ($F$(1, 20) = 1.53, $p$ = .23, $\eta^2$ = .07).

In the time-window of 264 – 350 ms, a main effect of SOA was found significant ($F$(1.7, 34.5) = 5.38, $p$ = .01, $\eta^2$ = .21). Pairwise comparisons showed that the amplitude difference of VA0 condition ($M$ = 0.98 μv, *SD* = 1.68 μv) was more positive than the VA100 ($M$ = -0.22 μv, *SD* = 1.64 μv, $p$ = .02), but was no different from the VA200 condition ($M$ = -0.07 μv, *SD* = 1.56 μv, $p$ = .10). No difference was found between the latter two SOA conditions ($p$ > .99). A significant main effect was also found on distance ($F$(2.0, 39.9) = 5.69, $p$ = .007, $\eta^2$ = .22). Pairwise comparisons showed that the amplitude difference of close distance ($M$ = 0.54 μv, $SD$ = 2.01 μv) was not different from standard trials ($M$ = 0.80 μv, $SD$ = 1.57 μv, $p$ > .99), while the amplitude difference of far distance ($M$ = -0.65 μv, $SD$ = 1.59 μv) was more negative than standard trials ($p$ = .01). The interaction between distance and SOA was not significant ($F$(2.7, 54.3) = 2.05, $p$ = .12, $\eta^2$ = .09) while the 3-way interaction between distance, SOA, and caudality was marginally significant ($F$(2.9, 57.5) = 2.63, $p$ = .061, $\eta^2$ = .12). Further analyses showed that the simple interaction between distance and SOA was only significant at the anterior electrodes ($F$(2.9, 58.8) = 3.55, $p$ = .02, $\eta^2$ = .15) but not at the posterior electrodes ($F$(2.7, 54.7) = 1.06, $p$ = .37, $\eta^2$ = .05). Further post-hoc comparisons for the amplitude difference at the anterior electrodes showed that the voltage difference of close distance ($M$ = 0.40 μv, $SD$ = 2.62 μv) was more positive than the far distance ($M$ = -1.40 μv, $SD$ = 3.38 μv, $p$ = .02) but was no significantly different from the standard at the VA0 condition ($M$ = -0.62 μv, $SD$ = 2.66 μv, $p$ = .37). There was no difference among the standard ($M$ = -0.43 μv, $SD$ = 1.93 μv), the close ($M$ = -1.45 μv, $SD$ = 2.82 μv), and the far distance ($M$ = -1.94 μv, $SD$ = 2.31 μv) at the VA100 condition ($p$-values of all comparisons > .05). At the VA200 condition, the amplitude difference of the close distance ($M$ = -0.73 μv, $SD$ = 2.52 μv) was not different from the standard ($M$ = 0.06 μv, $SD$ = 2.29 μv, $p$ = .60), whereas the amplitude difference of the far distance ($M$ = -1.83 μv, $SD$ = 2.76 μv) was more negative than the standard ($p$ = .02). There were no other significant effects related to the interaction between distance and SOA (see the means and *SD*s in Table C11 and other effects of ANOVA in Table C12 on page 310).

In the time-window of 350 – 398 ms, there was no significant effect on SOA ($F$(1.6, 32.0) = 1.90, $p$ = .17, $\eta^2$ = .09). A significant main effect was found on distance ($F$(1.8, 36.7) = 3.45 $p$ = .046, $\eta^2$ = .15). Pairwise comparisons showed that the amplitude difference of close distance ($M$ = 0.36 μv, $SD$ = 2.12 μv) was not different from the standard ($M$ = 0.15 μv, $SD$ = 1.82 μv, $p$ > .99), whereas the amplitude difference of far distance was marginally different from the standard ($M$ = -0.93 μv, $SD$ = 1.70 μv, $p$ = .09). The interaction between distance and SOA was not significant ($F$(2.4, 47.2) = 1.83, $p$ = .17, $\eta^2$ = .08). There were no other significant effects related to the interaction between distance and SOA (see the means and *SD*s in Table C13 on page 312 and other effects of ANOVA in Table C14 on page 313). The linear trend was not significant for the close distance ($F$(1, 20) = 0.19, $p$ = .67, $\eta^2$ < .01), or for the far distance ($F$(1, 20) = 0.85, $p$ = .37, $\eta^2$ = .04), nor for the standard ($F$(1, 20) = 3.47, $p$ = .077, $\eta^2$ = .15).

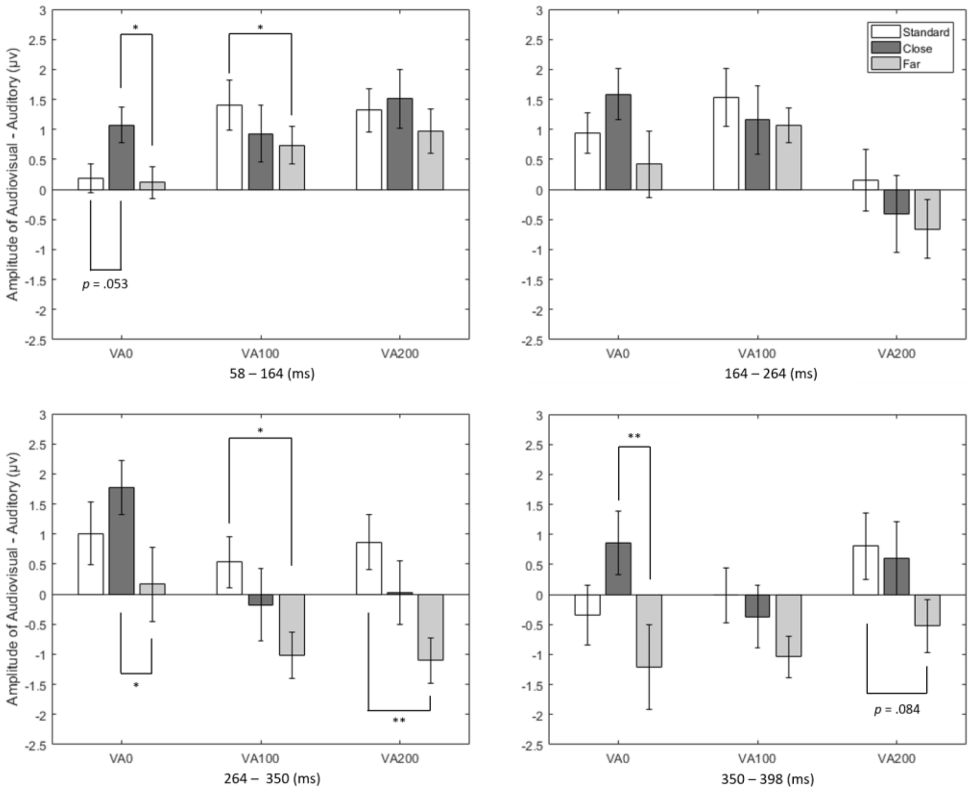


*Figure 5-7.* The amplitude difference of conditions (VA - A) for standard, close-, and far-distance trials by SOA in each time-window (±1 *SE*). * shows its significance at 0.05 level. ** shows its significance at 0.01 level.

In summary, the ANOVAs in four time-windows showed that the effects related to the interaction between SOA and distance were revealed in the time-window of 58 – 164 ms and 264 – 350 ms, showing that the distance effect was modulated by SOA. A distance effect was found in the time-window of 350 – 398 ms, but was not modulated by SOA (see Figure 5-7).

### 5.3.3 Correlational analyses

#### 5.3.3.1 MMN and AMN

The results showed significant correlations in the right ($r$ = .46) and midline posterior electrode ($r$ = .54) at VA100 condition for only close distances, but not for far distances. There was no correlation between individuals' WRAT scores and MMN amplitude difference at VA0 condition or at VA200 condition for both close and far distances.

For the AMN amplitude difference, significant correlations were found for far distances in the left and the midline electrodes, both anterior (left: $r$ = .51; midline: $r$ = .51) and posterior (left: $r$ = .49; midline: $r$ = .46). For more details about the correlations between WRAT scores and the amplitude of each component in each electrode group, see Table C15 on page 315.

#### 5.3.3.2 Raw waves

In the VA0 condition, the only significant correlation between amplitude differences (audiovisual minus auditory) and WRAT scores was found for far distances at the midline posterior electrodes ($r$ = .47), in the time-window of 350 – 398 ms. In the VA100 condition, significant correlations were found for close distances in the posterior electrode groups in the time-window of 58 – 164 ms ($r$s > .56), and left ($r$ = .48) and midline posterior ($r$ = .48) electrode groups in the time-window of 164 – 264 ms. In the VA200 condition, the only significant correlation was found for close distances at the right posterior electrodes ($r$ = .44), in the time-window of 58 – 164 ms. For more details about the correlations between WRAT scores and the amplitude of each component in each electrode group, see Table C16 on page 316.

In summary, some correlations were found in the correlational analyses, however, most of the correlations between EEG responses and mathematical performance were small and insignificant.

## 5.4 Discussion

The current EEG experiment is the first demonstrating the integration between spoken number words and Arabic digits. Without any responses, a larger visuo-audio MMN compared to the auditory-only MMN is found for far distances when the visual digit is displayed 100 ms (VA100) and 200 ms (VA200) before the spoken number word. This result indicates that the integration effect is modulated by distance as well as SOA. In addition, like in Chapter 4, different EEG responses for close and far distances, i.e., the distance effect, are also shown in the current study. Moreover, this distance effect is modulated by SOA.

Before a further discussion for the integration and the distance effect in the current experiment, I would like to point out that several results reported in the previous EEG experiments are replicated in the current experiment. They are the presence of the MMN and the distance effect of the MMN latency. The *t*-tests showed that the MMN amplitudes were significantly different from zero in both VA100 and VA200 conditions. The MMN latency of close distances was again found earlier than far distances. These replications show that these phenomena observed in the current auditory oddball paradigm are reliable. Also, the MMN was consistently found in both SOA conditions, showing that even there was a habituation effect in the MMN amplitudes (McGee et al., 2001), it might not influence the signal-to-noise ratio too much[28]. However, these results are independent of the main manipulation of the current experiment (SOA) and have been discussed in the previous chapters, so I will not address them in detail again in this discussion section.

[28] Also, a 4-way ANOVA (SOA: 0, 100, & 200; distance: close & far; caudality: anterior & posterior; hemisphere: left, right, & midline) showed that there were no significant differences in MMN amplitudes across SOA conditions ($F(1.4, 28.0) = 1.70$ $p = .021$, $\eta^2 = .08$).

### 5.4.1 MMN and Integration between spoken number words and Arabic digits

A significant difference between the audiovisual MMN and the auditory MMN was only revealed in the VA100 and the VA200 condition – not in the VA0, and only for far-distance numerals. According to previous reading research, the modulation of condition on the MMN amplitude is evidence for an early integration between letters and speech sounds (Froyen et al., 2009, 2008, 2011; Mittag et al., 2013). It has been suggested that the larger audiovisual MMN stems from the over-learned correspondence between letters and speech sounds causing an extra deviation: in addition to the deviation between the deviant speech sound and the previous standard speech sound, there is an extra deviation between the visual letter and the deviant speech sound. As a similar auditory oddball paradigm was used in the current study, the same explanation can apply to the current finding. That is, the over-learned mapping between Arabic digits and spoken number words causes the larger audiovisual MMN in two SOA conditions for far distances.

The visuo-audio MMN is only larger than the auditory-only MMN at the VA100 and VA200 condition, but is not different from the auditory MMN at the synchronous condition. This indicates that the integration effect between bimodal numerals is stronger when there is an SOA. Although this explains the reason that a similar integration effect was absent in Chapter 3 and Chapter 4 as there were no SOAs in the first two EEG experiments, it also raises the question why the integration is not the strongest when the bimodal numerals are displayed simultaneously. It is natural to assume that the integration effect should be the largest when bimodal stimuli are displayed synchronously. Some previous studies, including EEG (Froyen et al., 2008) and fMRI studies (van Atteveldt, Formisano, Blomert, et al., 2007), which investigated the integration between letters and sounds, indeed showed that the integration effect is larger when the bimodal stimuli are displayed simultaneously compared to asynchronous displays. I will further discuss possible reasons for this finding in the general discussion.

Another novel finding, is that the integration effect is modulated by distance. The audiovisual MMN was larger than the auditory-only MMN only for far distances, but not for close distances. The MMN performances by distance demonstrate that the deviant spoken number word is not merely detected; furthermore, the numerical distance between the preceding standard and the current deviant is also processed, at least differentiated. Thus, spoken number words with a small distance does not induce the larger audiovisual MMN amplitude, i.e., the integration effect. The exploratory analyses in Chapter 4 and 5 showed that different EEG responses to close and far distances were initiated as early as 60 ms after auditory stimulus onset. This early different EEG responses between distances supports the idea that the magnitude representations of numerals are automatically activated.

In addition, as it is discovered in the last chapter, an effect in the opposite direction was found for close distances with the current 21-subject sub-dataset: the audiovisual MMN was smaller than auditory MMN when audiovisual numerals were displayed at the same time. As it has been discussed in the last chapter, this effect with an opposite direction in the MMN for close distances may be due to the 'less surprise' in the audiovisual condition, because the representations of close-distance numerals have been 'double primed' by both visual digits and auditory number words in the standard trials. Nevertheless, it is unclear why this 'less surprise' for close distances only happened when stimuli were displayed simultaneously, but disappeared at other SOA conditions. Perhaps the synchronously display of bimodal close-distance numerals activates the neighbouring representations super-additively, thus making a larger difference between audiovisual and auditory-only condition in terms of the MMN amplitudes. This super-additive 'less surprise' effect of close-distance numerals then may be also a reflection of an integration effect. More research is needed to further clarify how integration and numerical distance interact with each other.

### 5.4.2 Distance effect is modulated by SOA

One of the main purpose of the current experiment is to observe the modulation of SOA on the distance effect.

For the MMN, the distance effect is only shown at the synchronous condition (VA0), but not at the other two SOA conditions. This result may suggest that the distance effect is modulated by SOA. As mentioned earlier, the SOA is essential for an integration effect, and the integration effect should be larger when multi-sensory stimuli are temporally close compared with stimuli are temporally further away (Froyen et al., 2008; van Atteveldt, Formisano, Blomert, et al., 2007). However, interaction between distance and SOA is only marginally significant, showing that although the distance effect in the MMN is gone in the VA100 and VA200 condition, the distance effect in the MMN may not be largely influenced by SOA.

For the raw waves, the interaction between distance and SOA is shown during the time-window of 58 – 164 ms and 264 - 350 ms, indicating that the distance effect is different among the SOA conditions in these two time-windows.

When looking into the EEG responses in details, interesting data patterns can be observed in both time-windows (see Figure 5-7 on page 198). That is, the EEG amplitude difference (audiovisual minus auditory deviants) of far distances are more similar to the standard trials, whereas the close distances are more different from the standard trials when the audiovisual numerals are displayed simultaneously, i.e, in the VA0 condition. In contrast, in the VA100 condition, the far distances are significantly different from the standard trials, whereas the close distances are similar to the standard trials in the VA100 condition. The VA200 condition has a similar pattern as the VA100 condition. These results indicate that the SOA between visual and auditory numerals can influence the processing of the numerically mismatch between cross-modal numerals. More specifically, it shows that only when there is an SOA between cross-modal numerals, far distances would induce a more negative EEG response for the audiovisual condition; whereas only when there is a simultaneous display, close distances would induce a more positive EEG response for the audiovisual condition.

An absent effect for far distances in the simultaneous condition (VA0) at an early stage, for example, during 58 – 164 ms after stimulus onset, can be due to an interference from the synchronous visual digit. Because far-distance numerals need more time to respond (unlike the close distances have been primed), the parallel display of the visual digit becomes an interference, and thus postpone the mismatch detection or making it more difficult. When a visual digit is displayed first, such as at the VA100 and the VA200 condition, there is more time to process the visual digit before the display of a far-distance number word, thus making the mismatch detection easier and faster for far distances. On the other hand, perhaps the priming effect only exists within a very short SOA. Hence, the 'less surprise' phenomenon in the audiovisual condition only appears in the VA0 condition for close-distance numerals. However, previous studies usually reported a priming distance effect with an interval between primes and targes from around 50 ms to around 120 ms (Reynvoet & Brysbaert, 2004; Reynvoet, Brysbaert, et al., 2002). Hence, it remains unclear why the close distances only elicit a more positive EEG response during VA0 condition.

As mentioned in Chapter 4, same EEG responses can represent different cognitive activities in brain, thus, the explanations above cannot simply apply to the similar data pattern in the later time-window, during 250 – 346 ms after stimulus onset. In this later time-window, perhaps the distance effect is more related to the magnitude processing but is less related to a mismatch detection. The EEG responses for far distances are more negative than for close distances, which is similar to the suggestion of previous research (Niedeggen &

Rösler, 1999) that more semantic incongruency should induce a more negative brain response. Moreover, the pattern of EEG responses in the VA100 and VA200 condition for standards, close and far distances is more consistent with the previous studies studying N400 (Niedeggen & Rösler, 1999). That is, a far distance induces a larger negativity, a close distance induces a moderate negativity, in comparison with the semantic congruent, standard trials. Hence, the outstanding positive EEG responses for close distances in the VA0 condition compared with other two SOA conditions, suggests a special cognitive activity which happens only for close distances and only when cross-modal numerals are displayed at the same time. This special cognitive activity only for close distances may point to the aforementioned priming mechanism.

To summarise, the distance effect is modulated by SOA. Although it is not statistically significant in MMNs, the investigation on raw waves shows the interaction between distance and SOA during an early time-window and a relatively later time-window. The EEG performances for different distances may be related to priming and magnitude processing. However, it is difficult to give a precise and complete explanation for all results. I will further discuss the interrelationship between integration, distance, and SOA in the general discussion.

### 5.4.3 Correlations between EEG responses and mathematical performance

Since the hypothesis about the integration between spoken number word and Arabic digit is supported in the current experiment with an SOA manipulation, it is thus interesting to observe the relationship between EEG responses in different SOAs and individual mathematical performance.

The results showed that the correlation between the EEG responses and individual mathematical performance were inconclusive. For example, some significant correlations were found in the MMN amplitude difference for close distances at VA100 condition; however, there was no significant condition difference for close distances at VA100 condition. Similar situations happened in the AMN amplitudes for far distances, as well as the amplitudes in other time-windows. This may indicate that the correlations between neural activities and cognitive abilities is not as strong as I thought (see also Bishop, 2007).

## 5.5 Conclusion

By adding two more SOA conditions in the auditory oddball paradigm, the current study was able to identify a larger audiovisual MMN in the VA100 and the VA200 conditions, which directly indicates a presence of the cross-format integration between spoken number words and Arabic digits. However, the evidence of the integration is limited to far distances, but not for both close and far distances. This implies that far- and close-distance numerals are treated differently in the current paradigm. In addition, in the raw EEG responses the distance effect is modulated by SOA. However, the underlying mechanism about this interaction is unclear. I will continue to discuss these findings in the general discussion.

# Chapter 6 – General discussion

## 6.1 Overview

The current thesis aimed to investigate the cross-format integration between Arabic digits and spoken number words. To the best of my knowledge, it was the first time the integration between these most commonly used numerals was systematically investigated by both behavioural and EEG experiments.

I started with a behavioural matching task following the design of Sasanguie and Reynvoet (2014) but with an SOA manipulation. Surprisingly, I did not replicate their main finding about the null distance effect between spoken number words and Arabic digits, on the contrary, a significant distance effect was observed in both of my behavioural tasks with different ranges of SOA. This indicates a shared magnitude representation is activated for bimodal numerals during same-different responses.

Next, to study the underlying neural mechanism of the cross-format integration without possible influences of responses, I then conducted three EEG experiments following the passive paradigm of Froyen et al. (2008). The MMN responses showed that the integration existed between spoken number words and Arabic digits, but was modulated by distance as well as SOA.

I will discuss the interrelationship between integration, distance, and the SOA in my thesis, and how the results can tell us about the relationship between spoken number words and Arabic digits.

## 6.2 Integration exists between cross-modal numerals but in limited situations compared to speech stimuli

The current study is first to identify the integration between spoken number words and Arabic digits in the MMN amplitudes in a passive oddball paradigm. Moreover, the integration effect is modulated by distance as well as SOA. According to the definition for the integration in terms of the MMN, the visuo-audio MMN should be larger than the auditory-only MMN if the cross-format integration exists between bimodal stimuli (Froyen et al., 2008). In the current study, this larger visuo-audio MMN was found only for far-distance numerals, and only when the auditory number word was displayed 100 ms and 200 ms after the visual Arabic digit (Chapter 5).

It has been suggested that the MMN can reflect not only the auditory short-term memory (Näätänen et al., 2007), but also the overlearned, automatic correspondence between artificial symbols, such as letters and sounds (Blomert & Froyen, 2010; Froyen et al., 2008). Thus, the larger visuo-audio MMN elicited by the far-distance bimodal numerals supports the original proposal of the current research. That is, there is a special correspondence between the two most commonly used numerical symbols, i.e., spoken number words and Arabic digits.

Moreover, it has been suggested that the integration between letters and sounds is different from an integration between lip movements and speech sounds, i.e., the McGurk effect (McGurk & MacDonald, 1976). That is, the correspondence between letters and sounds is more arbitrary and artificial compared to lip movements and corresponding sounds (Blomert & Froyen, 2010). For example, when hearing a speech sound of a letter, such as /a/, one can naturally think of a possible mouth shape for the sound, whereas it is impossible to think of the corresponding letter 'a' if one never learned this specific language. Thus, the latter cross-modal correspondence is less natural. Hence, this is probably why the integration between letters and speech sounds at a neural level is only acquired after years of usage and experience (Froyen et al., 2009).

Follow the explanation above, the correspondence between spoken number words and Arabic digits is also arbitrary and artificial, however, different results between the current study and previous reading research shows that the integration between bimodal numerals and the integration between bimodal speech stimuli may not be the same. There are a few points worth to be mentioned:

First, the same design did not show any evidence of integration. I followed the paradigm of Froyen et al. (2008) but replaced letters and sounds as visual digits and spoken number words in Chapter 3. I only used one standard and one deviant within subjects just as they did. The MMNs showed no difference, indicating that the extra visual digit in the audiovisual condition did not influence the early EEG responses at all.

Second, in Chapter 5 the integration effect was modulated by distance. The audiovisual MMN was larger than the auditory-only MMN only for far distances, but not for close distances.

Third, the integration effect is shown for far distances only at SOAs that spoken number words follows visual Arabic digits, but is absent when audiovisual numerals are displayed simultaneously, which indicates that the integration effect is modulated by distance as well as SOA.

Last, and is also the most unexpected one, is that the close distances induce an 'opposite integration effect' in terms of the MMN amplitudes.

The causes for these different findings between the current research and the previous reading studies may be related to each other. In the following sections I will try to discuss what these causes could be.

