Titia Gebuis

FROM QUANTITY TO NUMBER
studies on magnitude processing

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FROM QUANTITY TO NUMBER
Studies on magnitude processing

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(met een samenvatting in het Nederlands)

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Pythagoras

CONTENTS

CHAPTER 1

INTRODUCTION

THE POWER IN NUMBERS

Pythagoras claimed that numbers rule the universe. Although this remark may be somewhat exaggerated, fact is that man created number symbols long before letters. In prehistoric times, number symbols comparable to what we currently know as the Roman numerals were carved in wood to keep track of the number of animals in the flock. Even though this number system was useful at the time, it is difficult to use in more complex calculations. Because of the relative simplicity of everyday life in those days, there was no need for complex arithmetic yet. It therefore took about one and a half millennium before the Arabic number system that is currently used in western society was developed and that people understood that Pythagoras was, in fact, not that far off.

In the fifth century A.D., the Brahmi system was the number system used in the Indian world. In the Brahmi system numbers 1 to 9 are represented but for the numbers 10, 100, etc. special words were used. At the time, only astrologists were interested in the ability to describe information using large numbers. It is therefore not surprising that an Indian astrologist came up with the idea that not only the number itself but also the position of the number in a series, should define its magnitude. To allow this system to work, the Indian astrologist introduced the number zero. This newly developed system, which is currently referred to as the Arabic number system, made it possible to perform calculations very easily.

Around 775 A.D. a delegation of Indian scholarly introduced this new number system, the decimal system, in the Islamic world. The ability to perform (complex) calculations did not receive a warm welcome in the Islamic world at the time. Nevertheless, a Persian mathematician (Al-Khorezmi) created a handbook explaining the theory of the decimal system. Via the Muslims in Andalusia, the in Latin translated handbook arrived in Europe, which was received with the same disinterest as before in the Islamic world. The old Roman numerals or the wooden beads for counting were considered to be sufficient. It was only in the fourteenth century with the rise of the economy and trading that people became aware of the necessity of a system that not only allowed an accurate representation of quantity but also (in contrast to the Roman system) the ability to perform calculations easily.

Besides the Arabic number system in Europe, distinct cultures all over the world developed their own symbolic number system. Today, only a few Amazonian tribes still live without a symbolic number system. They just differentiate between one, two and few or many (Butterworth, Reeve, Reynolds, & Lloyd, 2008; Gordon, 2004; Pica, Lemer, Izard, & Dehaene, 2004). Today, we cannot even imagine that our complex world could function at all, using a number system similar to that of these Amazonian tribes, a fact that further underlines the necessity of number symbols in a technologically developed society.

THE POWER IN QUANTITIES

The integration of the number symbols in our society sets us apart from other species that only have a rudimentary sense of numbers. In contrast to humans, animals can only discriminate quantities presented in a non-symbolic format. Even though the non-symbolic system is of no use anymore in our present society, its necessity should not be underestimated in the animal kingdom. The chance to survive, the fitness of the animal, strongly depends on it. Imagine, for instance, what can happen when this system is less well developed. It could result in lions attacking another group of lions that outnumber them. Or what to think of a gorilla that wants to become a group leader but is unable to accurately estimate the size of the current one. This ability to compare or estimate distinct numerosities or physical sizes are what animals and humans are suggested to be born with and is referred to as "the number sense" (Dehaene, 1997).

Already at six months of age infants respond to visual changes in numerosities that differ substantially (Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). Since it is impossible to ask infants to press a button or point to the picture showing more dots, researchers came up with an indirect way of testing infants' numerical abilities. Infants are curious in nature but when a picture of a group of dots is presented repeatedly, the infant becomes disinterested. This process is called habituation. It is only when a picture of a new number of dots is presented that the infant regains his or her interest. The decrease of interest when perceiving the same number of dots over and over again and the increase of interest when perceiving a new number of dots can be expressed in the time the infant explores the screen before disengaging his or her gaze, the so-called looking time. One could argue that it is not number per se but instead the visual cues of the stimuli that draw the infant's attention to the screen when a novel numerosity is presented (Clearfield & Mix, 2001). When the number of dots changes, the number of black pixels or the area covered by the dots in the picture changes as well. This possible confound was taken into account in these habituation studies by manipulating the location as well as the sizes of the dots in such a manner that visual cues that covary with numerosity could not explain the results (Xu & Spelke, 2000; Xu et al., 2005).

Besides responding to numerosity changes, infants can also perform rudimentary mathematical operations such as ordering (Brannon, 2002), addition and subtraction (McCrink & Wynn, 2004; Wynn, 1992) as well as extracting ratios (McCrink & Wynn, 2007). An example of a paradigm that allows testing these mathematical abilities is the violation of expectation paradigm (Walden, Kim, McCoy, & Karrass, 2007; Wynn, 1992). Here, a doll or another object is first presented to the infant, and subsequently occluded from the infant's sight. Next, the experimenter adds, clearly visible for the infant, another object to the object already behind the occluder. When the experimenter removes the occluder and two objects appear the baby is not that interested in the expected scenario and hence looks away quite soon after the occluder is removed. However, when the experimenter tricks the infant and adds two objects, one object visible and the other not visible to the infant, the infant looks longer at the implausible scene.

As mentioned above, infants respond only to changes in numerosity when the two numerosities differ substantially. The mechanisms underlying the acuity with which infants still respond to changes in numerosity is dependent on the relative and not absolute difference between the numerosities presented (Xu et al., 2005) and become more accurate with increasing age. While infants of six months old can detect changes differing with a ratio of 2.0 (e.g. 16 versus 32) but not 1.5 (16 versus 24) (Xu & Spelke, 2000), infants of ten months old respond to changes in numerosity differing with either ratio (Brannon, Suanda, & Libertus, 2007; Lipton & Spelke, 2003; Wood & Spelke, 2005). Studies that use numerosity modalities such as puppet jumps (Wood & Spelke, 2005), area (Brannon, Lutz, & Cordes, 2006) or auditory sequences (Lipton & Spelke, 2003) revealed a similar ratio dependence and increase in accuracy with increasing age to those found with arrays of dots, suggesting that the input modality is not important to the numerosity system.

It should be noted, however, that the above outlined effects about numerosity detection only apply to large numerosities, not to numerosities smaller than five (Feigenson & Carey, 2005; Feigenson, Carey, & Hauser, 2002). Infants can detect the change between two and three, but not between four and six. It is therefore proposed that two magnitude systems underlie our ability to estimate numerosity, an accurate system for small and an approximate system for large numerosities (Feigenson, Dehaene, & Spelke, 2004). This is an intriguing dissociation that nicely reflects the adult ability to accurately name numerosities up to four or five (Mandler & Shebo, 1982). Whether indeed two distinct mechanisms underlie numerosity estimation is still highly debated (Revkin, Piazza, Izard, Cohen, & Dehaene, 2008; Vetter, Butterworth, & Bahrami, 2008).