### *6.2.1 Different binding windows of integration*

The results of my research suggest a different binding window for the cross-format integration between spoken number words and Arabic digits compared to speech stimuli. Previous studies have shown a strongest integration effect when letters and speech sounds are displayed simultaneously (Froyen et al., 2008; van Wassenhove et al., 2007). However, in the current study the binding window for the cross-format integration between numerals is that the auditory number word has to be displayed at least 100 ms later than the visual digit. This can be due to different processing time for numerals and speech stimuli.

Firstly, it has been suggested that it takes less time to transduce auditory stimuli (less than 1 ms) at the cochlea compared to transduce visual stimuli at the retina (30 – 40 ms). Hence, participants usually perceive the bimodal stimuli are presented simultaneously when the visual stimulus is actually displayed earlier than the auditory stimulus (Zampini et al., 2003). This may cause a larger integration effect, i.e., a larger MMN, when the visual stimulus precedes the auditory stimulus.

However, this phenomenon alone cannot explain why previous studies showed a larger integration effect for synchronous display of letters and sounds, as the similar situation also happen between letters and sounds. Hence, a complementary idea is the different processing time between spoken number words and letter sounds. When comparing the bimodal numerals and speech stimuli, the perceptual processing time for visual letters and digits should be very similar. In contrast, spoken number words are much more complicated than letter sounds, both acoustically and semantically. Thus, the discrepancy between the processing time of visual and auditory stimuli should be even larger in the current research when using numerals as stimuli, compared to previous studies using letters and speech sounds. This larger discrepancy might lead to a more 'biased perception' that the display of bimodal numerals is only seen as simultaneous when the visual digit is displayed much more earlier than the auditory number words, for example, at least 100 ms earlier than the auditory number words. Therefore, only when the auditory number word is played 'later enough' than the visual Arabic digit, participants would perceive the bimodal numerals as a simultaneous display, leading to a larger integration effect.

### 6.2.2 Numerals are less learned?

The integration effect only shown in asynchronous displays but not in a synchronous condition may suggest that the automatic correspondence between spoken number words and Arabic digits has not been formed completely.

Froyen and colleagues (2009) tested three groups of subjects, children with 1-year reading training, children with 4-year reading training, and adults in their oddball paradigm using letters and sounds with an EEG measurement. The results showed that children with 1-year reading training did not show any integration effect, i.e., the visuo-audio MMN was not different from the auditory-only MMN, in any SOA conditions. In contrast, adults showed a larger visuo-audio MMN, i.e, the integration effect at the synchronous condition, but not at the 200 ms SOA condition. Interestingly, children with 4-year reading experience did not show an integration effect at the synchronous condition like adults, but showed an integration at the 200 ms SOA condition (letters preceded sounds). The authors thus argued that children with 4-year reading experience have not acquired the automatic integration between letters and sounds as adults.

Considering that people have less experience regarding to numerals compared to speech stimuli, it is possible that the correspondence between Arabic digits and spoken number words is not as automatic as the mapping between letters and sounds even in adults. Hence, the integration effect only appears at the SOA conditions, but not at the synchronous display of bimodal numerals.

### 6.2.3 Priming only for close distances

The most unexpected finding is the ‘opposite integration effect’ for close distances in terms of the larger auditory MMN compared to the audiovisual MMN. This might indicate that the mismatch in the auditory-only condition was more surprising compared to the mismatch in the bimodal condition for close-distance numerals.

An explanation for this unexpected result is that the magnitude representations of close-distance numerals may have been already activated because of the repetitive appearance of standard trials. That is, because the semantic magnitude representations are close on the mental number line, the magnitude activation of standard number spreads to the neighbour numbers (Reynvoet & Brysbaert, 2004). Since there are dual stimuli, including visual digits in the visuo-audio condition, the magnitude representation of the standard and neighbour numbers should be more activated than in the auditory-only condition. Thus, this leads to a smaller surprise which reflects as the smaller audiovisual MMN amplitude than the auditory-only MMN when encountering the close-distance number words. In contrast, this spread-out effect does not reach the representation of far-distance numerals because the distance of 4 (number 1 and 9 as far-distance numerals) is too far away (Reynvoet, Brysbaert, et al., 2002). Thus, the magnitude representations of far-distance numbers are not more activated during the bimodal display compared to the unimodal condition. Consequently, the far-distance number words induce a larger 'surprise' in the visuo-audio condition because there are 'double mismatch' compared to the auditory-only condition, and is reflected in the MMN amplitudes.

In addition, an extensive thought from this unexpected finding for close distance is that, whether this early processing caused by priming effect can be seen as a reflection of an integration? There are several ways to investigate the integration. Although the MMN is a popular ERP component for integration studies because it is usually seen as automatic and pre-attentive (Tiitinen et al., 1994), the idea of the MMN is a mismatch detection. Compared to the original phenomena of integration, such as the McGurk effect (McGurk & MacDonald, 1976), the integration should be more like a fusion response. This means that for the multi-sensory stimuli which can induce an integration, they should be easily integrated with each other, rather than be easily detected from each other. Following this idea, a larger MMN may be able to tell an over-learned pairing of stimuli because a deviant is contradicted to the memory trace, whether it represents the same mechanism as a classic integration, is not very clear. In contrast, a priming distance effect, which is reflected by a smaller MMN, may be more similar to the original idea of integration. Because the magnitude representations of close-distance numerals are overlapped with the standard number, which means that they are more difficult to be differentiated. However, this is just a preliminary thought, future research can address on this issue to further clarify the interaction between distance and integration with cross-modal numerals.

## 6.3 Cross-modal symbolic distance effect

The distance effect is another major finding in the current thesis. The distance effect was found in both the behavioural matching task (Chapter 2) as well as the EEG experiments in which no responses required for the numerical symbols in an oddball paradigm (Chapter 4 and Chapter 5).

It has been widely suggested that the distance effect (Moyer & Landauer, 1967) reflects the overlap of numerical representations on the mental number line (e.g., Dehaene & Changeux, 1993). Hence, a larger distance effect indicates more overlaps between magnitude representations of numbers. The discovery of the numerical distance effect in my same-different task (Chapter 2) was consistent with previous research using simultaneously displayed written number words and Arabic digits (van Opstal & Verguts, 2011). The congruency effect (shorter RTs for 'same' compared to 'different' responses) was also clearly observed. These results showed that even when participants make a same-different judgement (but not a magnitude comparison task), they access a shared semantic magnitude representation of spoken number words and Arabic digits, which is line with the models suggesting a shared magnitude representation for all formats of numbers (e.g., Dehaene, 1992; McCloskey, 1992).

In a previous study with Arabic digits and spoken number words no distance effect was found (Sasanguie & Reynvoet, 2014). Moreover, they did not find a congruency effect either. In their same-different task the RTs of close and far distances were not different from each other, neither were the RTs of 'same' and 'different' responses. The authors thus concluded that the same-different judgment for bimodal numerals does not need to access the magnitude representation of numbers, instead, the judgment is made via an asemantic mapping between spoken number words and Arabic digits (Dehaene, 1992). The explanation for the conflicting results between mine and their experiments is twofold. First, in their study the average RT for close distances was descriptively 10 ms longer than for far distances, which was in the 'correct' direction for a classic distance effect (Moyer & Landauer, 1967). Thus, it is possible that the significant distance effect would have shown if more participants were recruited. Second, they had different numbers of 'same' and 'different' responses, which could largely influence the RT performance. The disapperance of the congruency effect was reported in previous same-different tasks using Arabic digits when the different responses were two times as many as the same responses (Hsu & Szűcs, 2011; van Opstal & Verguts, 2011), which was the same ratio as Sasanguie and Reynvoet (2014) used. In addition, when the numbers of different and same responses changes to a more equal ratio (from 2:1 to 3:2), the congruency effect appeared again and it was because the RTs of the incongruent trials became slower in the latter setting (van Opstal & Verguts, 2011). This shows that the absence of the congruency effect in Sasanguie and Reynvoet's study might because participants were more prepared to press the 'different' button as there were more 'different trials', leading to a faster response to these 'different responses', and thus weakening the congruency effect.

More importantly, in my EEG experiments, the distance effect in terms of the MMN amplitudes was only shown in the synchronous condition, but was not observed in the other two SOA conditions (Chapter 5). It has been proposed that the MMN reflects a pre-attentive, automatic detection of the auditory change (Tiitinen et al., 1994). Moreover, there was no response required for the visuo-audio numerals in the passive oddball paradigm I used. Thus, the distance effect in the MMN amplitudes of the EEG experiments was not because of a response-selection (e.g., Göbel et al., 2004) or a response-execution process, but should be related to an automatic, semantic processing of the numerals.

In addition to the MMN, the later component, the AMN, also showed a significant distance effect in Chapter 4 and Chapter 5. This indicates that the magnitude representation of numbers is involved not only in the early processing, but also in a relatively later time-window (240 – 300 ms after stimulus onset). The direction of the distance effect in the AMN amplitudes is consistent with previous research. That is, the close distances trigger an enhanced negativity in the ERPs (e.g., Hsu & Szűcs, 2011; Zhou et al., 2006). Also, although the distance was not manipulated and there was no integration in the MMN in my first EEG experiment (Chapter 3), the visuo-audio AMN was significantly more negative than the auditory-only AMN. This might indicate that the distance mismatch between visual digits and auditory spoken number word is processed in this relatively later time-window.

Some studies suggest that the AMN may reflect a more general mismatch detection in relation to the violation of strategic expectations and the distance effect just coincides with the AMN's time-window (Hsu & Szűcs, 2011; Szucs, Soltész, Czigler, & Csépe, 2007). This means that a similar negativity can be also observed in the similar time-window of the AMN in other tasks when encountering a mismatch between stimuli, such as in a colour matching task (Wang, Cui, Wang, Tian, & Zhang, 2004). However, different tasks are used between these previous studies (Hsu & Szűcs, 2011; Szucs et al., 2007; Wang et al., 2004) and the current research. In the previous studies participants were required to make a matching/non-matching responses, thus they might develop a strategic expectation to the stimuli so that they could make a response faster (Hsu & Szűcs, 2011). In contrast, in my EEG experiments participants were told to ignore the numerals, and the numerals were irrelevant to the categorisation task in the oddball paradigm. Hence, participants did not need to develop any specific strategies regarding to numerals. The difference between tasks makes this alternative explanation for the AMN less convincing in my EEG experiments.

Another possibility is that the AMN also reflects a general mismatch detection just like the MMN does, so that the AMN would be observed in both an active and a passive task when a mismatch is detected. However, the AMN-like EEG responses were not found in the previous reading studies with a passive oddball paradigm (Froyen et al., 2008; Mittag et al., 2013). Therefore, the distance effect shown in the AMN in the current thesis should reflect the magnitude processing of bimodal numerals.

The discoveries of the distance effect in the MMN and the AMN is temporally in line with previous EEG research using Arabic digits in an adaptation paradigm (Hsu & Szűcs, 2012). In the adaptation paradigm, a numerically deviant Arabic digit followed several to-be-adapted Arabic digits. The deviant digit was either numerically close, or numerically far to the standard digit. The results showed different EEG responses for close and far distances, i.e., the distance effect, in between 200 to 440 ms after stimulus onset, which indicated that the numerals irrelevant to the task can still trigger the underlying magnitude representations.

To summarise, from the previous adaptation study and the current EEG experiments, it is clear that the magnitude representations of numerals are activated even the numerals are totally irrelevant to the task. Hence, the current EEG results in terms of the MMN and the AMN amplitudes again supports the idea that the distance effect is not related to responses (Göbel et al., 2004), but is probably, at least partially, due to an automatic magnitude processing to numerals (den Heyer & Briand, 1986; Tzelgov, Meyer, & Henik, 1992).

### 6.3.1 Cross-modal distance effect is modulated by SOA

The distance effect was not only found in both the behavioural and EEG experiments. Moreover, the distance effect was modulated by SOA both behaviourally and neurally. That was, when the bimodal numerals were displayed simultaneously, in the behavioural matching task the difference in the RTs between close and far distances was larger; in the EEG experiments the difference in the MMN amplitudes between close and far distances was larger, compared to a sequential display for the visual and auditory numerals.

The smaller distance effect in the conditions where Arabic digits and number words were presented sequentially possibly indicates that the magnitude representation of the preceding numeral has been processed more completely, thus more precisely, when given more time (SOA). In contrast, the magnitude representations of visuo-audio numerals may be processed in parallel when the bimodal numerals are given simultaneously. It is thus possible that there is no one representation which has been more 'well-prepared' than the other compared to a sequential display with an SOA, thus leading to a larger distance effect.

An alternative explanation can be that participants employ a different strategy when the SOA is longer, which leads to a smaller (or even absent) distance effect. In the third experiment of Cohen and colleagues' study (D. J. Cohen et al., 2013), they happened to have a similar experimental setting as one of my SOA condition, the AV500 in my first behavioural experiment of Chapter 2 (on page 63). They gave the auditory number word first, and then displayed the visual digit on the screen after 500 ms. Participants were instructed to judge whether the bimodal numerals were same or different in quantity. They found that the physical similarity function of digits was the only significant predictor to the RTs, whereas the Welford function which accounts for the distance effect did not predict the RTs. They thus argued that the preceding auditory number word was transformed to an Arabic digit first, then was compared with the following digit depending on the physical similarity (of Arabic digits). Since both the design and the result were similar between theirs and mine experiment, this physical similarity hypothesis could be an explanation to the absent distance effect in the AV500 SOA condition in my audiovisual matching task (beta value of the distance effect was not significant different from zero, $t(37) = -1.10$, $p = .28$). However, a critical difference between D. J. Cohen et al. and my behavioural experiment is that there were 9 different SOA conditions in my audiovisual matching task; whereas the auditory numeral always preceded the visual numeral with a 500 ms SOA in the study of D. J. Cohen et al. (2013). It was likely that after certain amount of trials, their participants were already used of the experimental procedure and started to develop a more efficient strategy to react to the matching task, instead of accessing the magnitude of numerals. Hence, given plenty of time (500 ms), the strategy could be mentally transforming the auditory number word to an Arabic digit as the following stimulus was always a digit. In other words, their experimental design might encourage their participants to employ the transformation strategy. However, the same strategy is very difficult to apply to my experiment because there were different SOA conditions, and some of them were very short (e.g., 100 ms), which meant that the following numeral could be already displayed before the transformation was completed. This would make the transformation strategy not benefit to the RT performance in my experiment. Thus, although part of my results looks somewhat similar to D. J. Cohen et al. (2013), it would be too arbitrary to conclude that a similar strategy (based on physical similarity) is employed in my behavioural matching task. Instead, it is still more convincing that participants react to all trials in a similar way regardless of the SOA. That is, making a matching/non-matching judgment by accessing to the magnitude representations of numerals. Therefore, the smaller or absent of distance effect with the increase of the SOA is probably because the tuning curve of the preceding numeral's magnitude representation has become narrower when given enough time (SOA) to process, leading to a less overlap between magnitude representations, and hence diminishing the distance effect.

In addition, like the distance effect in RTs is modulated by SOA in the matching task, the amplitude difference between close and far distances is modulated by SOA in the MMN. For the MMN, the distance effect is only shown at the synchronous condition (VA0), but not at the other two SOA conditions. Because no response is required in a passive, oddball paradigm, this suggests that the modulation of SOA on distance is not related to response-selection (Göbel et al., 2004) or response-execution, but should be due to magnitude processing of stimuli. As similar modulation effect of SOA on distance is found in RTs of an audiovisual matching task as well as in MMN amplitudes of an oddball paradigm, this suggests that in both experiments the distance effect is due to the same processing: accessing the magnitude representation of bimodal numerals, and thus makes the alternative explanation about different strategy use in different SOA conditions more doubtful.

To the best of my knowledge, little research, either behaviourally or neurally, has systematically investigated the symbolic distance effect with SOAs.

The experimental setting of cross-format display of numerals in priming studies are somewhat similar to the cross-modal display of numerals in the current research (Kouider & Dehaene, 2009; Reynvoet & Brysbaert, 2004; Reynvoet, Brysbaert, et al., 2002). That is, a target numeral follows a prime numeral, just like an auditory numeral follows a visual numeral (or vice versa) in my research. The priming distance effect is opposite to the classic distance effect. That is, the RT becomes longer when the distance between primes and targets is larger. This phenomenon is usually interpreted as the magnitude representation is activated during the display of the prime, and the activation 'spread out' to the neighbouring numbers. Hence, when the target is numerically close to the prime, the magnitude representation of the target has been activated because of the prime, leading to a faster response. The priming distance effect is also found when using cross-format numerals, i.e., written number words and Arabic digits, thus, it also supports that there is a shared magnitude representation for different formats of numerals (Reynvoet & Brysbaert, 2004; Reynvoet, Caessens, & Brysbaert, 2002). However, Reynvoet and Brysbaert (2004) reported that the priming distance effect was not modulated by SOA. They explained their result as the semantic representation of prime has been already activated even in a short SOA (the SOAs were 43, 57, 86, & 115 ms), thus leading to the same priming distance effect across all SOA conditions. Since the distance effect was modulated by the SOA in both the matching task and the passive oddball paradigm in my research, this may indicate that although the sequential stimulus display in a priming paradigm looks similar to the SOA design in the current research, the magnitude representations of numbers are not activated and processed in a similar way.

In summary, the presence of the distance effect in my EEG experiments further extends the discoveries of my behavioural bimodal matching task, showing that the semantic magnitude representations of both Arabic digits and spoken number words are not only activated during a same-different judgment, but also automatically activated when these numerals are irrelevant to the task.

## 6.4 Correlation

Considering the large number of correlations but only with few significant finding, many of them do not survive after correction for multiple comparison, some correlations are in opposite directions across EEG experiments, the individual differences in mathematical abilities are not reliably correlated with the EEG or even the behavioural distance effect.

In my first behavioural experiment in Chapter 2, the RTs of the audiovisual matching task and the mathematical performance was negatively correlated. This indicates that people who are good at math (or arithmetic) can respond to the matching task faster, showing that they may access the magnitudes of bimodal numerals faster. This correlation is in line with the previous study in which the RTs of the audiovisual matching task was also negatively correlated with mathematical performance (Sasanguie & Reynvoet, 2014). However, this correlation disappeared in my second behavioural experiment (Chapter 2) which was exactly the same as the first experiment except for using a smaller range of SOAs.

In my EEG experiments, the direction of correlation between brain responses and mathematical performance changed from one experiment to another. In my first EEG experiment (Chapter 3) in which no manipulation of distance or SOA, the MMN and AMN amplitude differences (audiovisual minus auditory) and mathematical performance was negatively correlated. This indicates that people who are better in arithmetic show a smaller conditional difference; however, it became positive in Chapter 4 and Chapter 5, indicating an opposite explanation that people who are better in arithmetic abilities show a larger conditional difference.

Interestingly, although many reading studies have suggested a close relationship between the cross-modal integration of letters and sounds and reading abilities, most of them use a between-group design (Blau et al., 2009; Froyen et al., 2009; Mittag et al., 2013; Žarić et al., 2014, 2015). For example, recruiting a group of subjects with impaired reading abilities, such as dyslexic subjects, and then compare their EEG responses with a control group with normal reading abilities. However, although the MMN amplitude has been repeatedly mentioned as a crucial indication of deficit of auditory processing of speech stimuli in these studies, to date only one study has reported a just significant correlation ($r$ = -.45, $p$ = .046) between the MMN amplitude difference (auditory-only MMN minus audiovisual

MMN) and reading ability in 16 11-year dyslexic children (Froyen et al., 2011). This suggests that perhaps the evidence showing the MMN reflects the language impairment is not as strong as I thought. Thus, it is possible that the correlation between EEG responses and cross-format integration effect between spoken number words and Arabic digits is not strong either.

## 6.5 Future direction

There are two aspects that future studies can follow-up. Firstly, adding more SOA conditions for the EEG experiments. In the current thesis, only two SOA conditions other than the simultaneous display for the cross-modal numerals. As both the VA100 and the VA200 condition show an integration for far distances, it is not clear about the width of the binding window for the cross-format integration between spoken number words and Arabic digits. Moreover, a shorter interval (e.g., 50 ms interval), as well as auditory-precedes-visual SOA condition are also options for future studies, so that a better temporal resolution of the integration effect and the cross-modal distance effect in EEG responses can be acquired.

Secondly, adding more distances for the EEG experiments. In the current thesis only two distances, 1 and 4 were used. Hence, I only investigated difference between these manipulations. However, if more distances can be added, like what I did in my behavioural matching tasks, then the distance effect can be examined more carefully (like the beta values I calculated for the distance effect in each SOA, see Figure 2-8 on page 78). Moreover, the boundary of close and far distances which would/would not induce an integration effect would be clearer with more distances.

In addition, in the current thesis I tried several methods to reduce the possibility that the acoustic differences between spoken number words can explain any of my EEG results. For example, I used an average EEG response of two different spoken number words for each distance, I also carefully controlled the duration and intensity of spoken number words. I also used the subtraction method to acquire a difference wave. However, a more efficient way to eliminate the acoustic features of each spoken number word, is to have an extra condition for each word in which only shows the deviant spoken number word repetitively (Bishop, 2007).

Also, as mentioned earlier, the MMN in the current paradigm reflects the change detection, or change discrimination of the auditory stimuli. This is an automatic and pre-attentive processing, and thus should be related to the automatic correspondence between the stimuli. However, it is also an indirect way to point out the integration as cross-modal numerals are not really 'integrated'. Hence, another way to study the integration between spoken number words and Arabic digits, is to simply test whether the multi-modal condition behaved as super-additive when comparing to unimodal conditions (e.g., Giard & Peronnet, 1999). That is, whether the EEG responses of the audiovisual condition is larger than the combination of auditory and visual condition (i.e., VA > A + V). However, this approach is more exploratory and without a precise idea about when and where the EEG responses should show the super-additive pattern for the audiovisual numerals.

Last, as the current research is the first to study the cross-format integration between spoken number words and Arabic digits and some results are also novel as well as unexpected, a replication is needed to further confirm that the current findings are reliable.

## 6.6 Overall conclusion

In conclusion, the current series of experiments shed light on the cross-modal correspondence between Arabic digits and spoken number words. The distance effect shown in the behavioural matching task clearly indicates the presence of an amodal magnitude representation of numbers. The MMN responses in the oddball paradigm is first which shows that the cross-format integration exists between spoken number words and Arabic digits. Furthermore, this integration is modulated by distance as well as SOA, showing that the cross-modal correspondence between spoken number words and Arabic digits is unique as well as complicated. More research is needed to further disentangle these findings.

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Appendix A

Supplementary materials for Chapter 3 -

The full ANOVA reports for the MMN and the AMN amplitude

MMN results

A 4-way ANOVA (condition: auditory & audiovisual; caudality: anterior & posterior; hemisphere: left, right, and midline; stimuli group[29]: 1 to 4) was conducted for the examination of the difference in the MMN between the auditory and the audiovisual condition. Stimuli group was a between-subject factor. The results showed that the main effect of hemisphere was significant ($F(1.9, 87.7) = 4.51$, $p = .01$, $\eta^2 = .09$), as well as stimuli group ($F(3, 46) = 3.12$, $p = .04$, $\eta^2 = .17$), but there was no significant main effect for condition ($F(1, 46) = 0.44$, $p = .51$, $\eta^2 = .01$), or caudality ($F(1, 46) = 1.90$, $p = .18$, $\eta^2 = .04$). Bonferroni post-hoc comparisons indicated that the amplitude in the left electrode group ($M$ = 1.14 μv) was significant smaller than the amplitude in the midline electrode group ($M$ = 1.34 μv, $p = .005$). A significant interaction found between caudality and hemisphere ($F(1.8, 83.8) = 14.96$, $p < .001$, $\eta^2 = .25$). Bonferroni post-hoc comparisons showed that the amplitude of the MMN at the midline anterior electrodes ($M$ = 1.60 μv) was significantly larger than the MMN in the left anterior electrodes ($M$ = 1.11 μv, $p < .001$), and the MMN in the right anterior electrodes ($M$ = 1.33 μv, $p = .002$). While the amplitudes of MMN in the posterior sites were not significantly different in left ($M$ = 1.18 μv), right ($M$ = 1.21 μv), and midline electrode groups ($M$ = 1.08 μv, all $p > .10$). A significant interaction was found between Caudality and Stimuli group ($F(3, 46) = 3.59$, $p = .002$, $\eta^2 = .19$). Post-hoc comparisons showed that in Group 1 and 4, the amplitude of the MMN was larger in the anterior electrodes than in the posterior electrodes (Anterior vs Posterior: Group 1: 1.19 μv vs 0.58 μv, $p = .036$; Group 4: 1.99

[29] Group 1: 4 as standard 6 as deviant; Group 2: 6 as standard 4 as deviant; Group 3: 6 as standard 8 as deviant; Group 4: 8 as standard 6 as deviant. The reason to use more than a pair of numerals was to avoid possible alternative explanation that the observed effect only applied to a specific pair of numerals but not generalizable to other numerals.

μv vs 1.37 μv, *p* = .035), while in Group 3, the MMN was smaller in the anterior than in the posterior electrodes (1.14 μv vs 1.81 μv, *p* = .018), while there was no significant difference in Group 2 (0.57 μv vs 0.66 μv, *p* = .75). A 3-way significant interaction was found for caudality * hemisphere * stimuli group ($F(5.5, 83.8) = 2.54$, $p = .03$, $\eta^2 = .14$). No other significant 3-way or 4-way interactions were found.

AMN results

A 4-way ANOVA (Condition: Auditory & Audiovisual; Caudality: Anterior & Posterior; Hemisphere: Left, Right, and Midline; Stimuli group: 1 to 4) was then conducted for the AMN mean amplitude. Here, a significant main effect was found for condition ($F(1, 46) = 4.80$, $p = .034$, $\eta^2 = .09$), hemisphere ($F(1.9, 88.2) = 7.80$, $p = .001$, $\eta^2 = .45$) and stimuli group ($F(3, 46) = 30.66$, $p <.001$, $\eta^2 =$ ,67), but not for caudality ($F(1, 46) = 1.56$, $p = .22$, $\eta^2 = .03$). The two-way interaction was found significant for condition * hemisphere ($F(1.7, 76.6) = 5.36$, $p = .01$, $\eta^2 = .10$). Post-hoc comparisons revealed that although all amplitudes were smaller in the audiovisual condition than in the auditory condition, these differences were only significant on left ($p = .03$) and midline ($p = .007$) electrodes, but not on electrodes in the right hemisphere ($p = .22$). A two-way interaction was also found between hemisphere * stimuli group (F(5.8, 88.2) = 7.97, $p <.001$, $\eta^2 = .34$). A three-way interaction was found among caudality * hemisphere * stimuli Group ($F(5.4, 83.2) = 8.17$, $p < .001$, $\eta^2 = .35$). No other significant interactions were found.

# Appendix B

## Supplementary materials for Chapter 4

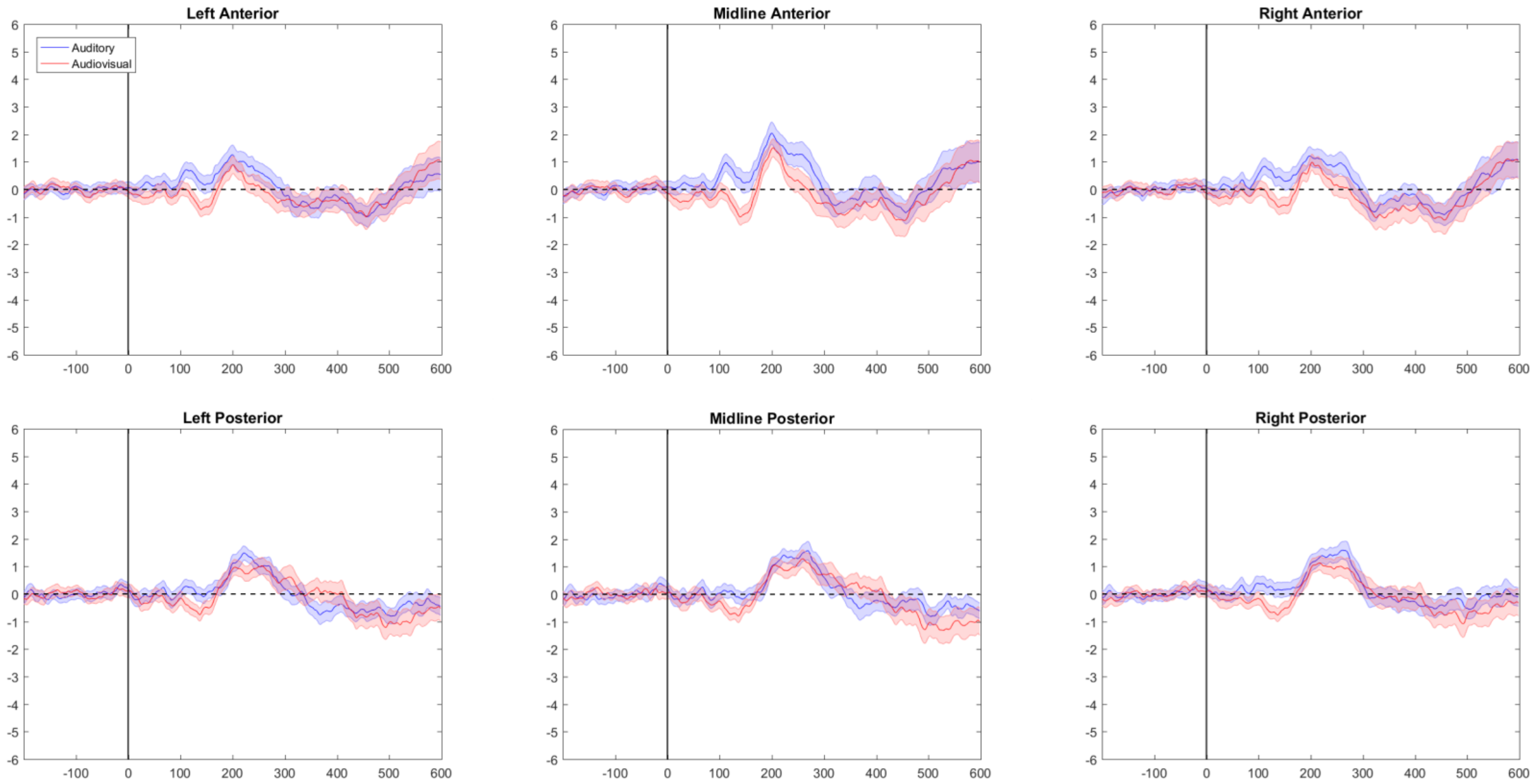


*Figure B1. The overall averaged difference waves of the auditory-only & audiovisual conditions by electrode groups (±1 SE). The amplitudes of difference waves were acquired from standard minus overall deviant trials (including both close and far distance).*

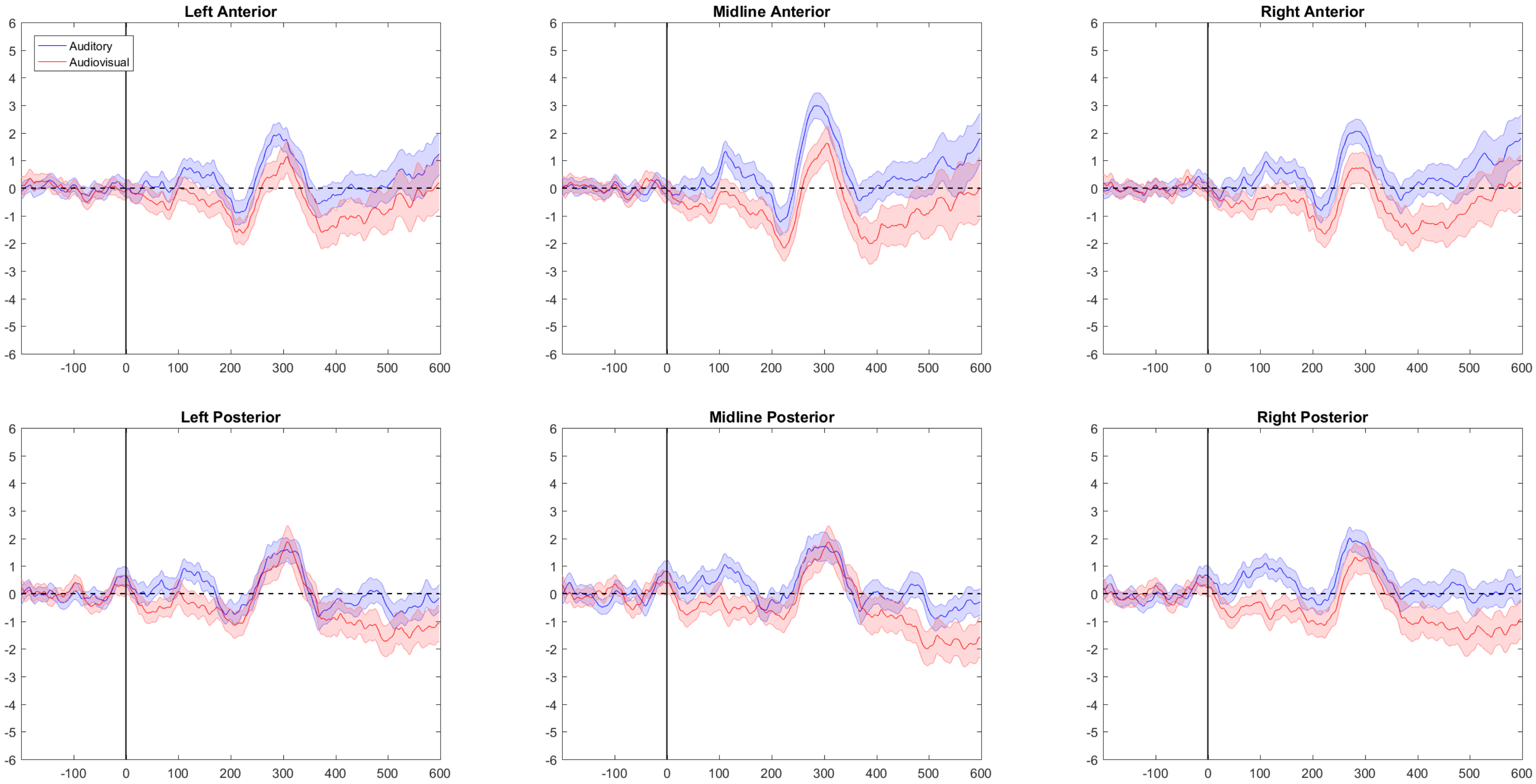


*Figure B2. The averaged difference waves of close distance in the auditory and the audiovisual condition in the six electrode groups (±1 SE). The amplitudes of difference waves were acquired from standard minus deviant trials for close distance only.*

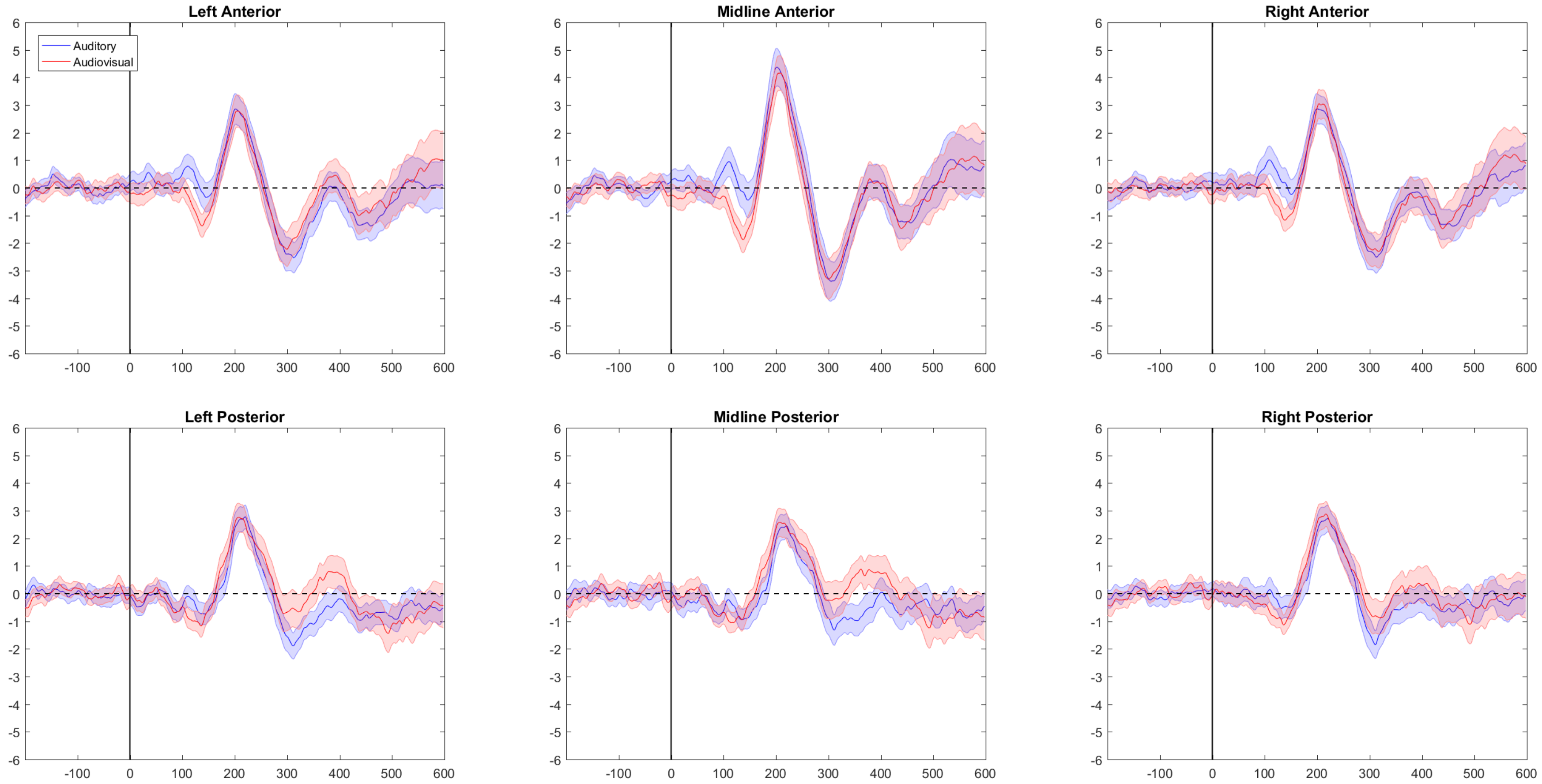


*Figure B3. The averaged difference waves of far distance in the auditory and the audiovisual condition in the six electrode groups (±1 SE). The amplitudes of difference waves were acquired from standard minus deviant trials for far distance only.*

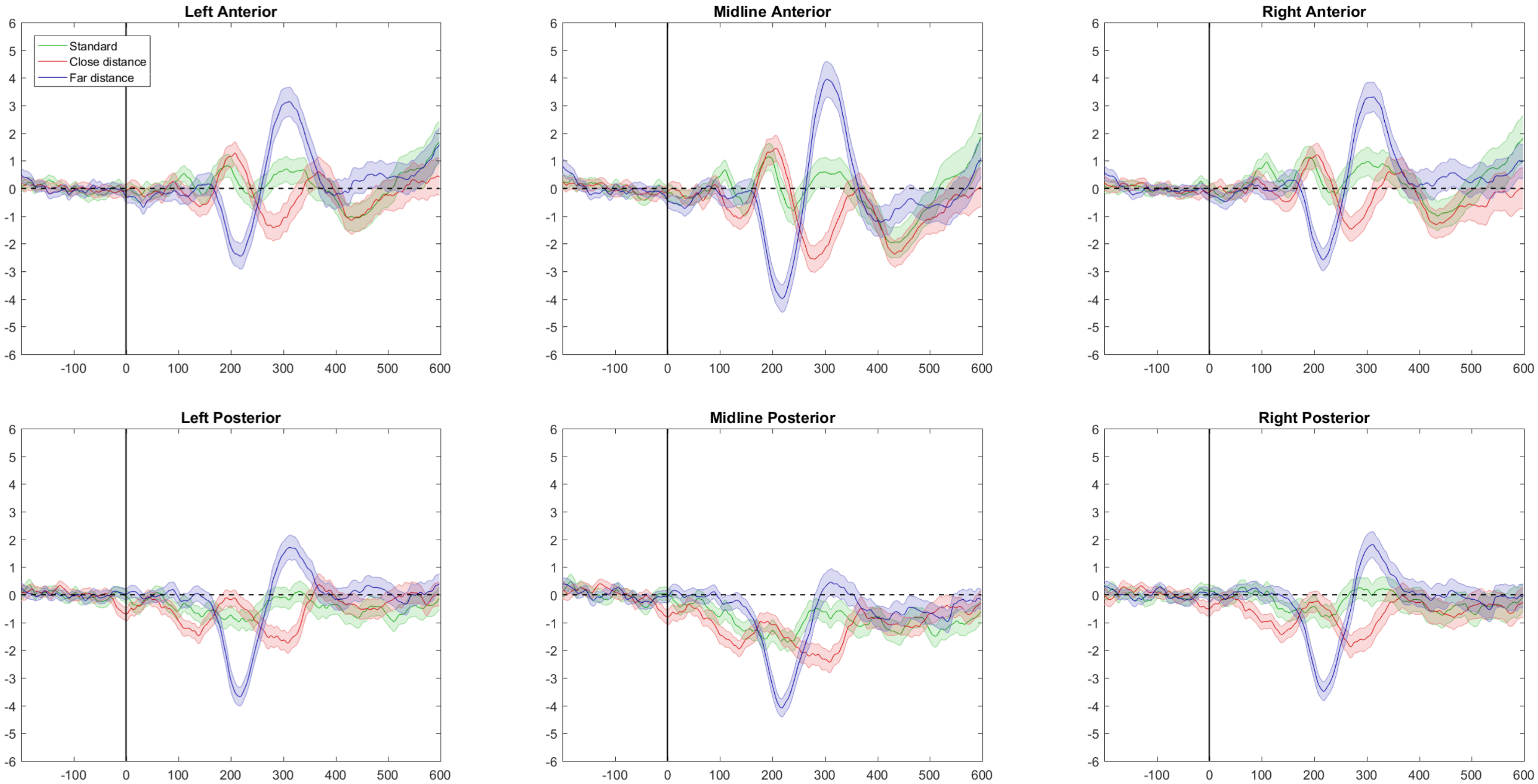


*Figure B4. Brain raw waves of standard, close deviant, and far deviant of the auditory condition in the six electrode groups (±1 SE).*

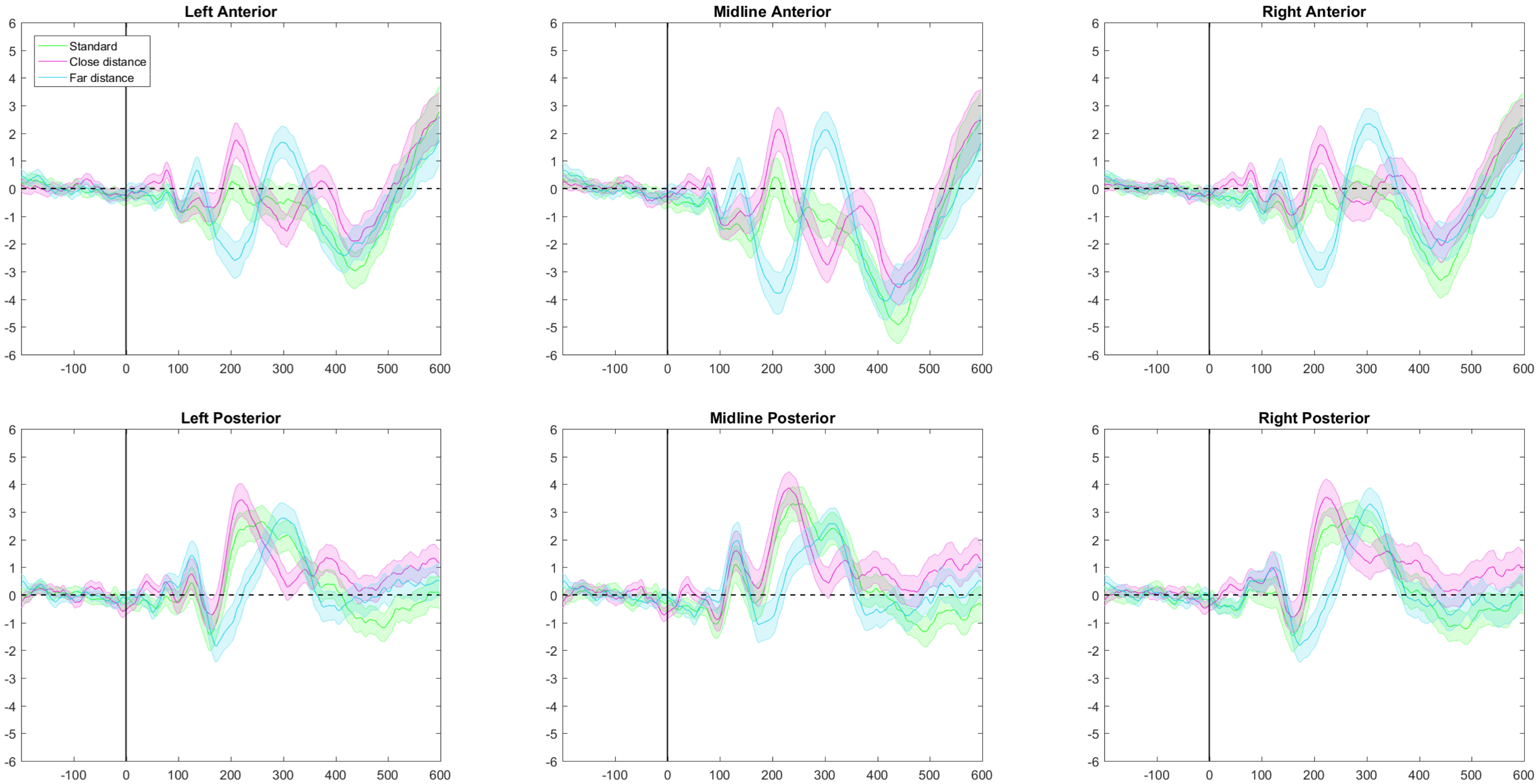


*Figure B5. Brain raw waves of standard, close deviant, and far deviant of the audiovisual condition in the six electrode groups (±1 SE).*