Even though it might appear that the symbolic number system defeated the non-symbolic number system in the sense that its usefulness is more prominent in everyday life, the non-symbolic system should not be underestimated. This non-symbolic number system, present in both humans and other animals, is suggested to be a good predictor of our ability to acquire symbolic number knowledge. A longitudinal study that tested children from kindergarten until the age of fourteen on dot-number estimation as well as symbolic math ability revealed that a child's dot-number estimation acuity can predict the later acquired symbolic number abilities (Halberda, Mazzocco, & Feigenson, 2008). Also, children that only received formal teaching of non-symbolic arithmetic such as addition and subtraction could perform such procedures with symbolic numbers (Gilmore, McCarthy, & Spelke, 2007). The children relied on their knowledge of non-symbolic arithmetic to solve comparison, addition and subtraction problems of large numerosities presented in number symbol notation. These results suggest that our evolutionary endowment of the non-symbolic numerosity system might be a necessary prerequisite to learn and understand our later acquired symbolic number system. Therefore, in contrast to what Pythagoras claimed about numbers, the establishment of a proper non-symbolic system should have ruled 'the universe'.

THE POWER IN MAGNITUDES

Numerosity can be presented in distinct modalities: visual, auditory or tactile. Even within a perceptual modality we can, due to our cultural development of symbolic codes, represent numbers in different notations: non-symbolic notation (e.g. dots), symbolic notation (e.g. Arabic numbers) or even number words. Processing of these different magnitudes is suggested to rely on the same metric (Walsh, 2003). If this was indeed the case, it would be the most efficient strategy for the brain to translate these initial distinct magnitude codes into a single, general code. This idea, that all magnitudes are transformed into a general code, has become an influential theory in the field of numerical cognition.

The mental number line

The hypothesis of a general magnitude code was derived from several behavioral effects that were initially observed with number symbols. When subjects are requested to respond to the numerically larger number of two numbers presented, they respond faster to numbers numerically far apart (e.g. 3 and 8) compared to numerically close numbers (e.g. 5 and 6). This effect is referred to as the numerical distance effect (Moyer & Landauer, 1967). Not only the distance between the two numbers but also the size of the numbers influences subjects' performance. Subjects discriminate much faster the numbers 1 and 2 compared to the numbers 8 and 9, this effect is referred to as the size effect (Moyer & Landauer, 1967). Moreover, subjects respond faster to mall numbers with the left hand while the opposite pattern holds for large numbers (Dehaene, Bossini, & Giraux, 1993). The spatial bias induced by numerical size is also obtained when hands are crossed suggesting that not the hand itself but its location is associated with the numerical size of the number. These three findings are captured in the metaphorical description called the mental number line. On this mental number line (MNL), numbers are presented from small to large from left to right and logarithmically compressed towards the end. This left to right orientation is dependent on reading direction (Shaki & Fischer, 2008) as well as the type of stimulus imagined while performing the task (clock versus ruler) (Bachtold, Baumuller, & Brugger, 1998). The MNL should by no means be interpreted as the manner in which numbers are encoded in the brain. Instead it is just a metaphor for the observed effects.

The three effects mentioned above have been observed using Arabic numbers and dots but also many other distinct forms of visual as well as auditory or even tactile stimuli (for an overview see: Cohen Kadosh, Lammertyn, & Izard, 2008). Even though these strikingly comparable behavioral results hint at a common underlying magnitude code, evidence from neuroimaging techniques is necessary to reveal that indeed similar neural processes are involved. The most frequently used methods to study the neural correlates of number processes are electro-encephalography (EEG), functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation (TMS). These methods are complementary: EEG is very accurate in time but has a poor spatial resolution, fMRI has a poor temporal resolution but has an excellent spatial resolution and TMS can interfere with ongoing brain processes and hence reveal a causal relationship between the activity of a brain region and the process at hand. Neuroimaging and TMS studies repeatedly show the involvement of the intraparietal sulcus (IPS) in magnitude processing (Cohen Kadosh, Cohen Kadosh, Schuhmann et al., 2007; Cohen Kadosh, Henik et al., 2005; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Pinel, Dehaene, Riviere, & LeBihan, 2001). Magnitudes are processed already around 200 ms after the subject perceived the stimulus (Libertus, Woldorff, & Brannon, 2007; Temple & Posner, 1998). There is only one problem concerning these studies. The brain is not, as suggested in phrenology, a patchwork of distinct areas, each being active for a distinct process. Instead, all processes are intertwined. For instance, the IPS is not only involved in magnitude processing but is also active for a wide range of other cognitive activities such as grasping, attention, saccades, etc. (Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002). Since task related processes are often correlated with the magnitude manipulation of the task at hand (e.g. response selection), the above-described results might well be confounded (Gobel, Johansen-Berg, Behrens, & Rushworth, 2004).

Early or late interaction account

Further evidence for a common magnitude system in the IPS resulted from studies investigating the interactions between distinct magnitudes. If indeed a general magnitude system exists, the magnitudes should not only reveal comparable behavioral and neuronal patterns but also interact with each other. The Stroop task is the most frequently used paradigm in experimental psychology to study interactions between different cognitive processes (e.g. colors and words) (Stroop, 1935). Initially, the Stroop task was used to test frontal functions such as attention, but it left its marks in a diverse range of applications in science and the clinical setting. In the original Stroop task color names printed in an ink color that is not in agreement with the color name (incongruent condition) or colored patches are presented (neutral condition). Subjects are slower in naming the ink color aloud in the incongruent compared to the neutral condition. Since it is difficult to inhibit reading the word in the incongruent condition, reading is considered an automatic process.

The Stroop task has been adopted in numerical cognition by changing the color names and ink colors in number symbols and physical sizes (Besner & Coltheart, 1979; Henik & Tzelgov, 1982; Tzelgov, Henik, & Berger, 1992). These two magnitudes are independently manipulated resulting in congruent (4 8), incongruent (4 8) and neutral (4 4 or 4 8) conditions. Here, instead of naming the ink color, subjects have to respond by pressing at the side of the numerically or physically larger number. If a subject is impaired in responding to the physical size of the stimulus in incongruent trials, as reflected by delayed manual response, it can be concluded that numerical size was automatically activated. Conversely, when a subject's reaction time is longer when responding to numerical size in incongruent trials, physical size was apparently accessed automatically. Using this "numerical Stroop task" also called the "size congruency task", it has been shown that distinct magnitude representations can interact. For instance, physical size interacts with Arabic numbers, dots, number words as well as different levels of luminance (Cohen Kadosh, 2008; Cohen Kadosh, Cohen Kadosh, & Henik, 2008; Cohen Kadosh & Henik, 2006b; Cohen Kadosh, Henik, & Rubinsten, 2008; Hurewitz, Gelman, & Schnitzer, 2006).

Interactions between distinct magnitudes do not necessarily implicate that distinct notations are subserved by the same neural substrate. These interaction effects can also be explained on the basis of similar response codes (Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; Santens & Gevers, 2008). For instance, when a subject has to compare the numerical size of the incongruent condition 4 and 8, initial activation of the incorrect response hand, due to faster processing of the physical size of number four, would result in a delayed response to the numerical size. Thus, in this case, the conflict would arise at the level of the response and not before. Disentangling the semantic from response processes is therefore a necessary step to infer the mechanisms underlying magnitude processing. The results of studies concerning the timing of interaction between two magnitudes are often explained in terms of the early and late interaction account (Schwarz & Heinze, 1998). The early interaction account states that two magnitudes interact at the level of the general magnitude system, the level before the response is prepared or initiated. The late interaction account suggests that both magnitudes are processed in parallel and only interact at the level of the response.