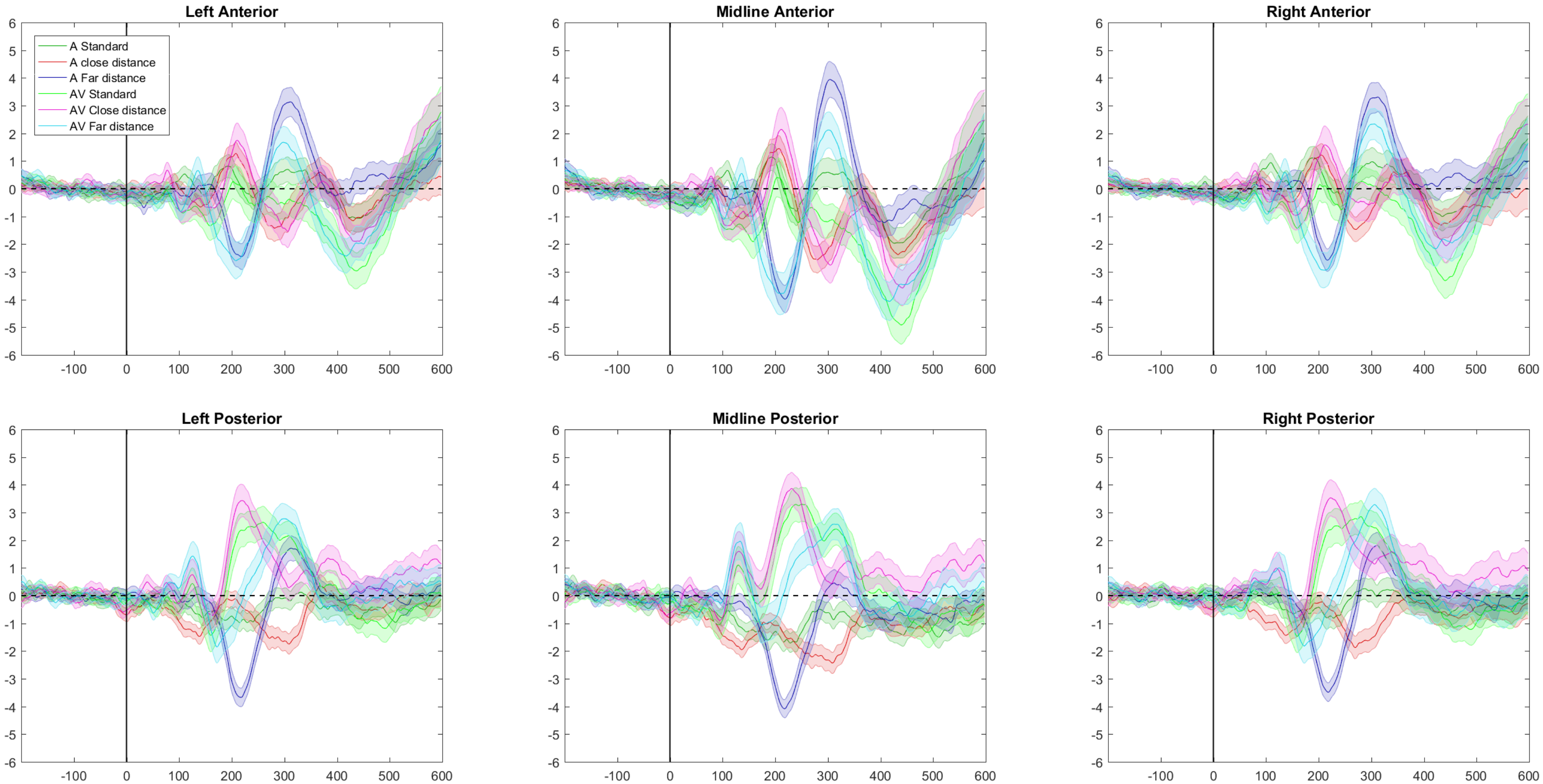


*Figure B6. Brain raw waves of standard, close deviant, and far deviant in both auditory and audiovisual condition in the six electrode groups (±1 SE).*

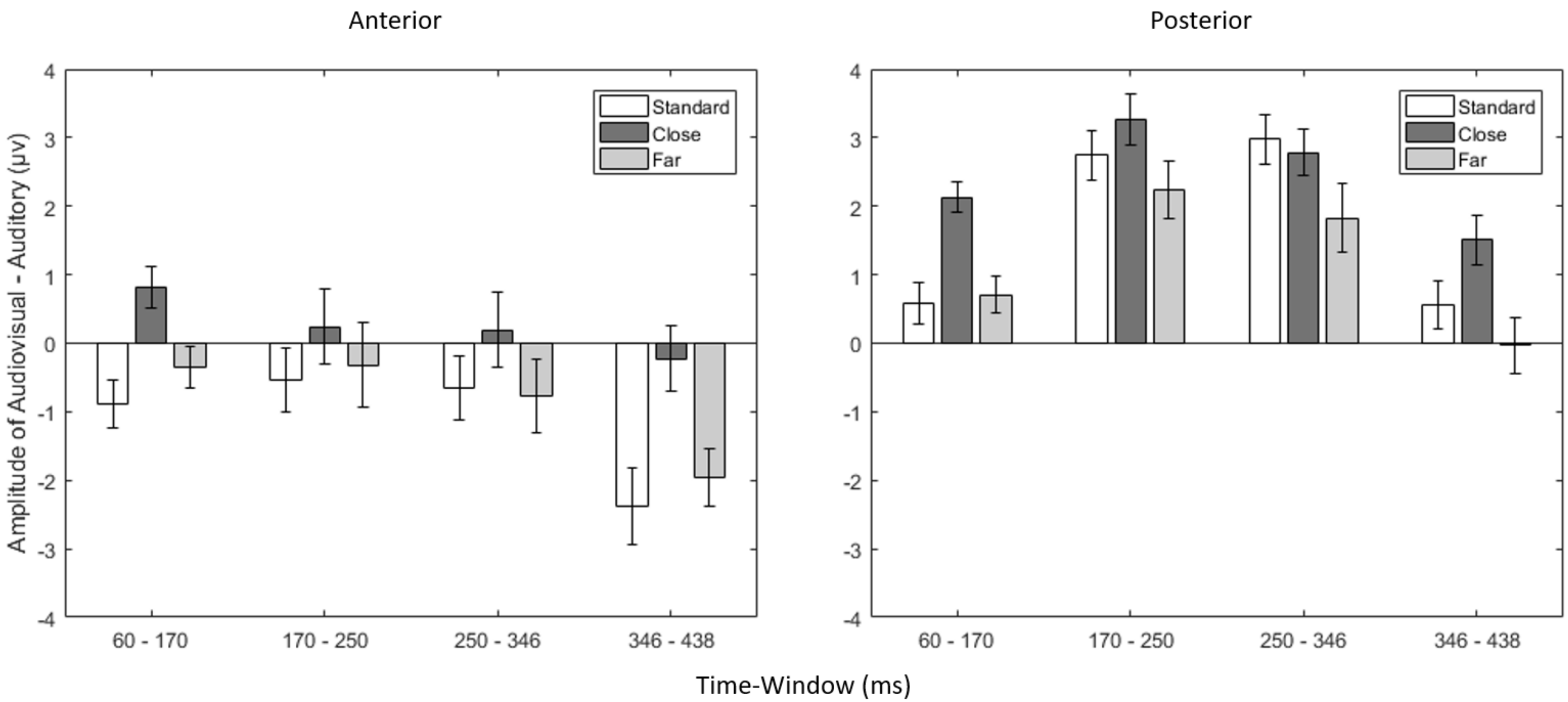


*Figure B7. The amplitude difference between conditions (VA minus A) by distance at the anterior and the posterior electrode group in different time-windows (±1 SE).*

Table B1

*MMN Amplitudes (μv) under the Auditory and the Audiovisual Condition by Electrode Group and Distance*

| Distance | Electrode Group | | Auditory | Audiovisual |
|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* |
| Close | Anterior | Left | 0.72 (1.38) | -0.12 (1.75) |
| | | Right | 0.77 (1.59) | -0.20 (1.68) |
| | | Midline | 0.85 (2.00) | -0.27 (1.87) |
| | Posterior | Left | 0.71 (1.34) | -0.13 (1.76) |
| | | Right | 0.86 (1.28) | -0.24 (1.54) |
| | | Midline | 0.92 (1.50) | 0.02 (1.83) |
| Far | Anterior | Left | 1.86 (2.37) | 1.67 (2.31) |
| | | Right | 1.94 (2.29) | 1.77 (1.93) |
| | | Midline | 2.76 (3.11) | 2.31 (2.79) |
| | Posterior | Left | 1.55 (1.78) | 1.76 (2.26) |
| | | Right | 1.73 (1.88) | 1.88 (2.03) |
| | | Midline | 1.31 (1.89) | 1.80 (2.44) |

Table B2

*The One-sample t-tests for Detecting an MMN in the Auditory-only and the Audiovisual Condition at each Electrode Group (N = 36)*

| Condition | Caudality | Hemisphere | *t*-score | *p*-value |
|---|---|---|---|---|
| Auditory-only | Anterior | Left | 4.6 | <.001 |
| | | Midline | 5.0 | <.001 |
| | | Right | 5.1 | <.001 |
| | Posterior | Left | 5.8 | <.001 |
| | | Midline | 6.0 | <.001 |
| | | Right | 6.1 | <.001 |
| Audiovisual | Anterior | Left | 2.6 | .013 |
| | | Midline | 3.1 | .004 |
| | | Right | 2.9 | .007 |
| | Posterior | Left | 3.1 | .004 |
| | | Midline | 3.4 | .002 |
| | | Right | 3.3 | .002 |

Table B3

*Summary of the 4-way ANOVA for MMN Amplitudes*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 511.63 | 1 | 511.63 | 64.85 | <.001 | .65 |
| Error (Distance) | 276.15 | 35 | 7.89 | | | |
| Condition | 49.01 | 1 | 49.01 | 2.17 | .15 | .06 |
| Error (Condition) | 790.20 | 35 | 22.58 | | | |
| Caudality | 5.54 | 1 | 5.54 | 1.00 | .32 | .03 |
| Error (Caudality) | 193.25 | 35 | 5.52 | | | |
| Hemisphere | 6.53 | 1.7 | 3.93 | 3.15 | .06 | .08 |
| Error (Hemisphere) | 72.60 | 58.1 | 1.25 | | | |
| Distance * Condition | 50.86 | 1 | 50.86 | 6.40 | .02 | .16 |
| Error (Distance * Condition) | 277.97 | 35 | 7.94 | | | |
| Distance * Caudality | 10.77 | 1 | 10.77 | 4.97 | .03 | .12 |
| Error (Distance * Caudality) | 75.87 | 35 | 2.17 | | | |
| Distance * Hemisphere | 2.26 | 1.9 | 1.20 | 2.25 | .11 | .06 |
| Error (Distance * Hemisphere) | 35.17 | 65.9 | 0.53 | | | |
| Condition * Caudality | 4.65 | 1 | 4.65 | 0.76 | .39 | .02 |
| Error (Condition * Caudality) | 212.80 | 35 | 6.08 | | | |
| Condition * Hemisphere | 0.46 | 1.4 | 0.32 | 0.23 | .80 | .01 |
| Error (Condition * Hemisphere) | 69.57 | 50.7 | 1.37 | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Caudality * Hemisphere | 6.43 | 1.7 | 3.83 | 7.03 | .002 | .17 |
| Error (Caudality * Hemisphere) | 31.99 | 58.7 | 0.55 | | | |
| Distance * Condition * Caudality | 3.76 | 1 | 3.76 | 1.17 | .28 | .03 |
| Error (Distance * Condition * Caudality) | 112.29 | 35 | 3.21 | | | |
| Distance * Condition * Hemisphere | 0.37 | 1.8 | 0.21 | 0.51 | .59 | .01 |
| Error (Distance * Condition * Hemisphere) | 25.60 | 62.2 | 0.41 | | | |
| Distance * Caudality * Hemisphere | 13.88 | 1.6 | 8.45 | 24.84 | <.001 | .42 |
| Error (Distance * Caudality * Hemisphere) | 19.56 | 57.5 | 0.34 | | | |
| Condition * Caudality * Hemisphere | 2.36 | 2.0 | 1.21 | 2.70 | .07 | .07 |
| Error (Condition * Caudality * Hemisphere) | 30.64 | 68.6 | 0.45 | | | |
| Distance * Condition * Caudality * Hemisphere | 0.25 | 1.6 | 0.15 | 0.72 | .46 | .02 |
| Error (Distance * Condition * Caudality * Hemisphere) | 11.97 | 57.0 | 0.21 | | | |

Table B4

*MMN Latencies (ms) under the Auditory and the Audiovisual Condition by Electrode Group and Distance*

| Distance | Electrode Group | | Auditory | Audiovisual |
|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* |
| Close | Anterior | Left | 140 (34) | 133 (31) |
| | | Right | 142 (31) | 133 (33) |
| | | Midline | 137 (35) | 126 (33) |
| | Posterior | Left | 134 (38) | 140 (39) |
| | | Right | 136 (30) | 132 (41) |
| | | Midline | 138 (49) | 137 (54) |
| Far | Anterior | Left | 179 (31) | 178 (38) |
| | | Right | 181 (28) | 190 (31) |
| | | Midline | 190 (34) | 189 (32) |
| | Posterior | Left | 188 (35) | 192 (31) |
| | | Right | 191 (32) | 198 (33) |
| | | Midline | 183 (45) | 191 (36) |

Table B5

*Summary of the 4-way ANOVA for MMN latencies*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 579100 | 1 | 579100 | 134.62 | <.001 | .79 |
| Error (Distance) | 150566 | 35 | 4302 | | | |
| Condition | 1.95 | 1 | 1.95 | 0.00 | .99 | < .01 |
| Error (Condition) | 204200 | 35 | 5834 | | | |
| Caudality | 2765 | 1 | 2765 | 0.88 | .36 | .03 |
| Error (Caudality) | 110051 | 35 | 3144 | | | |
| Hemisphere | 877.76 | 1.7 | 529.95 | 0.61 | .55 | .02 |
| Error (Hemisphere) | 50222 | 58.0 | 866.33 | | | |
| Distance * Condition | 3960 | 1 | 3960 | 2.08 | .16 | .06 |
| Error (Distance * Condition) | 66492 | 35 | 1900 | | | |
| Distance * Caudality | 1503 | 1 | 1503 | 1.23 | .28 | .03 |
| Error (Distance * Caudality) | 42883 | 35 | 1225 | | | |
| Distance * Hemisphere | 1830 | 2.0 | 919.59 | 1.62 | .21 | .04 |
| Error (Distance * Hemisphere) | 39565 | 69.6 | 568.19 | | | |
| Condition * Caudality | 2568 | 1 | 2568 | 1.08 | .31 | .03 |
| Error (Condition * Caudality) | 83398 | 35 | 2383 | | | |
| Condition * Hemisphere | 110.70 | 1.8 | 55.35 | 0.12 | .88 | < .01 |
| Error (Condition * Hemisphere) | 31251 | 61.6 | 446.45 | | | |
| Caudality * Hemisphere | 892.97 | 1.9 | 460.12 | 1.10 | .34 | .03 |
| Error (Caudality * Hemisphere) | 28449 | 67.9 | 418.82 | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Distance * Condition * Caudality | 415.28 | 1 | 415.28 | 0.28 | .60 | .01 |
| Error (Distance * Condition * Caudality) | 51617 | 35 | 1475 | | | |
| Distance * Condition * Hemisphere | 1449 | 1.8 | 820.96 | 1.53 | .22 | .04 |
| Error (Distance * Condition * Hemisphere) | 33081 | 61.8 | 535.40 | | | |
| Distance * Caudality * Hemisphere[a] | 4741 | 1.9 | 2528 | 8.60 | <.001 | .20 |
| Error (Distance * Caudality * Hemisphere) | 19304 | 65.6 | 294.07 | | | |
| Condition * Caudality * Hemisphere | 653.60 | 2.0 | 332.27 | 0.64 | .53 | .02 |
| Error (Condition * Caudality * Hemisphere) | 35505 | 68.8 | 515.70 | | | |
| Distance * Condition * Caudality * Hemisphere | 135.29 | 1.9 | 70.23 | 0.27 | .76 | .01 |
| Error (Distance * Condition * Caudality * Hemisphere) | 17299 | 67.4 | 256.57 | | | |

*Note.* [a]Further simple interaction effects showed that the significant 3-way interaction were not related to distance, but only related to caudality and hemisphere. This effect was thus not reported in the main text.

Table B6

*AMN Amplitudes (μv) under the Auditory and the Audiovisual Condition by Electrode Group and Distance*

| Distance | Electrode Group | | Auditory | Audiovisual |
|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* |
| Close distance | Anterior | Left | 1.10 (1.74) | 0.01 (2.53) |
| | | Right | 1.41 (2.13) | -0.11 (2.62) |
| | | Midline | 1.83 (2.34) | 0.09 (2.70) |
| | Posterior | Left | 0.88 (2.06) | 0.52 (2.45) |
| | | Right | 1.45 (1.97) | 0.44 (2.59) |
| | | Midline | 1.19 (2.14) | 0.67 (2.53) |
| Far distance | Anterior | Left | -0.91 (2.82) | -1.10 (3.16) |
| | | Right | -0.60 (3.15) | -0.95 (2.91) |
| | | Midline | -0.81 (4.06) | -1.41 (3.87) |
| | Posterior | Left | -0.09 (2.37) | 0.33 (3.12) |
| | | Right | 0.41 (2.51) | 0.53 (2.95) |
| | | Midline | 0.56 (2.66) | 0.92 (3.01) |

Table B7

*Summary of the 4-way ANOVA for AMN amplitudes*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 238.61 | 1 | 238.61 | 8.64 | .006 | .20 |
| Error (Distance) | 966.71 | 35 | 27.62 | | | |
| Condition | 63.46 | 1 | 63.46 | 1.34 | .25 | .04 |
| Error (Condition) | 1653 | 35 | 47.22 | | | |
| Caudality | 128.32 | 1 | 128.32 | 13.23 | .001 | .27 |
| Error (Caudality) | 339.52 | 35 | 9.70 | | | |
| Hemisphere | 13.26 | 1.9 | 6.96 | 3.59 | .03 | .09 |
| Error (Hemisphere) | 129.09 | 66.7 | 1.94 | | | |
| Distance * Condition | 54.03 | 1 | 54.03 | 6.17 | .02 | .15 |
| Error (Distance * Condition) | 306.29 | 35 | 8.75 | | | |
| Distance * Caudality | 86.72 | 1 | 86.72 | 16.63 | <.001 | .32 |
| Error (Distance * Caudality) | 182.51 | 35 | 5.22 | | | |
| Distance * Hemisphere | 1.26 | 1.9 | 0.67 | 1.12 | .33 | .03 |
| Error (Distance * Hemisphere) | 39.30 | 66.3 | 0.59 | | | |
| Condition * Caudality[a] | 30.46 | 1 | 30.46 | 5.08 | .03 | .13 |
| Error (Condition * Caudality) | 210.01 | 35 | 6.00 | | | |
| Condition * Hemisphere | 6.16 | 1.4 | 4.32 | 2.19 | .14 | .06 |
| Error (Condition * Hemisphere) | 98.37 | 49.9 | 1.97 | | | |
| Caudality * Hemisphere | 2.74 | 1.6 | 1.76 | 1.47 | .24 | .04 |
| Error (Caudality * Hemisphere) | 65.20 | 54.4 | 1.20 | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Distance * Condition * Caudality | 0.32 | 1 | 0.32 | 0.10 | .76 | < .01 |
| Error (Distance * Condition * Caudality) | 116.70 | 35 | 3.33 | | | |
| Distance * Condition * Hemisphere | 0.89 | 1.7 | 0.53 | 1.07 | .34 | .03 |
| Error (Distance * Condition * Hemisphere) | 29.29 | 59.6 | 0.49 | | | |
| Distance * Caudality * Hemisphere[b] | 9.95 | 1.2 | 8.12 | 9.91 | .002 | .22 |
| Error (Distance * Caudality * Hemisphere) | 35.13 | 42.9 | 0.82 | | | |
| Condition * Caudality * Hemisphere | 3.37 | 1.9 | 1.75 | 3.65 | .03 | .09 |
| Error (Condition * Caudality * Hemisphere) | 32.27 | 67.2 | 0.48 | | | |
| Distance * Condition * Caudality * Hemisphere | 0.12 | 1.7 | 0.07 | 0.31 | .73 | .01 |
| Error (Distance * Condition * Caudality * Hemisphere) | 12.89 | 60.1 | 0.22 | | | |

*Note.* [a]The 2-way interaction here was because a more positive AMN for the posterior electrode group than for the anterior electrode group was found in the audiovisual condition ($p < .001$) but not in the auditory condition ($p = .21$). However, this was not the main interest of the current study, hence it was not reported in the main text. [b]Under this significant 3-way interaction, a simple interaction was found significant between distance and hemisphere at the anterior electrodes ($F(1.9, 65.5) = 6.24$, $p = .003$, $\eta 2 = .15$), whereas the interaction was not significant at the posterior electrodes ($F(1.6, 55.6) = 2.79$, $p = .07$, $\eta 2 = .07$). However, further simple main effects analyses showed that the close-distance deviant induced a more positive AMN amplitude in all levels of hemisphere, i.e., left, right, and midline anterior electrodes (all *p*-values <= .001). These results indicated that the 3-way interaction was not due to the modulation of different numeral distances in a specific electrode group. Hence, this 3-way interaction was not reported in the main text.

Table B8

*Mean Peak Amplitudes differences across of Conditions by Distance (μv) in Different Time-Windows at each Electrode Group*

| Time-Window | Electrode Group | | Standard | Close | Far |
|---|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* | *M (SD)* |
| 60 – 170 ms | Anterior | Left | -0.72 (1.98) | 0.76 (1.80) | -0.16 (1.77) |
| | | Right | -0.98 (1.98) | 0.66 (1.79) | -0.57 (1.74) |
| | | Midline | -0.96 (2.45) | 1.03 (2.13) | -0.33 (1.99) |
| | Posterior | Left | 0.35 (1.82) | 1.96 (1.32) | 0.56 (1.43) |
| | | Right | 0.15 (1.73) | 1.87 (1.23) | 0.42 (1.65) |
| | | Midline | 1.25 (2.41) | 2.57 (1.97) | 1.14 (2.05) |
| 170 – 250 ms | Anterior | Left | -0.38 (2.72) | 0.20 (2.98) | -0.19 (3.55) |
| | | Right | -0.71 (2.71) | 0.20 (3.11) | -0.67 (3.42) |
| | | Midline | -0.55 (3.24) | 0.33 (3.88) | -0.10 (4.30) |
| | Posterior | Left | 2.46 (1.89) | 2.78 (2.28) | 1.99 (2.47) |
| | | Right | 2.24 (2.46) | 3.04 (2.43) | 1.73 (2.66) |
| | | Midline | 3.54 (2.68) | 3.98 (2.71) | 2.99 (2.77) |
| 250 – 346 ms | Anterior | Left | -0.50 (2.57) | 0.08 (3.16) | -0.82 (3.08) |
| | | Right | -0.59 (2.94) | 0.47 (3.14) | -0.48 (3.09) |
| | | Midline | -0.89 (3.27) | 0.04 (3.83) | -0.99 (3.62) |
| | Posterior | Left | 2.68 (2.02) | 2.23 (2.03) | 1.39 (2.74) |
| | | Right | 2.57 (2.37) | 2.85 (2.23) | 1.76 (2.94) |
| | | Midline | 3.69 (2.55) | 3.28 (2.58) | 2.34 (3.49) |
| 346 – 438 ms | Anterior | Left | -1.89 (3.21) | -0.22 (2.80) | -1.91 (2.63) |
| | | Right | -2.26 (3.41) | 0.05 (2.73) | -1.60 (2.62) |
| | | Midline | -3.00 (3.76) | -0.50 (3.32) | -2.37 (2.71) |

| | | | | |
|---|---|---|---|---|
| Posterior | Left | 0.37 (2.01) | 1.17 (2.09) | -0.32 (2.29) |
| | Right | 0.06 (2.33) | 1.49 (2.22) | -0.07 (2.67) |
| | Midline | 1.25 (2.38) | 1.87 (2.64) | 0.29 (2.86) |

*Note.* The amplitude differences here were calculated as the amplitude of audiovisual minus auditory trials.

Table B9

*Summary of the 3-way ANOVA for the Mean Peak Amplitudes during 60 – 170 ms*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 318.89 | 1.8 | 174.52 | 16.37 | < .001 | .32 |
| Error (Distance) | 681.65 | 64.0 | 10.66 | | | |
| Caudality | 266.98 | 1 | 266.98 | 20.90 | < .001 | .37 |
| Error (Caudality) | 447.04 | 35 | 12.77 | | | |
| Hemisphere | 30.28 | 2.0 | 15.46 | 11.37 | < .001 | .25 |
| Error (Hemisphere) | 93.20 | 68.6 | 1.36 | | | |
| Distance * Caudality | 4.61 | 2.0 | 2.33 | 0.75 | .48 | .02 |
| Error (Distance * Caudality) | 215.32 | 69.4 | 3.10 | | | |
| Distance * Hemisphere | 1.14 | 3.1 | 0.37 | 0.49 | .70 | .01 |
| Error (Distance * Hemisphere) | 82.27 | 109.0 | 0.76 | | | |
| Caudality * Hemisphere | 17.36 | 1.6 | 10.78 | 10.74 | < .001 | .24 |
| Error (Caudality * Hemisphere) | 56.60 | 56.4 | 1.00 | | | |
| Distance * Caudality * Hemisphere[a] | 3.91 | 3.5 | 1.10 | 4.09 | .005 | .11 |
| Error (Distance * Caudality * Hemisphere) | 33.50 | 124.1 | 0.27 | | | |

*Note.* [a]This three-way interaction between distance, caudality, and hemisphere was found significant. However, further post-hoc analyses showed that the simple 2-way interactions related to the distance factor were not significant (all p-values > .05), thus this interaction was not reported in the main text.

Table B10

*Summary of the 3-way ANOVA for the Mean Peak Amplitudes during 170 – 250 ms*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 78.09 | 1.7 | 46.25 | 1.81 | .18 | .05 |
| Error (Distance) | 1510 | 59.1 | 25.55 | | | |
| Caudality | 1417 | 1 | 1417 | 39.58 | < .001 | .53 |
| Error (Caudality) | 1253 | 35 | 35.81 | | | |
| Hemisphere | 62.35 | 1.9 | 33.34 | 12.22 | < .001 | .26 |
| Error (Hemisphere) | 178.53 | 65.5 | 2.73 | | | |
| Distance * Caudality | 15.00 | 1.5 | 9.75 | 1.33 | .27 | .04 |
| Error (Distance * Caudality) | 394.90 | 53.8 | 7.33 | | | |
| Distance * Hemisphere | 5.58 | 2.8 | 1.99 | 1.82 | .15 | .05 |
| Error (Distance * Hemisphere) | 107.26 | 98.1 | 1.09 | | | |
| Caudality * Hemisphere | 35.64 | 1.7 | 21.12 | 9.80 | < .001 | .22 |
| Error (Caudality * Hemisphere) | 127.28 | 59.0 | 2.16 | | | |
| Distance * Caudality * Hemisphere | 1.10 | 3.1 | 0.35 | 0.70 | .56 | .02 |
| Error (Distance * Caudality * Hemisphere) | 54.55 | 108.4 | 0.50 | | | |

Table B11

*Summary of the 3-way ANOVA for the Mean Peak Amplitudes during 250 – 346 ms*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 102.43 | 1.7 | 59.98 | 2.35 | .11 | .06 |
| Error (Distance) | 1526 | 59.8 | 25.54 | | | |
| Caudality | 1401 | 1 | 1401 | 43.81 | < .001 | .56 |
| Error (Caudality) | 1120 | 35 | 31.99 | | | |
| Hemisphere | 18.06 | 1.8 | 10.01 | 4.22 | .02 | .11 |
| Error (Hemisphere) | 149.79 | 63.2 | 2.37 | | | |
| Distance * Caudality | 39.42 | 1.6 | 25.04 | 3.59 | .045 | .09 |
| Error (Distance * Caudality) | 384.59 | 55.1 | 6.98 | | | |
| Distance * Hemisphere | 7.43 | 2.9 | 2.56 | 1.93 | .13 | .05 |
| Error (Distance * Hemisphere) | 135.10 | 101.6 | 1.33 | | | |
| Caudality * Hemisphere | 49.26 | 1.7 | 29.73 | 16.19 | < .001 | .32 |
| Error (Caudality * Hemisphere) | 106.48 | 58.0 | 1.84 | | | |
| Distance * Caudality * Hemisphere | 1.50 | 3.0 | 0.51 | 0.81 | .49 | .02 |
| Error (Distance * Caudality * Hemisphere) | 65.36 | 103.4 | 0.63 | | | |

Table B12

*Summary of the 3-way ANOVA for the Mean Peak Amplitudes during 346 – 438 ms*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 367.92 | 1.7 | 220.69 | 7.45 | .002 | .18 |
| Error (Distance) | 1729 | 58.4 | 29.63 | | | |
| Caudality | 784.33 | 1 | 784.33 | 32.21 | < .001 | .48 |
| Error (Caudality) | 852.24 | 35 | 24.35 | | | |
| Hemisphere | .75 | 1.9 | 0.40 | .20 | .81 | .01 |
| Error (Hemisphere) | 134.22 | 66.4 | 2.02 | | | |
| Distance * Caudality | 45.68 | 1.9 | 24.53 | 4.02 | .03 | .10 |
| Error (Distance * Caudality) | 397.81 | 65.2 | 6.10 | | | |
| Distance * Hemisphere | 9.93 | 2.8 | 3.50 | 2.60 | .06 | .07 |
| Error (Distance * Hemisphere) | 133.54 | 99.2 | 1.35 | | | |
| Caudality * Hemisphere | 64.44 | 1.7 | 36.95 | 24.79 | < .001 | .42 |
| Error (Caudality * Hemisphere) | 90.97 | 61.0 | 1.49 | | | |
| Distance * Caudality * Hemisphere | 7.23 | 3.2 | 2.28 | 4.09 | .008 | .11 |
| Error (Distance * Caudality * Hemisphere) | 61.87 | 110.8 | | | | |

Table B13

*The Correlations between Standardised WRAT Scores and MMN, and AMN Amplitude Differences across Conditions by Close and Far Distance*

| Distance | Close | | | | | | Far | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electrode Group | Anterior | | | Posterior | | | Anterior | | | Posterior | | |
| | L | R | M | L | R | M | L | R | M | L | R | M |
| MMN | .25 | .13 | .11 | .18 | .17 | .11 | .23 | .08 | .17 | .21 | .06 | .06 |
| AMN | .26 | .19 | .23 | .24 | .22 | .18 | .31 | .13 | .18 | .30 | .20 | .19 |

*Note.* The values in the table are the partial correlations between standardised WRAT scores and the amplitudes of each ERP component whilst controlling for standardised matrix reasoning IQ scores (N = 36). The amplitude differences were calculated as the amplitude of the audiovisual condition minus the amplitude of the auditory-only condition. L = Left; R = Right; *M* = Midline electrode group. No significant correlations found (all p-values > .07).

Table B14

*The Correlations between Standardised WRAT Scores and MMN, and AMN Amplitude Differences across Distances by Auditory and Audiovisual Condition*

| Condition | Auditory-only | | | | | | Audiovisual | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electrode Group | Anterior | | | Posterior | | | Anterior | | | Posterior | | |
| | L | R | M | L | R | M | L | R | M | L | R | M |
| MMN | .15 | .02 | .12 | .17 | -.03 | .04 | .08 | .07 | .00 | .06 | .08 | .07 |
| AMN | -.16 | -.08 | -.07 | -.20 | -.12 | -.14 | -.05 | -.13 | -.07 | -.10 | -.16 | -.11 |

*Note.* The values in the table are the partial correlations between standardised WRAT scores and the amplitudes of each ERP component whilst controlling for standardised matrix reasoning IQ scores (N = 36). The amplitude differences were calculated as the amplitude of the close distance minus the amplitude of the far distance. L = Left; R = Right; *M* = Midline electrode group. No significant correlations found (all p-values > .24).

Table B15

*The Correlations between Standardised WRAT Scores and Mean Peak Amplitudes Differences across Conditions by Close and Far Distance in each Time-Window*

| Distance | Close | | | | | | Far | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electrode group | Anterior | | | Posterior | | | Anterior | | | Posterior | | |
| | L | R | M | L | R | M | L | R | M | L | R | M |
| 60 – 170 | -.12 | -.18 | -.17 | .23 | -.11 | .09 | -.18 | -.23 | -.14 | -.15 | -.02 | -.01 |
| 170 – 250 | -.14 | -.27 | -.20 | .15 | .00 | .18 | -.21 | -.27 | -.22 | .10 | .09 | .23 |
| 250 – 346 | -.22 | -.38* | -.30 | -.10 | -.14 | -.02 | -.30 | -.35* | -.35* | -.20 | -.21 | -.10 |
| 346 – 438 | -.17 | -.39* | -.26 | -.18 | -.19 | -.07 | -.31 | -.38* | -.34* | -.30 | -.17 | -.12 |

*Note.* The values in the table are the partial correlations between standardised WRAT scores and the amplitudes of each mean peak amplitude in a time-window whilst controlling for standardised matrix reasoning IQ scores (N = 36). The amplitude differences were calculated as the amplitude of the audiovisual condition minus the amplitude of the auditory condition. L = Left; R = Right; *M* = Midline electrode group.

* $p < .05$.

Table B16

*The Correlations between Standardised WRAT Scores and Mean Peak Amplitudes Differences across Distances by Auditory and Audiovisual Condition in each Time-Window*

| Condition | Auditory-only | | | | | | Audiovisual | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electrode group | Anterior | | | Posterior | | | Anterior | | | Posterior | | |
| | L | R | M | L | R | M | L | R | M | L | R | M |
| 60 – 170 | -.09 | .03 | -.04 | -.17 | .08 | .01 | -.02 | -.04 | -.06 | .01 | -.14 | -.13 |
| 170 – 250 | -.18 | -.07 | -.13 | -.20 | -.08 | -.06 | -.00 | -.05 | -.02 | -.07 | -.10 | -.08 |
| 250 – 346 | -.20 | -.11 | -.10 | -.36* | -.25 | -.29 | -.09 | -.19 | -.09 | -.04 | -.13 | -.03 |
| 346 – 438 | -.21 | -.18 | -.12 | -.26 | -.30 | -.22 | -.01 | -.20 | -.08 | -.09 | -.19 | -.09 |

*Note.* The values in the table are the partial correlations between standardised WRAT scores and the amplitudes of each mean peak amplitude in a time-window whilst controlling for standardised matrix reasoning IQ scores (N = 36). The amplitude differences were calculated as the amplitude of the close distance minus the amplitude of the far distance. L = Left; R = Right; *M* = Midline electrode group.

* $p < .05$.

Appendix C

Supplementary materials for Chapter 5

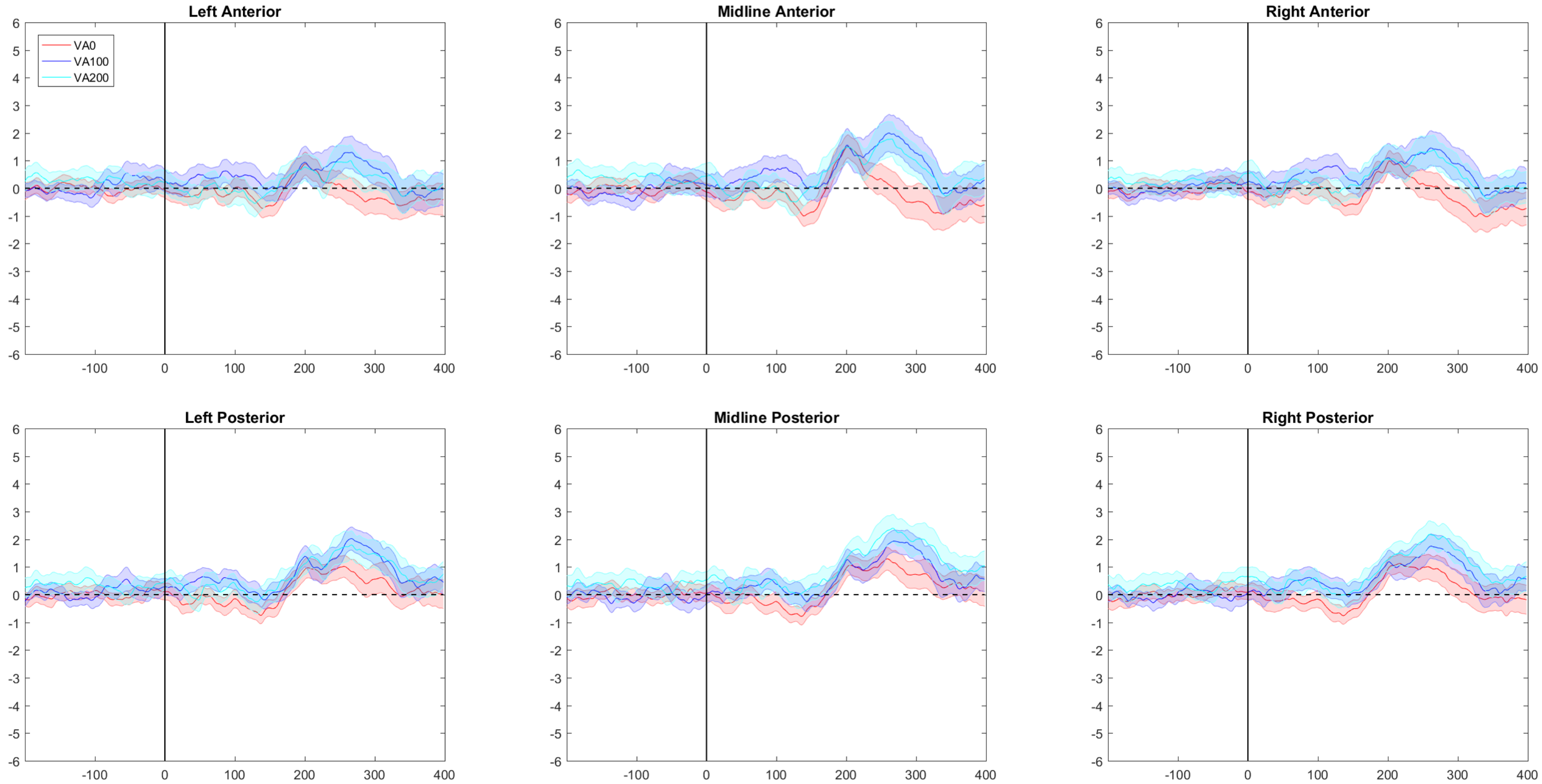


*Figure C1*. The overall averaged difference waves of the SOA conditions at the six electrode groups (±1 *SE*). The amplitudes of difference waves were acquired from standard minus overall deviant trials (including both close and far distance).

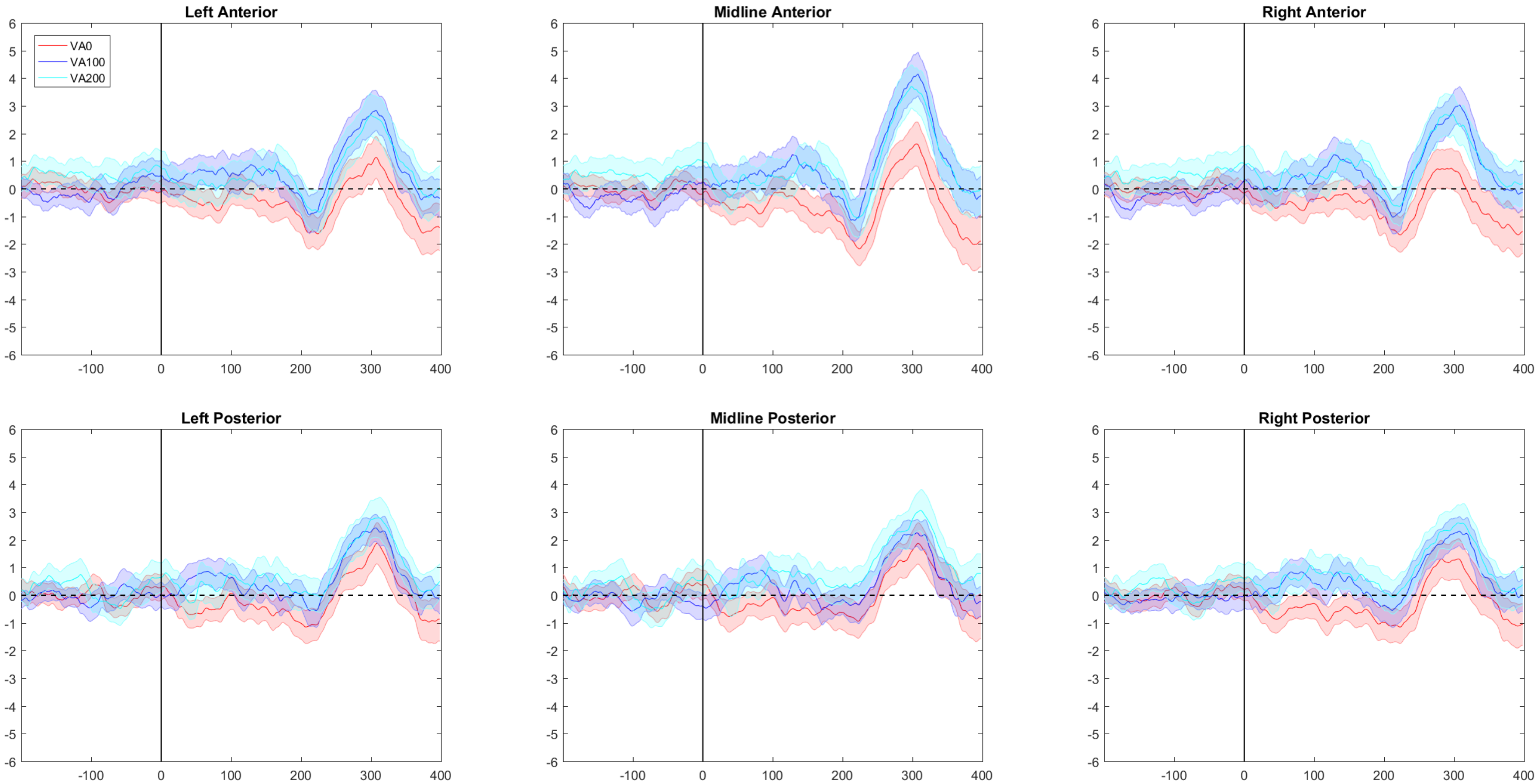


*Figure C2*. The averaged difference waves of close distance across SOA conditions at the six electrode groups (±1 *SE*). The amplitudes of difference waves were acquired from standard minus deviant trials for close distance only.

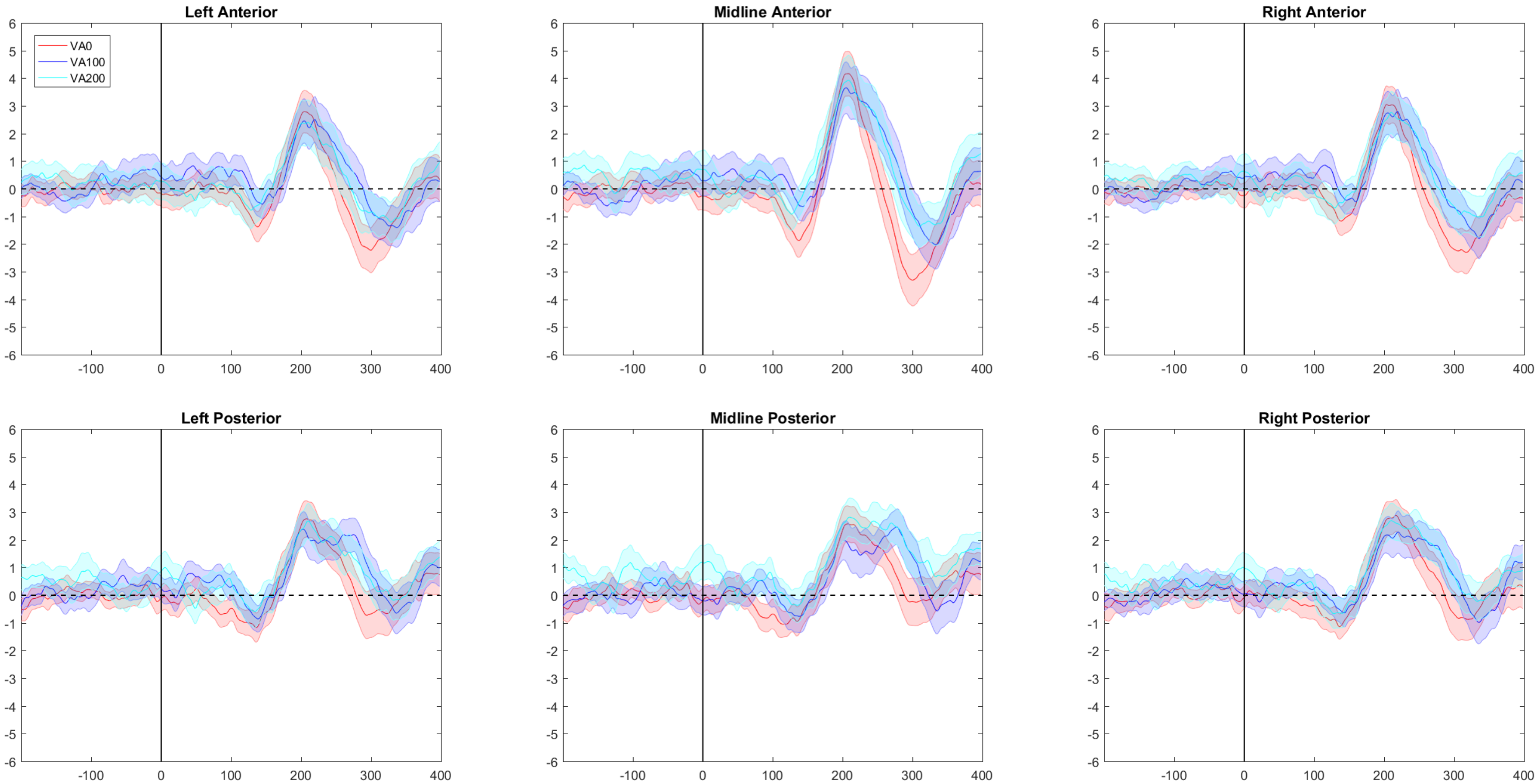


*Figure C3*. The averaged difference waves of far distance across SOA conditions at the six electrode groups (±1 *SE*). The amplitudes of difference waves were acquired from standard minus deviant trials for far distance only.