Neuroimaging studies have revealed a fronto-parietal network to be active when the numerical Stroop paradigm was used. The parietal areas were active for the numerical distance between the numbers presented whereas the frontal areas reflected the congruency effect (Ansari, Fugelsang, Dhital, & Venkatraman, 2006; Kaufmann et al., 2005; Tang, Critchley, Glaser, Dolan, & Butterworth, 2006). EEG studies specifically targeted the timing of the interaction between Arabic numbers and physical size and revealed results favoring the "early interaction account" (Cohen Kadosh, Cohen Kadosh, Linden et al., 2007; Schwarz & Heinze, 1998). However, the few studies addressing the interaction between distinct modalities (Arabic number and luminance) reported conflicting results (Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh, Henik et al., 2005; Pinel, Piazza, Le Bihan, & Dehaene, 2004).

Together, some of these results support the idea of a general magnitude code. More conclusive evidence is derived from studies revealing that the same groups of neurons code for Arabic numbers and number words in the right hemisphere (Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007) and for Arabic numbers and groups of dots in the left hemisphere (Piazza, Pinel, Le Bihan, & Dehaene, 2007). Furthermore, neurons of monkeys that were trained on the associations between number symbols and the numerosity they refer to, were responsive to groups of dots as well as Arabic number symbols. Unexpectedly, these neurons were located in the frontal and not the parietal areas often reported to be involved in number processes (Diester & Nieder, 2007). Since these frontal areas are known as association areas, it was suggested that in the initial phase of symbolic number learning, distinct processes are recruited to subserve symbolic number processes.

FROM QUANTITY TO NUMBER

The child's behaviour in mathematical development reflects the gradual processes with which the neural system subserving the Arabic number system develops. As outlined above, it is suggested that the neural system that underlies the symbolic system is the same mechanism that also subserves non-symbolic numerosity processes (for a review see: Cohen Kadosh, Lammertyn et al., 2008). Consequently, the current consensus is that a single neural substrate that at first codes for the non-symbolic numerosities is the basis for the later acquired symbolic system. This idea is consistent with the redeployment hypothesis that states that during the course of development, groups of neurons may shift their function from relatively simple to more complex forms of information processing (Anderson, 2007). The neural structures at first responsive to non-symbolic numerosity will become responsive to the number symbols after repeated exposure to them, thus after acces to number symbol meaning is automated.

When children receive formal schooling they learn a symbolic numerosity code (e.g. Arabic numbers). The names of the symbols are first recited without the child knowing the relation between the new symbolic and the familiar non-symbolic code. As soon as the child becomes aware of the association between both numerosity notations (ordinality) the child starts to understand that the last number of a counting sequence denotes the quantity of the whole set (cardinality) (Gelman and Galistel 1978). From here onwards, the established association between the number symbol and its reference to the quantity of a set of objects or items can become automated. This ability to access automatically number symbol meaning is necessary for learning the complex mathematical procedures. Children that do not establish an automatic link between a number symbol and its meaning, rely on strategies such as finger counting that are less efficient in solving the mathematical problems.

The automatization of Arabic number meaning is tested using the numerical Stroop paradigm. The link between a number symbol and its meaning gradually establishes in children and is fully automatized around the age of 7 to 8 (Girelli, Lucangeli, & Butterworth, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). Remarkably, even though the child has automatic access to number symbol meaning, when the child engages in a task that requires access to number symbol meaning, it still recruits different areas of the brain when compared to adults (Ansari, Garcia, Lucas, Hamon, & Dhital, 2005; Kaufmann et al., 2006; Rivera, Reiss, Eckert, & Menon, 2005). This recruitment of frontal processes is present in children around 10 years old and confined to symbolic numbers. When non-symbolic numerosities are presented to four-year old children, the same parietal areas for number processing as compared to adults are activated. Two hypotheses were raised to explain this ontogenetic shift from frontal to parietal areas for Arabic number processing. First, it is suggested that in the initial stages of automatization, frontal processes are involved since the child relies more on attentional and working memory processes to solve the task. Second, the parietal areas might become more functionally specialised with experience (Ansari et al., 2005). Whether one of these or both hypotheses hold is still a matter of scrutiny.

Elucidating the underlying ontogenetic shift from frontal to parietal areas is of great importance since it furthers our insight in the possible causes of mathematical difficulties. Moreover, the correlation between the knowledge of non-symbolic numerosity processes and later acquired symbolic arithmetic abilities would emphasize the importance of education in non-symbolic arithmetic in elementary school (see also epilogue). More insight in non-symbolic arithmetic might also help children with mathematical difficulties to grasp the concept of Arabic numbers, which has been suggested to be the bottle-neck (Rubinsten & Henik, 2005).

SYNESTHESIA

> *Each number had its own personality - masculine or feminine, perfect or incomplete, beautiful or ugly. Ten was the very best number: it contained in itself the first four integers - one, two, three, and four [1 + 2 + 3 + 4 = 10] - and these written in dot notation formed a perfect triangle.*
>
> -Pythagoras-

Pythagoras' fascination with numbers was possibly not only the result of the ability to represent numerosities more accurately but could also have been due to the fact that each number had, in his eyes, its own 'personality'. About 4% (Simner et al., 2006) of humans have a kind of arbitrary relationship, akin to the one by Pythagoras described above, between two sensory or cognitive dimensions. Some people, for instance, report to see colors when they hear tones, feel emotions when they touch specific textures or the more common variant, perceive colors when they see graphemes or words (Rich & Mattingley, 2002). For these people, the arbitrary sensations are real and they cannot suppress them. This phenomenon is called *synesthesia.*

Synesthesia is derived from the Greek and means joined perception: 'aesthesis' means perception and 'syn' means joined or together. In most cases, this joining of two senses occurs between a learned semantic and a sensory experience. For instance in the case of grapheme-color synesthesia, the synesthete perceives a synesthetic color experience when a number or letter is presented. It has been suggested that Pythagoras was a synesthete, but the first known official report on synesthesia was written by Sachs in 1812 (Hochel & Milan, 2008). Sachs described that both he and his sister experienced vivid color sensations when seeing, hearing or even thinking about graphemes. It was Francis Galton who put this phenomenon in the scientific spotlight in 1880, although the interest in synesthesia was short-lived due to the start of behaviorism that banned all research dealing with the 'internal state' of humans. Synesthetes who at the time openly discussed their synesthetic experiences were sent off to mental hospitals diagnosed as schizophrenics or drug addicts (Hochel & Milan, 2008). Currently, however, synesthesia again receives widespread scientific attention, since synesthesia can be used as a tool to gain insight into several important topics in neuroscience, such as automatization processes and inter-sensory integration (Cohen Kadosh & Henik, 2007).

The synesthetic experience is suggested to be *idiosyncratic*. Synesthetes have different synesthetic associations and report that the associations of other synesthetes are 'wrong'. Besides the idiosyncrasy, synesthesia is also an *automatic* and *involuntary* process. Comparable to the automaticity of number and reading processes discussed above, synesthetes cannot suppress the synesthetic experience. When reading a text or hearing tones they immediately perceive the induced synesthetic experience. Furthermore, the synesthetic experience does not change over time; it is *consistent*. Synesthetes are often requested to quantify their sensory experiences. Synesthetes can reproduce these quantifications of their synesthetic experiences extremely accurately after a time interval of hours and even months.