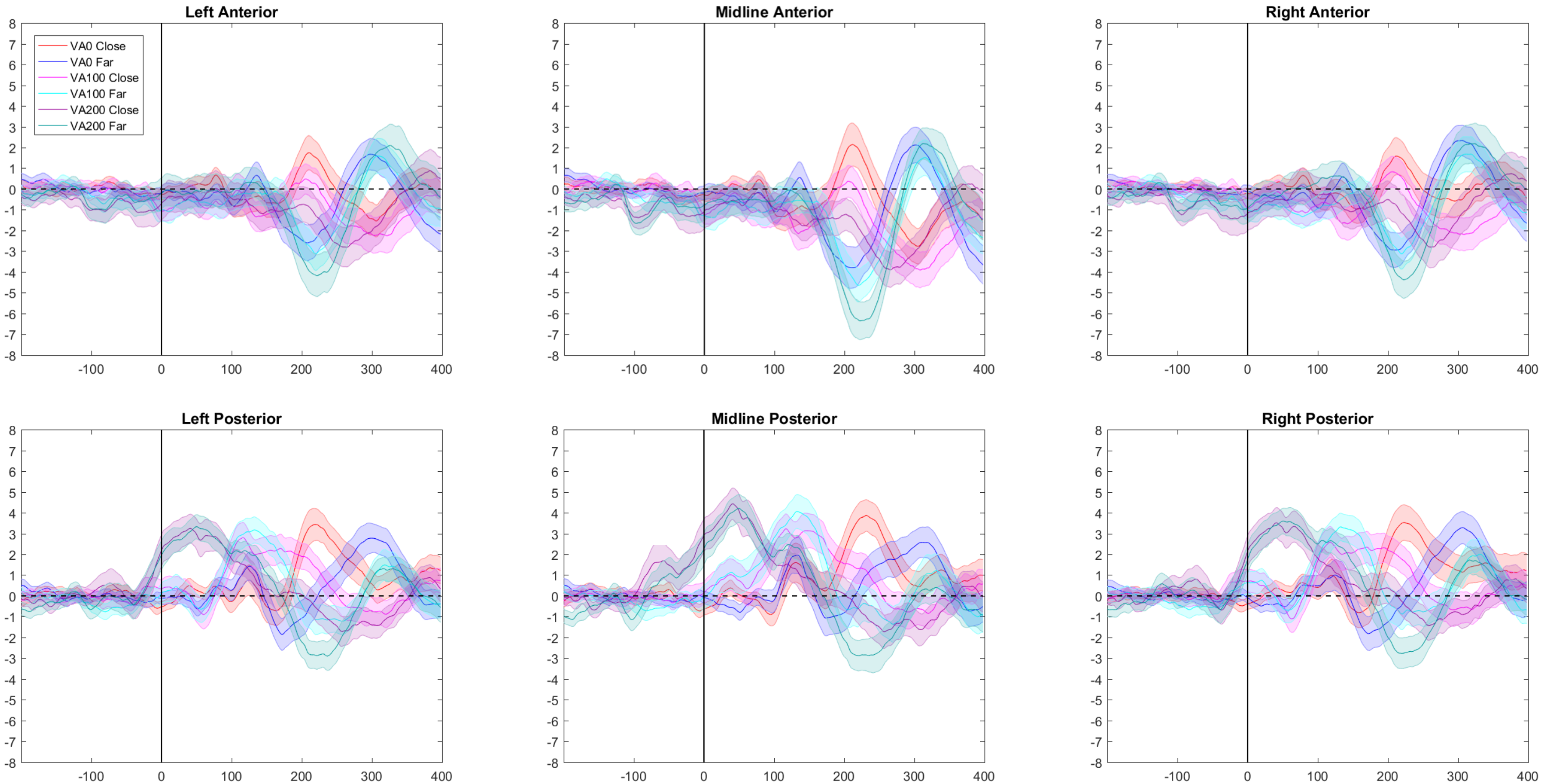


*Figure C4.* Brain raw waves of VA0, VA100, and VA200 condition by distance at the six electrode groups (±1 *SE*).

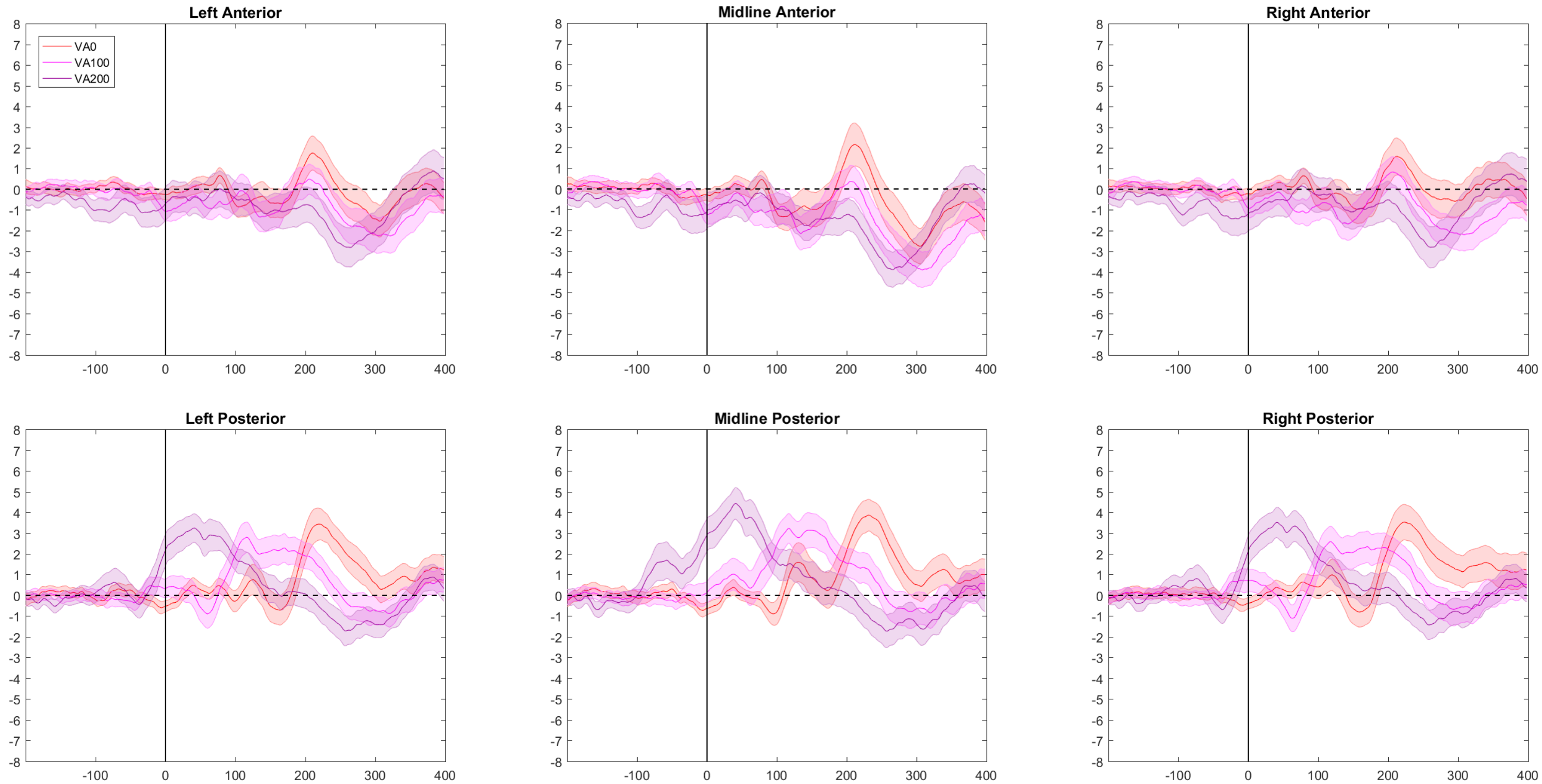


*Figure C5.* Brain raw waves of VA0, VA100, and VA200 condition with only close distance deviants at the six electrode groups (±1 *SE*).

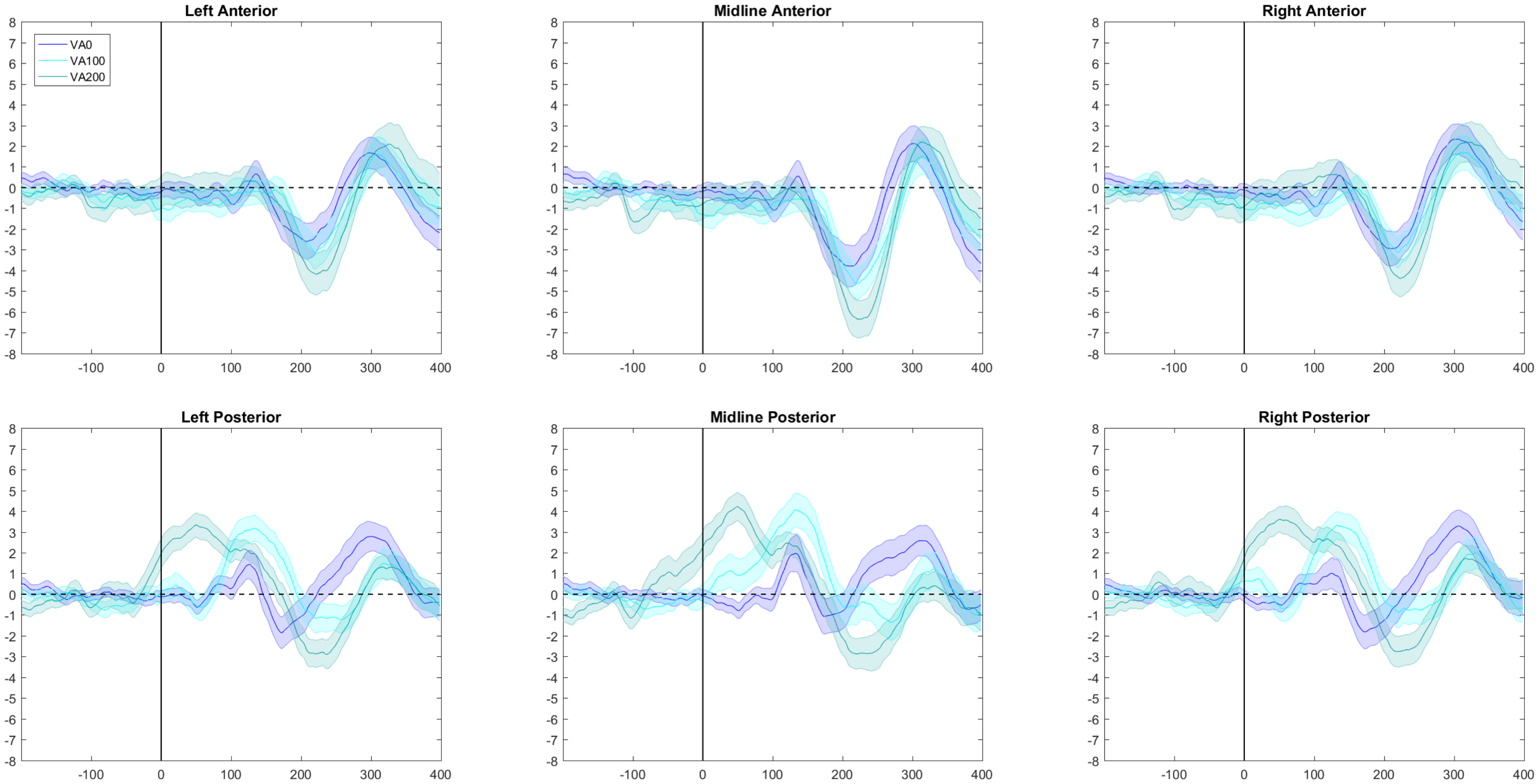


*Figure C6.* Brain raw waves of VA0, VA100, and VA200 condition with only far distance deviants at the six electrode groups (±1 *SE*).

Table C1

*The One-sample t-tests for Detecting an MMN in the VA100 and the VA200 Condition at each Electrode Group (N = 21)*

| Condition | Caudality | Hemisphere | *t*-score | *p*-value |
| --- | --- | --- | --- | --- |
| VA100 | Anterior | Left | 3.83 | .001 |
| | | Right | 3.56 | .002 |
| | | Midline | 3.76 | .001 |
| | Posterior | Left | 4.78 | < .001 |
| | | Right | 4.68 | < .001 |
| | | Midline | 4.79 | < .001 |
| VA200 | Anterior | Left | 4.13 | .001 |
| | | Right | 3.67 | .002 |
| | | Midline | 5.33 | < .001 |
| | Posterior | Left | 4.50 | < .001 |
| | | Right | 3.79 | .001 |
| | | Midline | 4.02 | .001 |

Table C2

*The One-sample t-tests for Detecting an MMN in the Auditory-only and the Audiovisual Condition at each Electrode Group (N = 21)*

| Condition | Caudality | Hemisphere | *t*-score | *p*-value |
|---|---|---|---|---|
| Auditory-only | Anterior | Left | 3.77 | .001 |
| | | Right | 3.51 | .002 |
| | | Midline | 3.81 | .001 |
| | Posterior | Left | 3.62 | .002 |
| | | Right | 3.35 | .003 |
| | | Midline | 3.16 | .005 |
| Audiovisual | Anterior | Left | 2.07 | .052 |
| | | Right | 3.88 | .001 |
| | | Midline | 3.18 | .005 |
| | Posterior | Left | 2.09 | .05 |
| | | Right | 3.37 | .003 |
| | | Midline | 2.60 | .02 |

AMN results

A 4-way (SOA: VA0, VA100, and VA200; distance: close & far distance; caudality: anterior & posterior; hemisphere: left, right, and midline) ANOVA was conducted for the AMN voltage difference (audiovisual minus auditory) as in the analysis for the MMN amplitude. For the means and *SD*s, see Table C5 on page 300 and see Table C6 on page 301 for the complete ANOVA table.

A significant main effect was found on SOA ($F(1.4, 28.0) = 6.85$, $p = .008$, $\eta^2 = .26$). Pairwise comparisons showed that the amplitude difference of VA0 ($M = 0.10$ μv, $SD = 2.82$ μv) was more positive than in the VA100 ($M = -1.85$ μv, $SD = 2.12$ μv, $p = .047$) and the VA200 condition ($M = -2.07$ μv, $SD = 2.81$ μv, $p = .03$). A significant main effect was also found on distance ($F(1, 20) = 6.01$, $p = .02$, $\eta^2 = .23$), indicating that the AMN amplitude difference of close distance ($M = -1.95$ μv, $SD = 2.10$ μv) was more negative than far distance ($M = -0.59$ μv, $SD = 2.56$ μv). A 3-way interaction between SOA, distance and caudality was significant ($F(1.6, 31.4) = 5.40$, $p = .02$, $\eta^2 = .21$). Further follow-up analyses showed a simple interaction effect between distance and caudality found in the VA100 ($F(1, 20) = 10.08$, $p = .005$, $\eta^2 = .34$) and in the VA200 condition ($F(1, 20) = 19.40$, $p < .001$, $\eta^2 = .49$), but not in the VA0 condition ($F(1, 20) = 1.40$, $p = 25$, $\eta^2 = .07$). Further pair-wise comparisons showed that the AMN amplitude difference of close distances was generally more negative than far distances in both the anterior ($p = .01$) and the posterior electrode group ($p = .07$) in the VA0 condition, whereas the AMN amplitude difference of close distances was more negative than far distances only in the anterior electrode group, but not in the posterior electrode group, for both the VA100 (anterior: $p = .08$; posterior: $p = .79$) and the VA200 condition (anterior: $p = .002$; posterior: $p = .27$) (Figure C1).

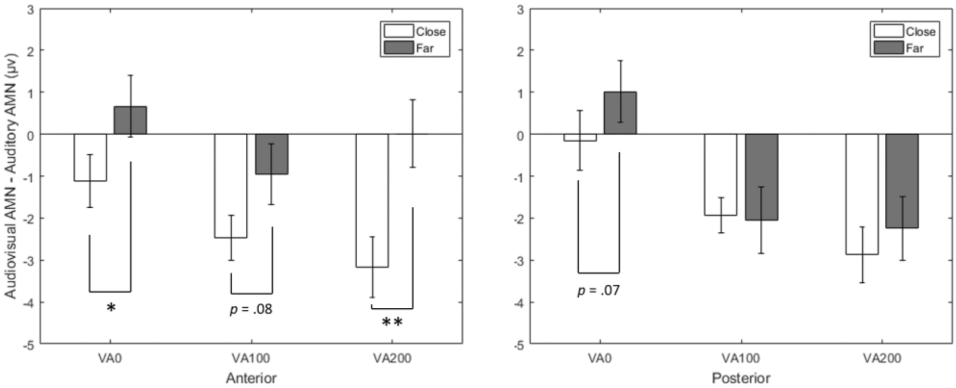


*Figure C1.* Amplitude difference of AMN by distance in each SOA condition. * shows its significance at 0.05 level. ** shows its significance at 0.01 level.

To examine whether the visuo-audio AMN was larger than the auditory-only AMN, I did similar one-sample tests for the AMN as I did for the MMNs. Because a three-way interaction was found between distance, SOA, and caudality, I further separated the condition difference by caudality. Thus, the AMN of condition was separated by distance, SOA, and caudality (see Figure C1). The results showed that: for close distance, the audiovisual AMN was similar to the auditory AMN at VA0 for both caudalities (both *p*s > .09); whereas the audiovisual AMN was more negative than the auditory-only AMN at VA100 and VA200 in both caudalities (all *p*s < .001). For the far distance, the audiovisual AMN was the same as the auditory-only AMN in the anterior electrodes in all SOA condition (all *p*s > .20), whereas in the posterior electrodes, the audiovisual AMN was significantly more negative than the auditory-only AMN at VA100 ($t(20) = -2.58$, $p = .02$) and VA200 ($t(20) = -2.98$, $p = .007$), but not at VA0 condition ($t(20) = 1.37$, $p = .19$).

The visual inspection for the raw waves

The raw waves of VA0, VA100, and VA200 by distance are demonstrated in Figure C1. Similar to Chapter 4, only midline electrodes are illustrated here because the ERP components were more salient in the midline electrodes, and the data patterns of brain responses are not markedly different between three levels of hemisphere groups (left, right, and midline). However, there were essential difference between brain responses of the anterior and the posterior electrode groups, thus both caudalities are illustrated in the figure. From visual inspection of Figure C2, the patterns of brain responses are mostly similar across SOAs in the midline anterior electrodes in both close and far distance. One difference in close distance is that the positive peak at 200 ms after auditory stimulus onset in the VA0 condition is the most positive, then is the VA100 condition, and the peak is hardly detectable in the VA200 condition. The other difference in far distance is that the negative peak is larger in the VA200 condition compared to the other two conditions.

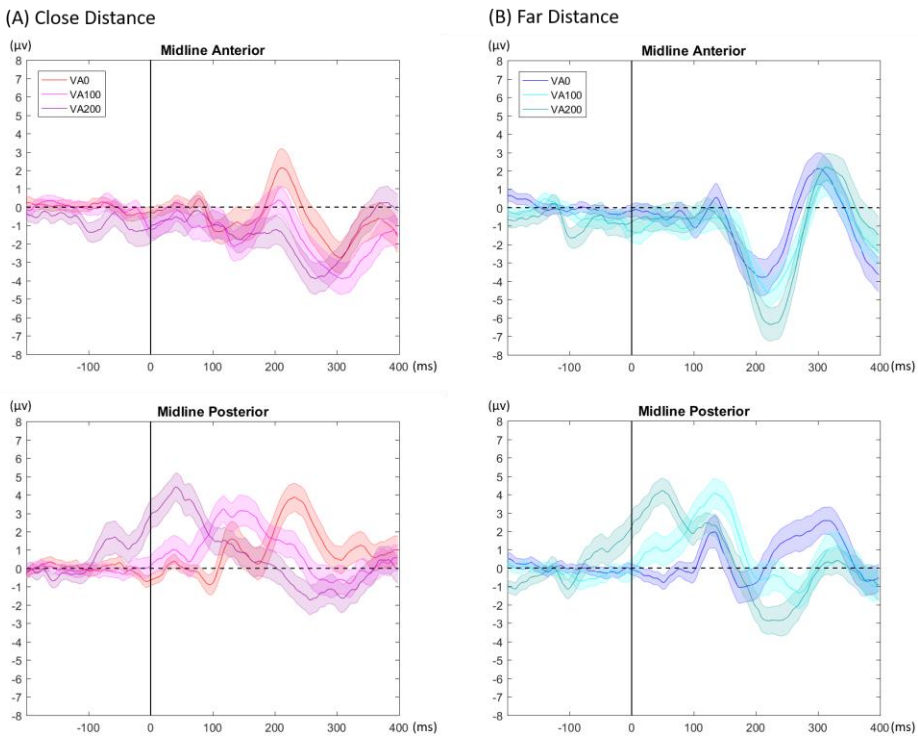


*Figure C1*. Raw waves of VA0, VA100, and VA200 deviants at the midline electrode groups by (A) close and (B) far distance (±1 *SE*).

The brain responses in the posterior electrode groups look very different across SOAs (see Figure C2). However, as the peaks are shifted approximate 100 ms between VA0 and VA100 as well as between VA100 and VA200, these differences are likely to be due to the preceding visual digit before the auditory stimulus onset. The data patterns look similar across SOAs in both close and far distance except the shifting. The only difference among SOAs is that the peaks in the VA0 condition are more distinct compared to other two SOA conditions. For example, two clear positive peaks can be found only in VA0 but not in other two SOA conditions with far distance deviants, one is in early 100 ms and the other one is around 300 ms after auditory stimulus onset. Figure C2 emphasises the differences between the close and far distance of deviants in different SOA conditions. It is obvious that latencies of the peaks induced by close distance and the far distance deviants are different in all SOAs. That is, the close distance has earlier peaks than the far distance.

The latency difference between close and far distance cannot be clearly observed in the posterior electrode group. As mentioned earlier, the brain responses in the posterior electrodes are likely influenced by the preceding visual digits in the VA100 and the VA200 condition. There are no big differences between close and far distance deviants until late 100 ms after auditory onset. However, from late 100 ms until around 300 ms, the amplitude of close distance is more positive than the far distance. After that the close distance becomes more negative than the far distance till nearly the end of the epoch (400 ms).

In general, from visual inspection it is clear that there are large differences in brain responses to close- versus far-distance deviants. The differences among SOAs are more obvious in the anterior electrodes in comparison with the posterior electrode. Non-parametric tests were conducted to further explore the difference between close and far distance deviants across SOAs.

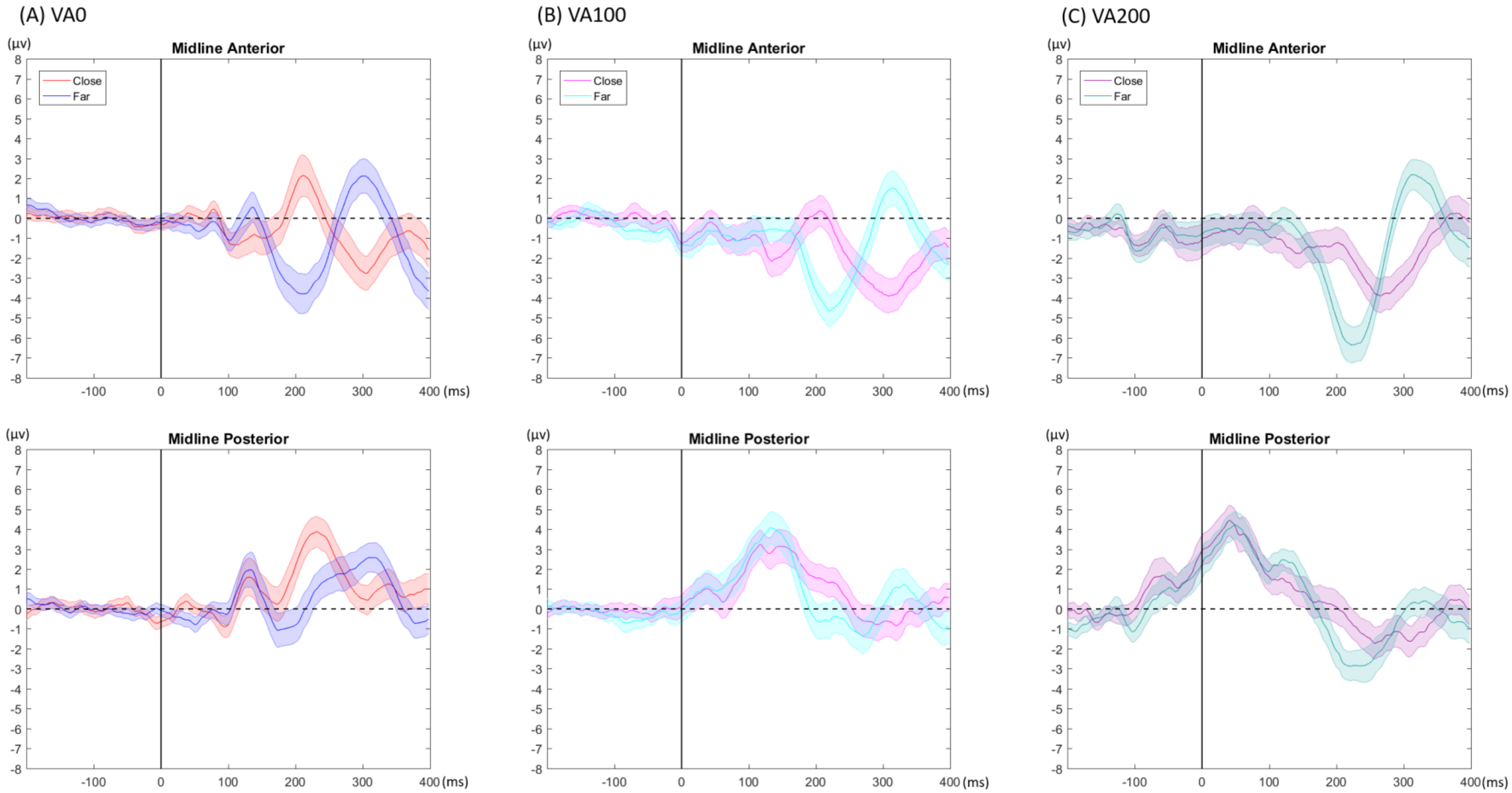


*Figure C2.* Raw waves of close and far deviants at the midline electrode groups by (A) VA0, (B) VA100, and (C) VA200 condition (±1 *SE*).

Table C1

*Descriptive Statistics of the MMN Amplitude Difference of SOA Conditions by Electrode Group and Distance*

| Distance | Electrode group | | VA0 | VA100 | VA200 |
|---|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* | *M (SD)* |
| Close | Anterior | Left | -0.95 (2.13) | 0.66 (2.92) | -0.05 (2.69) |
| | | Right | -0.60 (2.17) | 0.42 (3.03) | 0.00 (3.02) |
| | | Midline | -0.83 (2.62) | 0.90 (3.69) | 0.13 (3.59) |
| | Posterior | Left | -0.94 (1.83) | 0.49 (1.94) | 0.24 (2.49) |
| | | Right | -0.64 (1.85) | 0.50 (2.33) | 0.21 (2.29) |
| | | Midline | -0.63 (1.88) | 0.24 (2.34) | 0.47 (2.47) |
| Far | Anterior | Left | 0.42 (2.58) | 0.71 (2.15) | 0.56 (2.14) |
| | | Right | 0.60 (2.39) | 0.77 (2.21) | 0.55 (2.47) |
| | | Midline | 0.57 (3.07) | 0.61 (2.83) | 0.76 (2.87) |
| | Posterior | Left | 0.68 (2.58) | 0.83 (1.30) | 1.17 (1.73) |
| | | Right | 1.09 (2.38) | 0.93 (1.39) | 1.19 (2.43) |
| | | Midline | 1.15 (2.91) | 0.76 (1.96) | 1.77 (2.76) |

*Note.* The amplitude difference refers to the difference between each audiovisual condition and the auditory condition. VA0 = VA0 minus A; VA100 = VA100 minus A; VA200 = VA200 minus A.

Table C2

*Summary of the 4-way ANOVA for MMN Amplitude Difference of SOA Conditions*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 140.15 | 1 | 140.15 | 3.88 | .063 | .16 |
| Error (Distance) | 722.37 | 20 | 36.12 | | | |
| SOA | 65.93 | 1.4 | 47.17 | 1.70 | .21 | .08 |
| Error (SOA) | 776.70 | 28.0 | 27.79 | | | |
| Caudality | 10.64 | 1 | 10.64 | 0.64 | .43 | .03 |
| Error (Caudality) | 330.15 | 20 | 16.51 | | | |
| Hemisphere | 3.72 | 1.9 | 1.98 | 0.55 | .57 | .03 |
| Error (Hemisphere) | 135.73 | 37.6 | 3.61 | | | |
| Distance * SOA | 51.99 | 1.8 | 29.63 | 3.01 | .068 | .13 |
| Error (Distance * SOA) | 345.04 | 35.1 | 9.83 | | | |
| Distance * Caudality | 8.16 | 1 | 8.16 | 0.61 | .45 | .03 |
| Error (Distance * Caudality) | 268.93 | 20 | 13.45 | | | |
| Distance * Hemisphere | 0.17 | 1.8 | 0.10 | 0.07 | .92 | < .01 |
| Error (Distance * Hemisphere) | 49.74 | 35.9 | 1.38 | | | |
| SOA * Caudality | 10.29 | 2.0 | 5.27 | 1.18 | .32 | .06 |
| Error (SOA * Caudality) | 174.61 | 39.1 | 4.47 | | | |
| SOA * Hemisphere | 5.94 | 3.0 | 1.96 | 2.01 | .12 | .09 |
| Error (SOA * Hemisphere) | 59.05 | 60.6 | 0.97 | | | |
| Caudality * Hemisphere | 0.26 | 1.8 | 0.14 | .08 | .91 | < .01 |
| Error (Caudality * Hemisphere) | 67.03 | 36.5 | 1.84 | | | |
| Distance * SOA * Caudality | 0.07 | 1.9 | 0.04 | 0.02 | .98 | < .01 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Error (Distance * SOA * Caudality) | 70.83 | 39.0 | 1.82 | | | |
| Distance * SOA * Hemisphere | 1.39 | 2.7 | 0.50 | 0.93 | .43 | .05 |
| Error (Distance * SOA * Hemisphere) | 29.82 | 55.2 | 0.54 | | | |
| Distance * Caudality * Hemisphere | 1.02 | 1.3 | 0.81 | 0.51 | .53 | .03 |
| Error (Distance * Caudality * Hemisphere) | 40.30 | 25.2 | 1.60 | | | |
| SOA * Caudality * Hemisphere | 2.83 | 3.2 | 0.89 | 2.11 | .10 | .10 |
| Error (SOA * Caudality * Hemisphere) | 26.81 | 63.5 | 0.42 | | | |
| Distance * SOA * Caudality * Hemisphere | 1.07 | 3.0 | 0.35 | 1.35 | .27 | .06 |
| Error (Distance * SOA * Caudality * Hemisphere) | 15.81 | 60.4 | 0.26 | | | |

*Note.* The amplitude difference refers to the difference of mean peak amplitudes between each audiovisual condition (VA0, VA100, and VA200) and the auditory condition.

Table C3

*Descriptive Statistics of the MMN Latencies under Auditory, VA0, VA100, and VA200 Condition by Electrode Group and Distance (N = 21)*

| Distance | Electrode group | | Auditory | VA0 | VA100 | VA200 |
|---|---|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* | *M (SD)* | *M (SD)* |
| Close | Anterior | Left | 142 (33) | 133 (31) | 130 (37) | 137 (25) |
| | | Right | 140 (35) | 142 (28) | 139 (38) | 150 (37) |
| | | Midline | 136 (33) | 136 (33) | 135 (48) | 146 (33) |
| | Posterior | Left | 120 (35) | 143 (36) | 126 (46) | 128 (38) |
| | | Right | 126 (31) | 142 (42) | 130 (49) | 138 (42) |
| | | Midline | 116 (44) | 142 (55) | 118 (50) | 134 (47) |
| Far | Anterior | Left | 176 (37) | 179 (34) | 173 (42) | 185 (26) |
| | | Right | 187 (23) | 198 (22) | 186 (45) | 200 (24) |
| | | Midline | 184 (41) | 188 (31) | 192 (43) | 199 (20) |
| | Posterior | Left | 173 (39) | 191 (34) | 179 (46) | 189 (38) |
| | | Right | 183 (36) | 202 (32) | 186 (37) | 205 (24) |
| | | Midline | 169 (48) | 192 (37) | 176 (54) | 195 (48) |

*Note.* The auditory MMN latency was not included in the ANOVA of the MMN latencies.

Table C4

*Summary of the 4-way ANOVA for MMN Latencies in Chapter 5*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 546454 | 1 | 546454 | 114.16 | < .001 | .85 |
| Error (Distance) | 95733 | 20 | 4787 | | | |
| SOA | 18502 | 1.6 | 11650 | 1.16 | .32 | .06 |
| Error (SOA) | 318232 | 31.8 | 10019 | | | |
| Caudality | 599.71 | 1 | 599.71 | 0.37 | .55 | .02 |
| Error (Caudality) | 32059 | 20 | 1603 | | | |
| Hemisphere | 13643 | 1.9 | 7300 | 8.05 | .002 | .29 |
| Error (Hemisphere) | 33886 | 37.4 | 907 | | | |
| Distance * SOA | 903.42 | 1.9 | 469.72 | 0.14 | .86 | .01 |
| Error (Distance * SOA) | 130511 | 38.5 | 3393 | | | |
| Distance * Caudality | 2084 | 1 | 2084 | 1.25 | .28 | .06 |
| Error (Distance * Caudality) | 33462 | 20 | 1673 | | | |
| Distance * Hemisphere | 1331 | 2.0 | 675.38 | 1.18 | .32 | .06 |
| Error (Distance * Hemisphere) | 22507 | 39.4 | 570.86 | | | |
| SOA * Caudality | 5698 | 1.9 | 2931 | 1.80 | .18 | .08 |
| Error (SOA * Caudality) | 63413 | 38.9 | 1631 | | | |
| SOA * Hemisphere | 1108 | 2.8 | 390.91 | 0.33 | .79 | .02 |
| Error (SOA * Hemisphere) | 67519 | 56.7 | 1191 | | | |
| Caudality * Hemisphere | 2687 | 1.8 | 1496.9 | 3.30 | .053 | .14 |
| Error (Caudality * Hemisphere) | 16273 | 35.9 | 453.30 | | | |
| Distance * SOA * Caudality | 1151 | 2.0 | 587.41 | 0.61 | .55 | .03 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Error (Distance * SOA * Caudality) | 37966 | 39.2 | 968.54 | | | |
| Distance * SOA * Hemisphere | 1018 | 3.2 | 314.51 | 0.64 | .61 | .03 |
| Error (Distance * SOA * Hemisphere) | 31903 | 64.7 | 493.02 | | | |
| Distance * Caudality * Hemisphere | 559.79 | 2.0 | 286.43 | 1.03 | .36 | .05 |
| Error (Distance * Caudality * Hemisphere) | 10850 | 39.1 | 277.58 | | | |
| SOA * Caudality * Hemisphere | 1684 | 3.4 | 488.35 | 1.41 | .24 | .07 |
| Error (SOA * Caudality * Hemisphere) | 23885 | 69.0 | 346.36 | | | |
| Distance * SOA * Caudality * Hemisphere | 70.31 | 3.5 | 20.11 | 0.06 | .99 | < .01 |
| Error (Distance * SOA * Caudality * Hemisphere) | 23322 | 69.9 | 333.57 | | | |

Table C5

*Descriptive Statistics of the AMN Amplitude Difference of SOA Conditions by Electrode Group and Distance*

| Distance | Electrode group | | VA0 | VA100 | VA200 |
|---|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* | *M (SD)* |
| Close | Anterior | Left | -1.12 (2.96) | -2.06 (2.27) | -2.60 (3.18) |
| | | Right | -0.88 (2.98) | -2.22 (2.46) | -2.95 (3.29) |
| | | Midline | -1.34 (3.03) | -3.13 (2.85) | -3.97 (3.67) |
| | Posterior | Left | -0.32 (3.12) | -1.91 (2.18) | -2.65 (3.17) |
| | | Right | -0.15 (3.68) | -2.08 (2.14) | -2.91 (3.20) |
| | | Midline | -0.01 (3.29) | -1.81 (2.02) | -3.07 (3.13) |
| Far | Anterior | Left | 0.64 (3.42) | -0.44 (3.09) | 0.50 (3.41) |
| | | Right | 0.62 (3.22) | -0.99 (3.35) | -0.06 (4.09) |
| | | Midline | 0.72 (3.69) | -1.43 (4.05) | -0.40 (4.30) |
| | Posterior | Left | 0.84 (3.39) | -1.92 (3.61) | -1.68 (3.20) |
| | | Right | 1.09 (3.43) | -2.11 (3.72) | -2.11 (3.80) |
| | | Midline | 1.12 (3.57) | -2.12 (3.93) | -2.94 (3.71) |

*Note.* The amplitude difference refers to the difference between each audiovisual condition and the auditory condition. VA0 = VA0 minus A; VA100 = VA100 minus A; VA200 = VA200 minus A.

Table C6

*Summary of the 4-way ANOVA for AMN Amplitude Difference of SOA Conditions*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 349.97 | 1 | 349.97 | 6.01 | .02 | .23 |
| Error (Distance) | 1165 | 20 | 58.25 | | | |
| SOA | 719.96 | 1.4 | 513.71 | 6.85 | .008 | .26 |
| Error (SOA) | 2103 | 28.0 | 75.04 | | | |
| Caudality | 7.72 | 1 | 7.72 | 0.69 | .42 | .03 |
| Error (Caudality) | 223.52 | 20 | 11.18 | | | |
| Hemisphere | 28.64 | 1.6 | 17.45 | 3.13 | .07 | .14 |
| Error (Hemisphere) | 183.00 | 32.8 | 5.58 | | | |
| Distance * SOA | 47.14 | 2.0 | 23.78 | 1.70 | .20 | .08 |
| Error (Distance * SOA) | 555.30 | 39.6 | 14.01 | | | |
| Distance * Caudality | 120.40 | 1 | 120.40 | 14.99 | .001 | .43 |
| Error (Distance * Caudality) | 160.66 | 20 | 8.03 | | | |
| Distance * Hemisphere | 0.86 | 1.6 | 0.54 | 0.21 | .76 | .01 |
| Error (Distance * Hemisphere) | 83.03 | 31.6 | 2.63 | | | |
| SOA * Caudality | 85.21 | 1.8 | 48.39 | 8.70 | .001 | .30 |
| Error (SOA * Caudality) | 195.87 | 35.2 | 5.56 | | | |
| SOA * Hemisphere | 26.03 | 2.7 | 9.72 | 4.71 | .007 | .19 |
| Error (SOA * Hemisphere) | 110.53 | 53.6 | 2.06 | | | |
| Caudality * Hemisphere | 10.39 | 1.9 | 5.62 | 2.88 | .07 | .13 |
| Error (Caudality * Hemisphere) | 72.13 | 37.0 | 1.95 | | | |
| Distance * SOA * Caudality | 29.89 | 1.6 | 19.01 | 5.40 | .02 | .21 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Error (Distance * SOA * Caudality) | 110.73 | 31.4 | 3.52 | | | |
| Distance * SOA * Hemisphere | 0.62 | 2.8 | 0.22 | 0.23 | .86 | .01 |
| Error (Distance * SOA * Hemisphere) | 54.64 | 55.6 | 0.98 | | | |
| Distance * Caudality * Hemisphere | 7.21 | 1.9 | 3.87 | 4.47 | .02 | .18 |
| Error (Distance * Caudality * Hemisphere) | 32.28 | 37.3 | 0.87 | | | |
| SOA * Caudality * Hemisphere | 3.60 | 3.1 | 1.16 | 1.51 | .22 | .07 |
| Error (SOA * Caudality * Hemisphere) | 47.72 | 62.3 | 0.77 | | | |
| Distance * SOA * Caudality * Hemisphere | 1.70 | 2.8 | 0.60 | 1.64 | .19 | .08 |
| Error (Distance * SOA * Caudality * Hemisphere) | 20.73 | 56.3 | 0.37 | | | |

*Note.* The amplitude difference refers to the difference of mean peak amplitudes between each audiovisual condition (VA0, VA100, and VA200) and the auditory condition.

Table C7

*Mean Amplitude Differences by Distance (μv) in each SOA Condition at each Electrode Group during 50 – 164 ms after Stimulus Onset*

| SOA | Electrode Group | | Standard | Close | Far |
|---|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* | *M (SD)* |
| VA0 | Anterior | Left | -0.21 (1.69) | 0.60 (1.53) | -0.30 (1.74) |
| | | Right | -0.12 (1.32) | 0.37 (1.62) | -0.28 (1.61) |
| | | Midline | -0.16 (1.99) | 0.56 (1.70) | -0.36 (2.04) |
| | Posterior | Left | 0.23 (1.34) | 1.28 (1.56) | 0.21 (1.08) |
| | | Right | 0.32 (1.42) | 1.70 (1.79) | 0.63 (1.42) |
| | | Midline | 1.02 (1.67) | 1.93 (2.01) | 0.81 (1.72) |
| VA100 | Anterior | Left | 0.06 (2.32) | -0.56 (2.60) | -0.67 (1.93) |
| | | Right | -0.10 (2.41) | -0.77 (2.53) | -0.83 (1.97) |
| | | Midline | -0.11 (2.80) | -0.92 (3.20) | -0.78 (2.34) |
| | Posterior | Left | 2.47 (2.08) | 2.05 (2.13) | 1.65 (1.68) |
| | | Right | 2.51 (2.43) | 2.50 (2.40) | 2.13 (2.03) |
| | | Midline | 3.59 (3.01) | 3.28 (2.54) | 2.93 (2.41) |
| VA200 | Anterior | Left | -0.20 (2.20) | -0.02 (2.57) | -0.39 (1.94) |
| | | Right | 0.43 (2.04) | 0.31 (2.69) | 0.24 (1.77) |
| | | Midline | -0.40 (2.50) | -0.29 (2.97) | -0.71 (2.20) |
| | Posterior | Left | 2.36 (1.69) | 2.61 (2.08) | 1.79 (1.70) |
| | | Right | 2.81 (2.31) | 3.26 (2.72) | 2.65 (2.27) |
| | | Midline | 2.92 (2.93) | 3.19 (2.78) | 2.23 (2.68) |

*Note.* The amplitude differences here were calculated as the amplitude of each audiovisual (VA0, VA100, & VA200) minus the auditory deviant.