Multiple dimensions of synesthesia

Besides these consistencies, differences have been reported as well. In the case of grapheme-color synesthesia, the synesthete either perceives the color in the 'minds eye' as if it appears 'somewhere in the head', or directly projected onto the grapheme. These distinct phemenological reports resulted in the classification of synesthetes in two groups, the *associators* and the *projectors* (Dixon, Smilek, & Merikle, 2004). The two forms of synesthesia can be differentiated on the basis of their phemenological but also more objective performance measures (e.g. synesthetic Stroop paradigm). In the synesthetic Stroop paradigm (Dixon et al., 2004; Ward, Li, Salih, & Sagiv, 2007) a grapheme is colored in the ink color that is consistent or inconsistent with the synesthetic experience. Synesthetes are requested to name aloud the color of the ink or of the synesthetic experience with that number. It appeared that projectors are more hindered to name the ink color of the grapheme while associators are more hindered to name the synesthetic color. This is of course due to the stronger experience of the synesthetic color percept for projectors compared to associators. In contrast to the phemenological division of synesthetes, a distinct division, based on the neural processes involved, has also been proposed (Ramachandran & Hubbard, 2001). According to these authors, lower perceptual (lower synesthetes) as well as higher cognitive processes (higher synesthetes) can play a role in the elicitation of the synesthetic experience. For lower synesthetes, the inducer of the synesthetic experience is the form of the grapheme, whereas for higher synesthete, the inducer is a more abstract conceptual aspect, for instance the meaning of the number.

Whether both categories of synesthetes (projector/associators versus lower/higher synesthetes) refer to the same phenomena (Dixon & Smilek, 2005; Hubbard & Ramachandran, 2005; Ward et al., 2007) is a matter of recent debate. Conflicting results have been reported with studies revealing the involvement of early visual processes (Beeli, Esslen, & Jancke, 2008; Nunn et al., 2002; Paulesu et al., 1995) and studies showing the involvement of higher order processes (Cohen Kadosh, Cohen Kadosh, & Henik, 2007; Weiss, Zilles, & Fink, 2005). The lack of consensus between these studies led to the idea that synesthesia might not be a unitary phenomenon (Dixon & Smilek, 2005; Hubbard, Arman, Ramachandran, & Boynton, 2005). This was further underlined by a recent study revealing that within the group of color-grapheme synesthetes differences can be obtained. The synesthetes in this study were grouped on the basis of their performance in a behavioral task testing early perceptual effects. After this division, the fMRI results measured on a different task could be better explained (Hubbard et al., 2005). Whether indeed multiple dimensions of synesthesia exist and whether these dimensions coincide with the phemenological dissociation of projectors versus associators or lower versus higher synesthetes remains a question.

Synesthesia and number processes

As reported above, synesthetic associations are present in many distinct forms of which number-form synesthesia can be especially helpful to guide research in the number field. In numerical cognition, (non-synesthetic) subjects have been shown to implicitly associate small numbers with the left and large numbers with the right side of space (Dehaene, Bossini, & Grireaux, 1993).

Number-form synesthetes perceive numbers as presented in specific configurations (Tang, Ward, & Butterworth, 2008), for instance numbers one to ten from left to right and higher numbers go rightwards-up in circles. When tested on paradigms that asses the association between number and space, these subjects will not reveal the number-space associations as can be expected on the basis of the number line theory. Since not all non-synesthetic subjects reveal this spatial bias for numbers, it is suggested that the same diversity in spatial number forms might exist in subjects that do not have explicit access to these number forms (non-synesthetes) (Cohen Kadosh & Henik, 2007). Such diversity in the space-number associations could explain that not all non-synesthetes reveal the number-space associations.

Furthermore, whether numbers are presented 'holistic' or as separate units is under fierce debate as well (Nuerk, Kaufmann, Zoppoth, & Willmes, 2004; Zhou, Chen, Chen, & Dong, 2008). On the basis of number-form synesthesia it is suggested that numbers are presented holistic, since synesthetic number-forms continue beyond the number nine. However, in the most common form of synesthesia, grapheme-color synesthesia, colors are reported for single digits only. Although one case is reported where the synesthete perceived colors for two-digit numbers (Gevers, Imbo, Cohen Kadosh, Fias, & Hartsuiker, accepted). The finding that synesthetes predominantly associate single and not two digit numbers with a color contradicts the idea that two digit numbers are presented holistically. However, it can be argued that if the synesthetic effect arises on the basis of the number-form, and not the semantic content, synesthetic color experiences for two-digit numbers should not be expected in the first place.

Interestingly, at first glance no consistency appears between the colors reported by different synesthetes. All appear to have completely different number-color associations. However, scrutinization of the properties of the synesthetic color experience such as brightness, hue and luminance, revealed that the level of luminance (of the synesthetic percept) correlated with numerical size (Cohen Kadosh, Henik, & Walsh, 2007). Similar associations between numerical size and luminance level have been obtained in the number field as well (Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh & Henik, 2006b). Both instances emphasize the common neural code that might underlie processing of magnitudes presented in distinct modalities, notations and possibly even synesthetic quantity associations. Furthermore, one case has been reported of a synesthete who had similar color experiences for Arabic numbers, dice patterns, and the fingers of the hand (Ward & Sagiv, 2007). This not only implies that both the non-symbolic and symbolic system merge, but also suggests the close relationship with finger counting. Finger counting is used by children to grasp the concept of numerosity and is abandoned as soon as the more accurate symbolic number system is learned. But even in adults these early established associations between numbers and fingers remain intact (Brozzoli et al., 2008).

The neurocognitive models

Different hypotheses have been raised to explain the extraordinary synesthetic associations on a neuronal level. One of the most prominent is the idea of *cross-wiring* (Hubbard & Ramachandran, 2005; Ramachandran & Hubbard, 2003). We are born with an abundance of connections of which a large number is discarded in the first stages of development. This process called neuronal pruning is suggested to fail to a certain extent in synesthetes. Connections between sensory modalities that should normally be pruned remain intact, possibly due to some inherited chromosomal difference. Whether these connections exist between neighboring areas at an early level in the processing stream or at a higher cognitive level is still debated. A second prominent theory is the *disinhibited feedback theory* (Grossenbacher & Lovelace, 2001). According to this theory there are no structural, but instead only functional differences in the brain. In non-synesthetes the concurrent (e.g. color) is suppressed from giving feedback to the bottom-up inducer (e.g. grapheme). A dysfunctional inhibitory mechanism would not prevent the concurrent to give feedback to the inducer and hence the synesthetic experience arises.

Several studies have revealed abnormal connections between areas, favoring the hypothesis of cross-wiring (Rouw & Scholte, 2007; Weiss & Fink, 2009). However, this might well be described as a form of the chicken-egg problem (Cohen Kadosh & Henik, 2007). Disinhibited feedback can lead to structural changes and hence these abnormal connections to arise. Using posthypnotic suggestion, it appeared that non-synesthetic subjects had similar synesthetic experiences as synesthetes have (Cohen Kadosh, Henik, Catena, Walsh, & Fuentes, 2009). Since the subjects were non-synesthetic subjects and hence did not have abnormal connections before hypnosis, this result suggests that indeed functional changes might induce the structural changes.

THE OUTLINE OF THIS THESIS

This thesis deals with the mechanisms underlying the human ability to process numerosities, either presented in symbolic or non-symbolic notation, as well as the development of these mechanisms. Non-symbolic numerosity is considered to be the precursor of our symbolic system, which suggests that both magnitude systems should rely on the same neural mechanisms. Not only distinct notations but also different modalities that have the same metric are expected to rely on this general magnitude system. Even though it appears likely that it would be more efficient to translate distinct codes into a common code, it appears equally likely that they are processed by the same mechanisms while they remain in a distinct code. Thus the main question in this thesis can be formulated as: how does the human brain process magnitudes in distinct notation, and how do these mechanisms develop?

Chapter 2 explores the boundaries of the child's numerical abilities. We specifically question whether the relatively late onset of the child's ability to automatically process Arabic numbers is due to the child's cognitive skills that are still under development or to the number symbols the child is not sufficiently acquainted with. Using both symbolic and non-symbolic Stroop paradigms we could disentangle these distinct possibilities. In chapter 3, we investigated the stage at which the conflict between the distinct magnitude representations happens using the same symbolic and non-symbolic Stroop paradigm. We dissociate between the early and late interaction account. Excluding a late interaction for both numerosities would agree with the notion that the symbolic system is integrated with the non-symbolic system. In chapter 4, we address the development of the neural mechanisms underlying the automatization of symbolic and non-symbolic numerosity processing. Before number symbols are automatic, the recruitment of distinct processes is expected. To test this hypothesis, we include in this study children that just learned the number symbols as well as children that already worked with these numbers for two years and use EEG as a measure. We again compare the results of the symbolic and non-symbolic size congruency task so cognitive and numerical processes can be disentangled.

The chapters 2 to 4 rely on the notion that number sense is already present at birth and eventually develops into the more accurate numerosity systems adults rely on. But no direct comparison of the infant and adult ability to respond to numerosity changes using comparable tasks have been done so far. To address this issue, we investigated in chapter 5 the neural correlates of non-symbolic numerosity processing in adults, using an implicit as well as explicit paradigm. Chapter 6 deals with inconsistencies reported in the literature about the interactions between distinct magnitudes addressing the question whether the general magnitude code only subserves numerosities with a spatial content. Moreover, the origins of the interactions between magnitudes are further elucidated.

While Arabic number symbols are learned through one to one mappings between the non-symbolic and symbolic code, some subjects reveal abnormal mappings, which is the case in synesthesia. Synesthetes do not explicitly report to perceive a number when a color is perceived, but only the reverse. Since humans reveal a bi-directional interaction between symbolic and non-symbolic numerosity it can be expected that such a bi-directional interaction might be present implicitly in synesthetes as well. In chapter 7 and 8 we will investigate whether the synesthetic experiences reported by color-grapheme synesthetes happen in both directions. In chapter 8, we also reveal the underlying neural correlates and add evidence to the notion that multiple dimensions of synesthesia exist.

CHAPTER 2

AUTOMATIC QUANTITY PROCESSING IN 5-YEAR OLDS AND ADULTS

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ABSTRACT

In this study adults performed numerical and physical size judgments on a symbolic (Arabic numerals) and non-symbolic (groups of dots) size congruity task. The outcomes would reveal whether a size congruity effect (SCE) can be obtained irrespective of notation. Subsequently, 5-year-old children performed a physical size judgment on both tasks. The outcomes will give a better insight in the ability of 5-year-olds to automatically process symbolic and non-symbolic numerosities. Adult performance on the symbolic and non-symbolic size congruity tasks revealed a SCE for numerical and physical size judgments, indicating that the non-symbolic size congruity task is a valid indicator for automatic processing of non-symbolic numerosities. Physical size judgments on both tasks by children revealed a SCE only for non-symbolic notation, indicating that the lack of a symbolic SCE is not related to the mathematical or cognitive abilities required for the task but instead to an immature association between the number symbol and its meaning.

INTRODUCTION

In the last decades, evidence has accumulated that numbers may be presented in the mind as an "inner number line" (e.g., logarithmic curve, Dehaene 2003, or linear curve with a scalar variability, Gallistel and Gelman 1992; Zorzi and Butterworth 1999, but see Verguts, Fias, and Stevens 2005, for a different opinion). On this mental number line, small numbers are represented on the left while large numbers are represented on the right. The effect supporting this theory is the Spatial-Numerical Association of Response Codes (SNARC) effect, which relates to the phenomenon that people are faster to respond to numerically small numbers with the left hand and to numerically large numbers with the right hand (Dehaene et al. 1993; see Fischer, Warlop, Hill, and Fias 2004; Gevers, Lammertyn, Notebaert, Verguts, and Fias 2006, for recent reviews). It has been suggested that the mapping of Arabic numerals on the mental number line happens automatically (Dehaene, 1992). Strong evidence for the automatic processing of numbers (e.g. the meaning of the number symbol is directly accessed although it is not part of a task requirement) has been derived from the size congruity task (Algom, Dekel, & Pansky, 1996; Cohen Kadosh, Cohen Kadosh, Linden et al., 2007; Cohen Kadosh, Cohen Kadosh, Schuhmann et al., 2007; Henik & Tzelgov, 1982; Kaufmann et al., 2006; Schwarz & Heinze, 1998; Szucs & Soltesz, 2007; Szucs, Soltesz, Jarmi, & Csepe, 2007; Tzelgov et al., 1992).

In the size congruity task participants perceive two stimuli that are varied in their numerical value and physical size throughout the trials. In the size comparison task, participants have to decide which number is physically larger while ignoring the numerical value. In the numerical comparison task they have to decide which number is numerically larger while ignoring the physical size. Due to the different sizes and numbers used, three conditions can be distinguished: (1) a congruent condition where the numerically larger number is also physically larger (e.g. 1-4), (2) an incongruent condition where the numerically larger number is physically smaller (e.g. 1-4) and (3) a neutral condition where, in the size comparison task, the same numbers are presented in distinct sizes (e.g. 4-4) or where, in the numerical comparison task, different numbers are presented in the same size (e.g. 1-4). Performance on the task is influenced by the ability to ignore the irrelevant dimension, which is reflected in the reaction times. The reaction times in the congruent condition are shorter (facilitation effect) whereas the reaction times in the incongruent condition are longer (interference effect), when compared to the neutral condition. The difference between the incongruent and congruent condition is called the size congruity effect (SCE) and reflects the integration of both dimensions.

At which age can we process numerical magnitude automatically? Girelli et al. (2000) used the size congruity task to get more insight into the development of automatic number processing in children. When children had to judge physical size, a SCE effect emerged in 3rd grade children (mean age 8.3 years). This finding is comparable with the results of Rubinsten et al. (2002) who found a SCE in 1st grade children (mean age 7.32 years). But a recent study of Zhou et al. (2007) revealed a SCE already in Chinese kindergartners (mean age 5.8 years) and suggested that this was related to cross-cultural differences. Importantly, the children of the youngest age groups in the studies of Rubinsten et al. (2002) and Girelli et al. (2000) did not reveal automatic mapping of numbers, but could still perfectly decide which number was numerically larger (Girelli et al., 2000; Rubinsten et al., 2002), indicating that these children did have knowledge of the number symbols. Therefore, these studies nicely demonstrate the distinction between intentional processing of numbers and automatic access to them.

We expect that the inability of 5-year-old children to process numbers automatically is related to an immature link between the number symbol and its meaning and not to the underlying mathematical or cognitive abilities required for the task. Support for our view comes from studies that reveal that 5-year-old children already have an understanding of the number symbols (Lipton & Spelke, 2005) that is comparable to that of adults (Huntley-Fenner, 2001; Temple & Posner, 1998) and they can, as well as infants can, perform basic mathematical procedures with non-symbolic stimuli e.g. arrays of dots (Barth, Kanwisher, & Spelke, 2003; Barth et al., 2006; Barth, La Mont, Lipton, & Spelke, 2005; Brannon, 2002; Brannon, Abbott, & Lutz, 2004; Feigenson, 2005; Jordan & Brannon, 2006; Mix, Huttenlocher, & Levine, 2002; Xu & Spelke, 2000; Xu et al., 2005). Note however, that Rousselle et al. (2004) disentangled the effect of each continuous variable (e.g. density, area, contour length) on numerosity judgment performance in 3-year-old children and revealed that they performed at chance level in the condition that controlled for surface area.