Table C8

*Summary of the 4-way ANOVA for the Mean Amplitude Differences during 58 – 164 ms*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 61.16 | 1.4 | 42.95 | 1.91 | .18 | .09 |
| Error (Distance) | 642.15 | 28.5 | 22.55 | | | |
| SOA | 130.27 | 2.0 | 65.93 | 2.67 | .08 | .12 |
| Error (SOA) | 974.63 | 39.5 | 24.66 | | | |
| Caudality | 1432 | 1 | 1432 | 41.85 | < .001 | .68 |
| Error (Caudality) | 684.38 | 20 | 34.22 | | | |
| Hemisphere | 22.21 | 1.9 | 11.44 | 3.61 | .04 | .15 |
| Error (Hemisphere) | 122.91 | 38.8 | 3.16 | | | |
| Distance * SOA | 58.91 | 3.0 | 19.78 | 2.85 | .045 | .13 |
| Error (Distance * SOA) | 413.24 | 59.6 | 6.94 | | | |
| Distance * Caudality | 9.08 | 2.0 | 4.57 | 0.77 | .47 | .04 |
| Error (Distance * Caudality) | 236.14 | 39.8 | 5.94 | | | |
| Distance * Hemisphere | 1.99 | 2.9 | 0.68 | 0.80 | .50 | .04 |
| Error (Distance * Hemisphere) | 49.57 | 58.9 | 0.84 | | | |
| SOA * Caudality | 264.68 | 1.5 | 180.47 | 9.28 | .002 | .32 |
| Error (SOA * Caudality) | 570.65 | 29.3 | 19.46 | | | |
| SOA * Hemisphere | 27.37 | 3.2 | 8.48 | 7.11 | < .001 | .26 |
| Error (SOA * Hemisphere) | 77.01 | 64.5 | 1.19 | | | |
| Caudality * Hemisphere | 45.76 | 1.7 | 27.09 | 12.67 | < .001 | .39 |
| Error (Caudality * Hemisphere) | 72.23 | 33.8 | 2.14 | | | |
| Distance * SOA * Caudality | 1.58 | 3.5 | 0.46 | 0.33 | .83 | .02 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Error (Distance * SOA * Caudality) | 95.28 | 69.0 | 1.38 | | | |
| Distance * SOA * Hemisphere | 1.39 | 3.9 | 0.36 | 0.76 | .55 | .04 |
| Error (Distance * SOA * Hemisphere) | 36.31 | 77.6 | 0.47 | | | |
| Distance * Caudality * Hemisphere | 3.01 | 2.6 | 1.14 | 1.71 | .18 | .08 |
| Error (Distance * Caudality * Hemisphere) | 35.22 | 52.8 | 0.67 | | | |
| SOA * Caudality * Hemisphere | 5.77 | 2.8 | 2.03 | 2.55 | .07 | .11 |
| Error (SOA * Caudality * Hemisphere) | 45.33 | 57.0 | 0.80 | | | |
| Distance * SOA * Caudality * Hemisphere | 0.43 | 5.4 | 0.08 | 0.56 | .75 | .03 |
| Error (Distance * SOA * Caudality * Hemisphere) | 15.54 | 107.8 | 0.14 | | | |

*Note.* The amplitude difference refers to the difference of mean peak amplitudes between each audiovisual condition (VA0, VA100, and VA200) and the auditory condition.

Table C9

*Mean Amplitude Differences by Distance (µv) in each SOA Condition at each Electrode Group during 164 – 264 ms after Stimulus Onset*

| SOA | Electrode Group | | Standard | Close | Far |
|---|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* | *M (SD)* |
| VA0 | Anterior | Left | -0.85 (2.24) | 0.17 (2.85) | -1.14 (3.47) |
| | | Right | -0.71 (2.38) | -0.04 (2.84) | -1.27 (3.70) |
| | | Midline | -0.80 (2.72) | 0.08 (3.24) | -1.31 (4.22) |
| | Posterior | Left | 2.01 (1.27) | 2.37 (2.10) | 1.46 (2.30) |
| | | Right | 2.36 (2.17) | 3.33 (2.17) | 2.16 (2.80) |
| | | Midline | 3.62 (2.24) | 3.62 (2.07) | 2.64 (2.91) |
| VA100 | Anterior | Left | 0.05 (2.10) | -0.57 (2.94) | -0.56 (1.72) |
| | | Right | 0.38 (2.40) | 0.19 (2.60) | -0.28 (2.17) |
| | | Midline | -0.07 (3.01) | -0.70 (3.50) | -0.62 (2.56) |
| | Posterior | Left | 2.64 (2.21) | 1.93 (2.57) | 2.07 (1.40) |
| | | Right | 2.93 (2.86) | 3.25 (3.07) | 2.95 (2.23) |
| | | Midline | 3.25 (3.42) | 2.85 (3.36) | 2.85 (2.81) |
| VA200 | Anterior | Left | -1.19 (2.35) | -1.75 (3.10) | -1.81 (2.74) |
| | | Right | -0.92 (2.62) | -1.22 (2.72) | -1.52 (2.75) |
| | | Midline | -1.66 (2.62) | -2.33 (3.52) | -2.41 (3.19) |
| | Posterior | Left | 1.12 (1.96) | 0.22 (2.95) | 0.11 (1.82) |
| | | Right | 1.36 (3.04) | 1.49 (3.33) | 0.99 (2.76) |
| | | Midline | 2.24 (3.30) | 1.15 (3.40) | 0.70 (3.27) |

*Note.* The amplitude differences here were calculated as the amplitude of each audiovisual (VA0, VA100, & VA200) minus the auditory deviant.

Table C10

*Summary of the 4-way ANOVA for the Mean Amplitudes during 164 – 264 ms*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 77.71 | 1.6 | 48.68 | 1.04 | .35 | .05 |
| Error (Distance) | 1496 | 31.9 | 46.87 | | | |
| SOA | 522.16 | 1.7 | 315.64 | 6.38 | .007 | .24 |
| Error (SOA) | 1637 | 33.1 | 49.47 | | | |
| Caudality | 2521 | 1 | 2521 | 44.49 | < .001 | .69 |
| Error (Caudality) | 1134 | 20 | 56.68 | | | |
| Hemisphere | 52.55 | 1.8 | 28.42 | 6.84 | .004 | .26 |
| Error (Hemisphere) | 153.78 | 37.0 | 4.16 | | | |
| Distance * SOA | 67.27 | 2.9 | 23.60 | 1.79 | .16 | .08 |
| Error (Distance * SOA) | 753.07 | 57.0 | 13.21 | | | |
| Distance * Caudality | 0.48 | 1.7 | 0.28 | 0.03 | .96 | < .01 |
| Error (Distance * Caudality) | 393.92 | 34.1 | 11.56 | | | |
| Distance * Hemisphere | 13.36 | 2.9 | 4.58 | 3.36 | .03 | .14 |
| Error (Distance * Hemisphere) | 79.60 | 58.4 | 1.36 | | | |
| SOA * Caudality | 16.00 | 1.6 | 10.30 | 0.69 | .48 | .03 |
| Error (SOA * Caudality) | 466.83 | 31.1 | 15.03 | | | |
| SOA * Hemisphere | 21.47 | 3.1 | 6.90 | 4.01 | .01 | .17 |
| Error (SOA * Hemisphere) | 107.17 | 62.2 | 1.72 | | | |
| Caudality * Hemisphere | 72.91 | 1.5 | 47.45 | 10.21 | .001 | .34 |
| Error (Caudality * Hemisphere) | 142.86 | 30.7 | 4.65 | | | |
| Distance * SOA * Caudality | 5.50 | 3.8 | 1.45 | 0.86 | .49 | .04 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Error (Distance * SOA * Caudality) | 127.44 | 76.0 | 1.68 | | | |
| Distance * SOA * Hemisphere | 3.94 | 4.8 | 0.82 | 1.41 | .23 | .07 |
| Error (Distance * SOA * Hemisphere) | 56.06 | 96.1 | 0.58 | | | |
| Distance * Caudality * Hemisphere | 7.94 | 3.1 | 2.54 | 2.42 | .07 | .11 |
| Error (Distance * Caudality * Hemisphere) | 65.69 | 62.7 | 1.05 | | | |
| SOA * Caudality * Hemisphere | 4.30 | 2.7 | 1.58 | 1.48 | .23 | .07 |
| Error (SOA * Caudality * Hemisphere) | 58.04 | 54.4 | 1.07 | | | |
| Distance * SOA * Caudality * Hemisphere | 1.45 | 5.7 | 0.26 | 1.39 | .23 | .07 |
| Error (Distance * SOA * Caudality * Hemisphere) | 20.85 | 113.2 | 0.18 | | | |

*Note.* The amplitude difference refers to the difference of mean peak amplitudes between each audiovisual condition (VA0, VA100, and VA200) and the auditory condition.

Table C11

*Mean Amplitude Differences by Distance (µv) in each SOA Condition at each Electrode Group during 264 – 350 ms after Stimulus Onset*

| SOA | Electrode Group | | Standard | Close | Far |
|---|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* | *M (SD)* |
| VA0 | Anterior | Left | -0.73 (2.52) | 0.33 (2.46) | -1.59 (3.16) |
| | | Right | -0.10 (2.57) | 0.66 (2.58) | -0.77 (3.39) |
| | | Midline | -1.02 (3.10) | 0.22 (3.12) | -1.83 (3.74) |
| | Posterior | Left | 2.12 (2.72) | 2.53 (2.16) | 0.96 (2.88) |
| | | Right | 2.58 (3.12) | 3.61 (2.51) | 2.38 (3.50) |
| | | Midline | 3.22 (3.45) | 3.27 (2.60) | 1.84 (3.59) |
| VA100 | Anterior | Left | -0.39 (2.01) | -1.28 (2.82) | -1.94 (2.06) |
| | | Right | -0.14 (1.91) | -1.24 (2.63) | -1.46 (2.27) |
| | | Midline | -0.75 (2.41) | -1.84 (3.25) | -2.41 (2.96) |
| | Posterior | Left | 1.23 (2.19) | 0.51 (2.77) | -0.86 (1.94) |
| | | Right | 1.46 (2.66) | 1.53 (3.28) | 0.81 (2.35) |
| | | Midline | 1.78 (2.99) | 1.27 (3.44) | -0.20 (2.57) |
| VA200 | Anterior | Left | 0.10 (2.67) | -0.70 (2.77) | -1.68 (2.74) |
| | | Right | 0.24 (2.18) | -0.45 (2.25) | -1.46 (2.66) |
| | | Midline | -0.17 (2.52) | -1.02 (2.92) | -2.34 (3.22) |
| | Posterior | Left | 1.32 (2.21) | 0.18 (2.42) | -0.90 (1.44) |
| | | Right | 1.51 (2.48) | 1.39 (2.75) | 0.44 (2.08) |
| | | Midline | 2.16 (2.85) | 0.77 (3.00) | -0.65 (2.54) |

*Note.* The amplitude differences here were calculated as the amplitude of each audiovisual (VA0, VA100, & VA200) minus the auditory deviant.

Table C12

*Summary of the 4-way ANOVA for the Mean Amplitudes during 264 – 350 ms*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 451.66 | 2.0 | 226.41 | 5.69 | .007 | .22 |
| Error (Distance) | 1587 | 39.9 | 39.77 | | | |
| SOA | 324.52 | 1.7 | 188.39 | 5.38 | .01 | .21 |
| Error (SOA) | 1207 | 34.5 | 35.04 | | | |
| Caudality | 1401 | 1 | 1401 | 31.58 | < .001 | .61 |
| Error (Caudality) | 887.35 | 20 | 44.37 | | | |
| Hemisphere | 86.95 | 1.8 | 49.41 | 11.27 | < .001 | .36 |
| Error (Hemisphere) | 154.28 | 35.2 | 4.38 | | | |
| Distance * SOA | 105.32 | 2.7 | 38.81 | 2.05 | .12 | .09 |
| Error (Distance * SOA) | 1026 | 54.3 | 18.91 | | | |
| Distance * Caudality | 0.86 | 1.5 | 0.56 | 0.04 | .93 | < .01 |
| Error (Distance * Caudality) | 419.02 | 31.0 | 13.53 | | | |
| Distance * Hemisphere | 26.09 | 3.1 | 8.34 | 5.63 | .002 | .22 |
| Error (Distance * Hemisphere) | 92.70 | 62.6 | 1.48 | | | |
| SOA * Caudality | 110.44 | 1.5 | 74.61 | 4.46 | .03 | .18 |
| Error (SOA * Caudality) | 494.88 | 29.6 | 16.72 | | | |
| SOA * Hemisphere | 3.22 | 2.6 | 1.23 | 0.72 | .53 | .04 |
| Error (SOA * Hemisphere) | 89.09 | 52.4 | 1.70 | | | |
| Caudality * Hemisphere | 54.66 | 1.8 | 30.91 | 8.36 | .002 | .30 |
| Error (Caudality * Hemisphere) | 130.77 | 35.4 | 3.70 | | | |
| Distance * SOA * Caudality | 13.52 | 2.9 | 4.70 | 2.63 | .06 | .12 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Error (Distance * SOA * Caudality) | 103.00 | 57.5 | 1.79 | | | |
| Distance * SOA * Hemisphere | 3.36 | 3.9 | 0.86 | 0.96 | .43 | .05 |
| Error (Distance * SOA * Hemisphere) | 69.88 | 78.0 | 0.90 | | | |
| Distance * Caudality * Hemisphere | 14.93 | 3.4 | 4.43 | 4.13 | .007 | .17 |
| Error (Distance * Caudality * Hemisphere) | 72.25 | 67.3 | 1.07 | | | |
| SOA * Caudality * Hemisphere | 2.02 | 2.5 | 0.81 | 0.71 | .53 | .03 |
| Error (SOA * Caudality * Hemisphere) | 56.88 | 50.1 | 1.14 | | | |
| Distance * SOA * Caudality * Hemisphere | 1.97 | 5.1 | 0.39 | 1.36 | .24 | .06 |
| Error (Distance * SOA * Caudality * Hemisphere) | 28.99 | 102.4 | 0.28 | | | |

*Note.* The amplitude difference refers to the difference of mean peak amplitudes between each audiovisual condition (VA0, VA100, and VA200) and the auditory condition.

Table C13

*Mean Amplitude Differences by Distance (µv) in each SOA Condition at each Electrode Group during 350 – 398 ms after Stimulus Onset*

| SOA | Electrode Group | | Standard | Close | Far |
|---|---|---|---|---|---|
| | | | *M (SD)* | *M (SD)* | *M (SD)* |
| VA0 | Anterior | Left | -1.49 (3.05) | -0.21 (2.63) | -2.51 (3.49) |
| | | Right | -0.97 (2.82) | 0.31 (2.88) | -1.60 (3.79) |
| | | Midline | -1.99 (3.43) | -0.27 (3.34) | -2.83 (4.10) |
| | Posterior | Left | 0.32 (2.40) | 1.19 (2.37) | -0.71 (3.24) |
| | | Right | 0.73 (2.63) | 2.18 (2.79) | 0.34 (3.50) |
| | | Midline | 1.29 (2.71) | 1.96 (2.88) | 0.04 (3.47) |
| VA100 | Anterior | Left | -0.68 (2.31) | -1.19 (2.73) | -1.67 (2.15) |
| | | Right | -0.47 (2.48) | -0.97 (2.42) | -1.39 (2.06) |
| | | Midline | -0.89 (2.94) | -1.63 (2.95) | -1.81 (2.67) |
| | Posterior | Left | 0.52 (2.13) | -0.06 (2.33) | -0.96 (2.06) |
| | | Right | 0.63 (2.41) | 0.96 (2.62) | 0.12 (2.02) |
| | | Midline | 0.81 (2.74) | 0.67 (2.94) | -0.52 (2.78) |
| VA200 | Anterior | Left | 0.58 (2.97) | 0.19 (3.27) | -0.79 (3.18) |
| | | Right | 0.76 (2.47) | 0.68 (2.75) | -0.54 (3.06) |
| | | Midline | 0.40 (2.91) | 0.25 (3.52) | -1.15 (3.56) |
| | Posterior | Left | 0.70 (2.56) | 0.26 (2.64) | -0.65 (1.67) |
| | | Right | 0.91 (2.80) | 1.36 (2.95) | 0.25 (2.16) |
| | | Midline | 1.48 (3.41) | 0.86 (3.19) | -0.28 (2.86) |

*Note.* The amplitude differences here were calculated as the amplitude of each audiovisual (VA0, VA100, & VA200) minus the auditory deviant.

Table C14

*Summary of the 4-way ANOVA for the Mean Amplitudes during 350 – 398 ms*

| Source | *SS* | *df* | *MS* | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Distance | 359.86 | 1.8 | 196.26 | 3.45 | .046 | .15 |
| Error (Distance) | 2087 | 36.7 | 56.92 | | | |
| SOA | 115.81 | 1.6 | 72.35 | 1.90 | .17 | .09 |
| Error (SOA) | 1219 | 32.0 | 38.06 | | | |
| Caudality | 511.27 | 1 | 511.27 | 14.53 | .001 | .42 |
| Error (Caudality) | 703.78 | 20 | 35.19 | | | |
| Hemisphere | 65.67 | 2.0 | 33.60 | 9.89 | < .001 | .33 |
| Error (Hemisphere) | 132.78 | 39.1 | 3.40 | | | |
| Distance * SOA | 110.41 | 2.4 | 46.83 | 1.83 | .16 | .08 |
| Error (Distance * SOA) | 1207 | 47.2 | 25.59 | | | |
| Distance * Caudality | 0.06 | 1.7 | 0.03 | < .01 | > .99 | < .01 |
| Error (Distance * Caudality) | 500.35 | 35.0 | 14.30 | | | |
| Distance * Hemisphere | 12.74 | 3.3 | 3.92 | 2.09 | .11 | .10 |
| Error (Distance * Hemisphere) | 121.80 | 65.0 | 1.87 | | | |
| SOA * Caudality | 122.33 | 1.5 | 83.59 | 4.99 | .02 | .20 |
| Error (SOA * Caudality) | 490.64 | 29.3 | 16.76 | | | |
| SOA * Hemisphere | 2.53 | 3.0 | 0.85 | 0.68 | .57 | .03 |
| Error (SOA * Hemisphere) | 74.18 | 59.6 | 1.24 | | | |
| Caudality * Hemisphere | 35.99 | 1.8 | 19.90 | 5.44 | .01 | .21 |
| Error (Caudality * Hemisphere) | 132.28 | 36.2 | 3.66 | | | |
| Distance * SOA * Caudality | 10.34 | 2.8 | 3.66 | 1.95 | .14 | .09 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Error (Distance * SOA * Caudality) | 106.13 | 56.6 | 1.88 | | | |
| Distance * SOA * Hemisphere | 2.31 | 4.17 | 0.55 | 0.53 | .72 | .03 |
| Error (Distance * SOA * Hemisphere) | 87.64 | 83.4 | 1.05 | | | |
| Distance * Caudality * Hemisphere | 7.54 | 3.2 | 2.37 | 1.44 | .24 | .07 |
| Error (Distance * Caudality * Hemisphere) | 104.68 | 63.7 | 1.64 | | | |
| SOA * Caudality * Hemisphere | 4.89 | 2.4 | 2.02 | 1.35 | .27 | .06 |
| Error (SOA * Caudality * Hemisphere) | 72.55 | 48.4 | 1.50 | | | |
| Distance * SOA * Caudality * Hemisphere | 3.64 | 4.8 | 0.76 | 1.88 | .11 | .09 |
| Error (Distance * SOA * Caudality * Hemisphere) | 38.65 | 95.7 | 0.40 | | | |

*Note.* The amplitude difference refers to the difference of mean peak amplitudes between each audiovisual condition (VA0, VA100, and VA200) and the auditory condition.

Table C15

*The Correlations between Standardised WRAT Scores and MMN, and AMN Amplitude Differences across Conditions by Close and Far Distance*

| | | Close | | | | | | Far | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Anterior | | | Posterior | | | Anterior | | | Posterior | | |
| | | L | R | M | L | R | M | L | R | M | L | R | M |
| MMN | VA0 | -.06 | .004 | -.08 | -.18 | -.06 | -.08 | .06 | .07 | .11 | -.08 | -.12 | -.19 |
| | VA100 | .22 | .16 | .16 | .44 | .46* | .54* | .12 | .14 | .12 | .18 | .12 | .04 |
| | VA200 | .17 | .09 | .18 | .33 | .30 | .42 | -.001 | .03 | -.02 | .04 | -.03 | -.01 |
| AMN | VA0 | .12 | .06 | .06 | -.02 | .07 | .002 | .17 | .17 | .10 | .19 | .27 | .20 |
| | VA100 | -.03 | -.04 | .16 | -.04 | .03 | .16 | .31 | .14 | .31 | .39 | .22 | .44 |
| | VA200 | .15 | .18 | .26 | .06 | .24 | .29 | .51* | .32 | .51* | .49* | .29 | .46* |

*Note.* The values in the table are the partial correlations between standardised WRAT scores and the amplitudes of each ERP component whilst controlling for standardised matrix reasoning IQ scores (N = 21). The amplitude differences were calculated as the amplitude of each audiovisual condition minus the amplitude of the auditory-only condition. VA0 = VA0 minus Auditory; VA100 = VA100 minus Auditory; VA200 = VA200 minus Auditory; L = Left; R = Right; *M* = Midline electrode group. * $p < .05$.

Table C16

*The Partial Correlations between Standardised WRAT Scores and Mean Amplitudes Differences across Conditions by Close and Far Distance in each Time-Window*

| | | Close | | | | | | Far | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Anterior | | | Posterior | | | Anterior | | | Posterior | | |
| | | L | R | M | L | R | M | L | R | M | L | R | M |
| 58 – 164 | VA0 | -.08 | .02 | -.06 | -.16 | .12 | .002 | -.07 | .11 | -.01 | -.16 | -.11 | -.21 |
| | VA100 | .26 | .19 | .21 | .56* | .57** | .60** | .14 | -.03 | .08 | .09 | .10 | .07 |
| | VA200 | .27 | .15 | .30 | .42 | .44* | .42 | .24 | .18 | .26 | .09 | .05 | .06 |
| 164 – 264 | VA0 | .13 | .04 | .09 | .10 | .09 | .14 | .10 | .09 | .07 | .05 | -.03 | -.03 |
| | VA100 | .21 | .13 | .16 | .48* | .37 | .48* | .16 | .10 | .07 | .18 | .08 | -.04 |
| | VA200 | .14 | .08 | .21 | .37 | .32 | .43 | -.11 | -.08 | -.15 | .11 | -.01 | .06 |
| 264 – 350 | VA0 | .17 | .14 | .15 | .01 | .04 | .03 | .20 | .19 | .16 | .26 | .27 | .28 |
| | VA100 | .39 | .22 | .32 | .40 | .38 | .42 | .30 | .21 | .26 | .33 | .36 | .28 |
| | VA200 | .18 | .01 | .25 | .29 | .23 | .26 | .08 | -.03 | .02 | .39 | .25 | .31 |
| 350 – 398 | VA0 | .21 | .17 | .22 | .26 | .27 | .33 | .29 | .27 | .29 | .39 | .35 | .47* |
| | VA100 | .07 | -.06 | .001 | .19 | .17 | .23 | -.003 | -.11 | -.09 | .02 | .02 | .002 |
| | VA200 | .11 | -.04 | .14 | .16 | .15 | .18 | .05 | .01 | -.06 | .18 | .08 | .14 |

*Note.* The values in the table are the partial correlations between standardised WRAT scores and the amplitudes of each mean peak amplitude difference in a time-window whilst controlling for standardised matrix reasoning IQ scores (N = 21). The amplitude differences were calculated as the amplitude of each audiovisual condition minus the amplitude of the auditory condition, and then compared with the amplitude difference of standard trials (standard minus deviant). L = Left; R = Right; *M* = Midline electrode group. * $p < .05$; ** $p < .01$.