In the current study we aimed to gain further insight in the automatic processing of number symbols in 5-year-old children. We used children of this age group because they have understanding of the number symbols (Huntley-Fenner, 2001; Lipton & Spelke, 2005; Temple & Posner, 1998) but do not have automatic access to those number symbols yet (Girelli et al., 2000; Rubinsten et al., 2002). First, we intended to investigate whether a non-symbolic Stroop task (see Figure 1) leads to a size congruity effect just like the symbolic Stroop task. Secondly, we intended to investigate automatic processing of symbolic and non-symbolic numerosities in 5-year-old children. To this extent we looked at the performance of adults when they have to make a numerical or a physical size judgment on a symbolic and a non-symbolic size congruity task. Comparing the response patterns of the symbolic and non-symbolic tasks gave us insight in the effect of continuous variables in the non-symbolic task, which leads to a better interpretation of the performance of the children on this task. For the non-symbolic task, groups of dots with a large numerosity were used to avoid the problem of differences in individuals subitizing range (the range up to which one can directly estimate the correct number presented). When a SCE is obtained in the non-symbolic task, it can be concluded that the non-symbolic task measures automatic numerosity processing. Secondly, we investigated the performance of the 5-year-old children on both the symbolic and non-symbolic tasks by only judging physical size. Based on previous reports we do not expect a SCE on the symbolic task. If a SCE is present on the non-symbolic task, it can be concluded that children have direct access to non-symbolic numerosities although it is not part of the task requirement. Moreover, the presence of a SCE on the non-symbolic and the absence of a SCE on the symbolic task indicate that 5-year-old children have an immature connection between the number symbol and its meaning and do not lack the mathematical abilities necessary to reveal a SCE on the task (i.e. knowledge about physical and numerical sizes, and the fact that they can be in conflict or agreement with each other).

METHODS

In the adult experiment, the symbolic (Arabic numerals) and non-symbolic (groups of dots) tasks were performed by university students that had to make a numerical as well as a physical size comparison judgment. For the symbolic size congruity task participants were presented with two Arabic numerals that differed in their physical size and numerical value. In the physical size comparison task subjects had to judge at which side the physically larger number was presented. In the numerical comparison task subjects had to judge at which side the numerically larger number was presented. Similarly, in the non-symbolic size congruity tasks participants were presented arrays of dots and were instructed to judge which side contained physically larger dots (physical size comparison task) or which side contained more dots (numerical comparison task).

In the child study, the symbolic and non-symbolic size congruity tasks were performed by 5-year-old children that only had to make a physical size judgment to investigate whether they can process symbolic and/or non-symbolic quantities automatically.

Participants

For the adults study, sixteen students aged between 19 and 23 years (M = 20.7, SD = 1.4; 13 female, 3 male) from the University of Utrecht participated. All participants were native Dutch speakers and had normal or corrected-to-normal vision. The students were paid for their participation in this experiment.

For the child study, sixteen children aged 5 years and 3 months to 5 years and 10 months (M = 5 years and 7 months, 7 female, 9 male) from an elementary school in Utrecht participated. All participants were native Dutch speakers and had normal or corrected-to-normal vision. In order to keep the group as homogenous as possible we only included children that had LVS scores (the school education system scores) of level 1 or 2 out of 5, meaning that their overall performance was average or well above average. It was tested in advance whether they had knowledge of the Arabic numerals 1 to 9 and their relations. The children had to judge which number was numerically larger for all the possible conditions that were used in the symbolic task. Only children that gave immediate responses (excluding children counting on the fingers or reciting the number line) and had 95 percent or more of the trials correct were included the in the study. Three children were excluded because they were unable to do so. The children afterwards received a present for participation.

Stimuli and materials

Symbolic comparison In each trial, two numbers were displayed simultaneously at 2.75° at the right and left side from the centre of the screen. The stimuli consisted of Arabic numbers ranging from 1 to 9, which were presented in pairs with a small (1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, 8-9) or large (1-6, 2-7, 3-8, 4-9) numerical distance in two different font sizes: 1.7° (small) and 2.4° (large).

Non-symbolic comparison In each trial, groups of dots ranging from 11 to 20 were randomly distributed. This relatively large number of dots had been used to rule out possible subitizing effects. Again, two numerical distances were used, a small numerical distance of 4 (11-15, 12-16, 13-17, 14-18, 15-19, 16-20) and a large numerical distance of 7 (11-18, 12-19, 13-20) and two dots sizes were used. Small dots had a diameter of 0.38° and the large dots had a diameter of 0.53°. To exclude the possibility that the participant could derive the correct answer on the basis of visual sensory properties, we controlled for the *area subtended* by the group of dots presented in one array and the *total surface area* of the dots (i.e. luminance of the stimulus, similar to experiment 1 of the Hurewitz et al. (2006) study). The *area subtended* by the stimulus was the same in each condition (width and height of 3.05°). The dots were scattered randomly over the whole surface area and did not overlap. The *total surface area* of the dots was calculated by multiplying the surface area of one dot with the number of dots present in the stimulus. Thus, in the *congruent condition* an array of dots with more and physically larger dots (which together constitute a larger surface area), has to be compared with an array of dots with fewer and physically smaller dots (which together constitute a smaller surface area). In the *incongruent condition* an array with more but physically smaller dots (which together constitute a smaller surface area) is compared to an array with fewer but physically larger dots (which together constitute a larger surface area). In the neutral condition two arrays that contain the same number of dots are presented of which one array contains physically larger dots.

Stimuli were presented on a 17 inch computer screen. Stimuli were presented using the Presentation software (Neurobehavioral Systems).

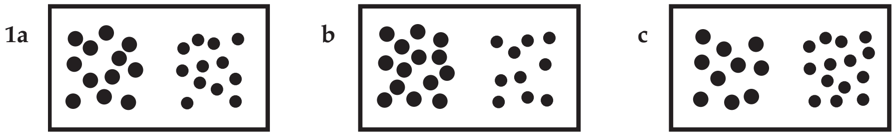

Fig. 1. Stimuli presented in the non-symbolic task. (a) Neutral condition of the physical size comparison task; the number of dots is the same but the physical size differs. (b) Congruent condition; more and physically larger dots have to be compared to less and physically smaller dots that together have a smaller total surface area (i.e. luminance) (c) Incongruent condition; more but physically smaller dots have to be compared to less but physically larger dots that together have a larger total surface area (i.e. luminance).

Procedure

Two tasks were constructed in different blocks. In the symbolic experiment there were two different instruction conditions (physical size comparison and numerical comparison) and three congruency conditions (congruent, incongruent and neutral). Each congruency condition consisted of 32 trials (total of 192 trials per task). For the non-symbolic number comparison task it was not possible to create a neutral condition while taking into account the additional visual-sensory properties of the stimulus. When the number of dots varies while the physical size of the dots remains the same it is inevitable that the side with the numerically more dots is darker and denser. These aspects of the stimulus serve as a marker for the side that contains more dots; the stimulus is not neutral. Therefore, the non-symbolic number comparison task comprised 2 instruction conditions (physical size and numerical comparison) and only 2 congruency conditions (congruent and incongruent) while the non-symbolic size comparison task consisted of 2 instruction conditions (physical size and numerical comparison) and three congruency conditions (congruent, incongruent and neutral). The order of the tasks was counter balanced between participants. Participants sat at a distance of approximately 57 centimeters and had to respond by pressing the button at the corresponding side of the target (the physically or numerically larger number). Half of the trials were presented with the correct answer on the left side and half of the trials with the correct answer on the right side. Before the experimental trials started participants received instructions and performed 10 practice trials. Between each task participants could take a break. Each trial began with a fixation point (500ms), followed by the stimulus (until response) and an inter-trial interval (500ms).

For the children only, the experimental tasks comprised 10 cartoon pictures that were randomly presented throughout each experiment to keep them motivated. They were told that cartoon pictures would appear on the screen, the better and faster they performed the task.

Analyses

For each participant, median reaction times of the correct trials were calculated in each condition and used as a dependent variable in the 4-way ANOVA with notation (symbolic and non-symbolic), order of task (physical size or numerical comparison first), task (physical or numerical comparison) and congruity (congruent and incongruent) as within participant factors. The median instead of the mean was used to deal with possible outliers. The neutral condition was not included in the overall repeated measures ANOVA because this condition was not present in the non-symbolic numerical comparison task. In the case of interactions additional analyses were done. In this case, in order to examine whether the SCE was interference and/or facilitatory based, we compared the neutral condition to the congruent and the incongruent condition except for the non-symbolic numerical comparison task.

As mentioned in the methods section, the children only performed physical size judgments. Therefore a 2-way ANOVA was conducted with notation (symbolic and non-symbolic) and congruency (congruent, incongruent and neutral).

Results of the adult study

The four-way ANOVA revealed significant main effects for task [$F(1, 14) = 160.33$, $p < .001$] and congruency [$F(1, 14) = 124.37$, $p < .001$]. The two-way interaction between task and congruency [$F(1, 14) = 68.60$, $p < .001$] and task and notation [$F(1, 14) = 20.29$, $p < .005$] and notation and congruency [$F(1, 14) = 8.51$, $p < .03$] were significant. No triple or four way interactions were significant. To further our understanding regarding the source of the two-way interactions, we conducted simple effects analyses for numerical and size comparisons separately under notation (for the interaction between task and notation), and under congruency (for the interaction between task and congruency) (Keppel, 1991).

Numerical comparison The simple main effect for notation was significant for reaction time [$F(1, 14) = 4.61$, $p < .05$] but not for error rate [$F < 1$]. This means that adults performed significantly slower but equally well in the non-symbolic (576 ms) compared to the symbolic numerical comparison task (492 ms). In addition, a simple main effect for congruency was present for both the reaction times [$F(1, 14) = 173.07$, $p < .001$] and the error rate [$F(1, 14) = 21.544$, $p < .001$] (see Figure 2). Adults were significantly slower and made more errors on the incongruent (579 ms, 9 %) compared to the congruent trials (488 ms, 3 %).

In order to examine whether the SCE was interference and/or a facilitatory based, we analyzed the congruency effect under symbolic notation for the symbolic numerical comparison task only because the non-symbolic condition did not consist of a neutral condition. A significant

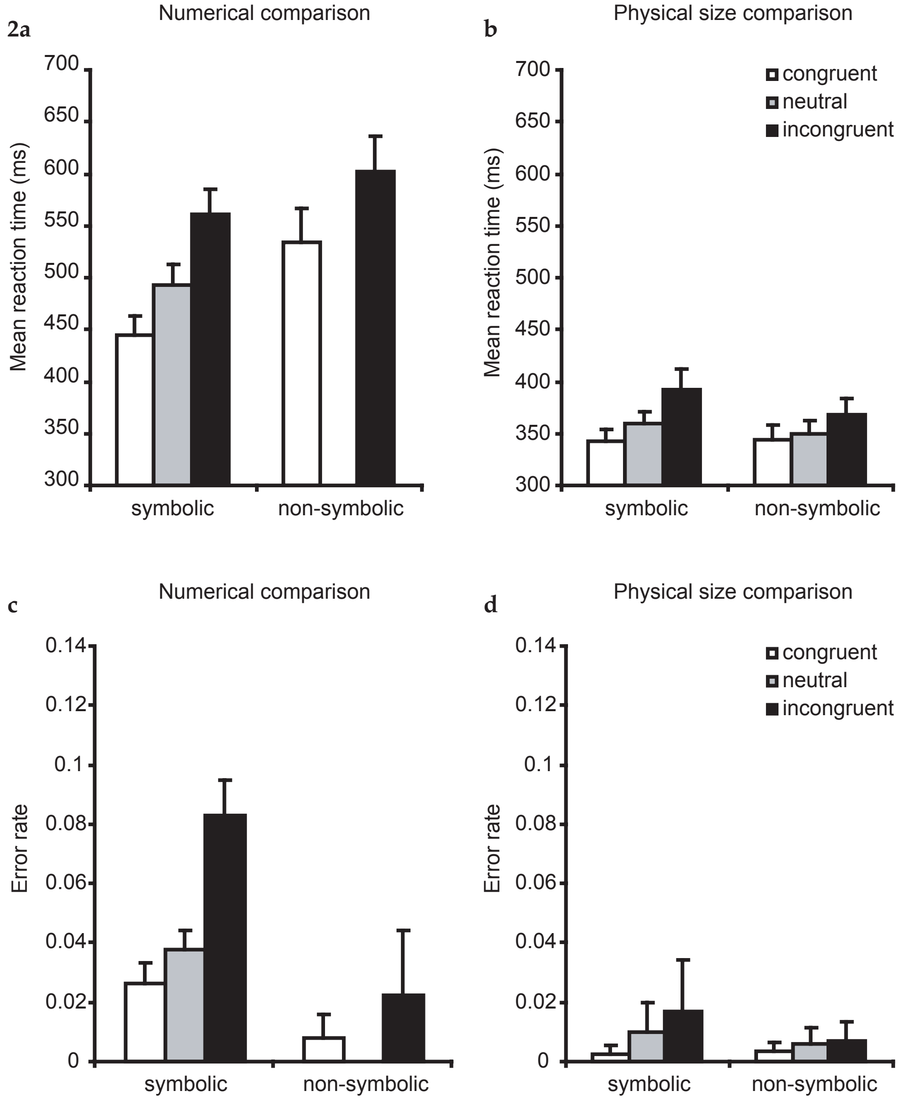

Fig. 2. The performance of the adults on the symbolic and non-symbolic size congruity tasks. (a) Mean reaction time on the symbolic and non-symbolic numerical comparison task, (b) mean reaction time on the symbolic and non-symbolic physical size comparison task, (c) error rates on the symbolic and non-symbolic numerical comparison task, (d) error rates on the symbolic and non-symbolic physical size comparison task. The results are divided by congruency (congruent, neutral and incongruent). Note that neutral is not present in the non-symbolic number comparison task because it is not possible to create a neutral condition while taking into account the effects of the visual stimulus properties.

facilitation effect of 47 ms [F(1, 14) = 42.71, p < .001] as well as a significant interference effect of 64 ms [F(1, 14) = 80.29, p < .001] was present. In addition, the participants made only significantly more errors in the incongruent (4 %) [F(1, 14) = 8.66, p < .02] compared to the neutral condition.

Size comparison The simple main effect for notation did not reveal a significant difference for reaction times [F < 1] or error rates [F < 1] indicating that both size comparison tasks were of similar difficulty. In addition, the simple main effect for congruency revealed a significant effect for both reaction time [F(1, 14) = 23.62, p < .001] and error rate [F(1, 14) = 19.82, p < .001]. The adults responded slower and made more errors in the incongruent (376 ms, 4 %) compared to the congruent condition (341 ms, 1 % errors).

The SCE was further analyzed with a one-way ANOVA in order to examine the facilitation and interference components. The results showed that only the main effect for congruency was significant for reaction time [F(2, 26) = 20.90, p < .001] and error rate [F(2, 26) = 17.34, p < .001] (see Figure 2b and d). When both congruency conditions were compared to the neutral condition it appeared that the facilitation (11 ms) effect [F(1, 14) = 22.87, p < .001] and the interference (25 ms) effect [F(1, 14) = 16.70, p = .001] were significant. In addition, the participants made significantly fewer errors (1 %) in the congruent [F(1, 14) = 4.78, p < .05] and more errors (3 %) in the incongruent condition [F(1, 14) = 17.57, p = .001] when compared to the neutral condition.

Overall, it can be concluded that the symbolic and non-symbolic comparison tasks were of equal difficulty in the size comparison condition. In addition, the results of the adults of both the numerical and physical size congruity tasks revealed a SCE. More importantly, under each task the SCE pattern was similarly independent of the notation. Thus the non-symbolic tasks measure automatic quantity processing in the same manner as their symbolic counter parts.

Results of the Child study

The two-way ANOVA revealed a significant congruency effect [F(2, 28) = 16.18, p < .001] as well as an interaction effect between notation and congruency [F(2, 28) = 19.23, p < .001] (see Figure 3a). To further our understanding regarding the source of the two-way interaction, we conducted simple effects analyses for symbolic and non-symbolic notation separately (Keppel, 1991).

Symbolic notation The simple main effect for congruency did not reveal a significant effect for reaction time [F(2, 28) = .018, p = .98] (see Figure 3a) or error rate [F(2, 28) = 2.68, p = .12] (see Figure 3b).

Non-symbolic notation The simple main effect for congruency was significant for reaction time [F(2, 28) = 26.4, p < .001] (see Figure 3a) but not for error rate [F(2, 28) = 2.79, p = .12] (see Figure 3b). When both congruency conditions were compared to the neutral condition it appeared that the facilitation (40 ms) effect [F(1, 14) = 5.27, p < .05] and the interference (93 ms) effect [F(1, 14) = 31.07, p < .001] were significant. To exclude the possibility of large inter-individual differences we also looked at the individual response patterns and found that only one subject did not reveal an interference effect and three subjects did not reveal a facilitation effect.

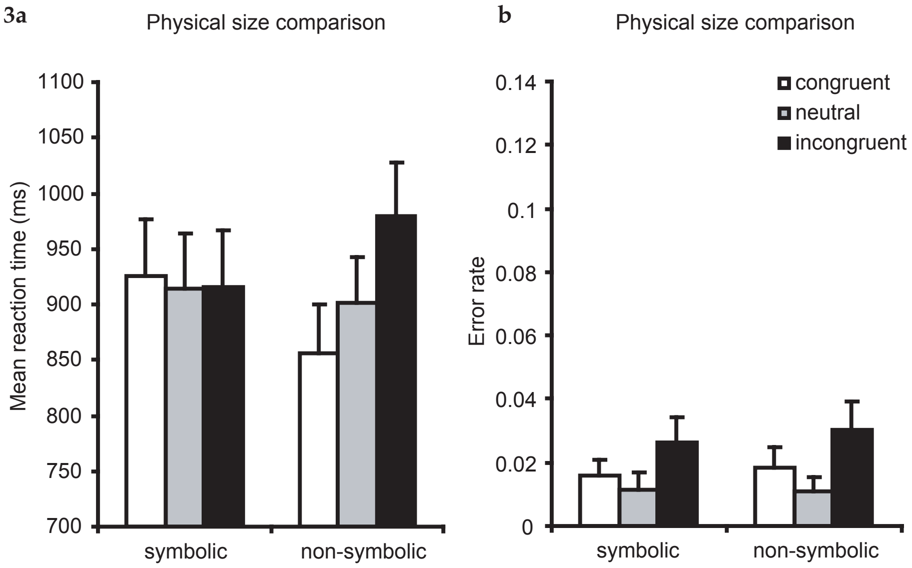

Fig. 3. The performance of the children on the symbolic and non-symbolic size congruity tasks. (a) Mean reaction time on the symbolic and non-symbolic numerical comparison task, (b) error rates on the symbolic and non-symbolic numerical comparison task. The results are divided by congruency (congruent, neutral and incongruent). Note that the scale is different than the one used for the adult studies.

The interference effect compared between adults and children

In addition, we compared the performance of both children and adults on the symbolic and non-symbolic size comparison task on the basis of the SCE effect. In order to deal with the overall slower responses of the children we standardized the data by subtracting the median reaction times of the congruent from the incongruent trials (i.e., the SCE), and divided the difference by the neutral condition for each participant (Cohen Kadosh et al 2007a). This standardized SCE factor was entered into a two-way ANOVA with notation (symbolic, non-symbolic) and group (adults, children). The two-way interaction of notation and group was significant [F(1, 56) = 23.13, p < .001] (see Figure 4).

Symbolic notation The simple effects analysis for symbolic notation showed a larger standardized SCE effect for the adults (10) than the children (1) [F(1, 56) = 10.57, p = .001].

Non-symbolic notation The simple effects analysis for non-symbolic notation showed a larger standardized interference effect for the children (15) than for the adults (5) [F(1, 56) = 12.60, p < .001].

In conclusion, the adults revealed a larger SCE than the children in the symbolic notation task, which is in accordance with the previous finding that no significant SCE was present for children in this task. In the non-symbolic notation task a larger SCE was obtained for children than for adults.

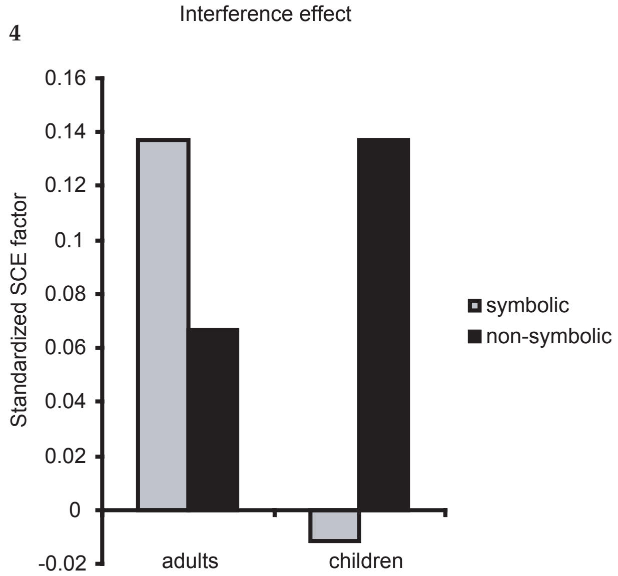

Fig. 4. The standardized interference component of the mean reaction times of the adults and the children on the symbolic and non-symbolic physical size congruity task.

DISCUSSION

Previous studies have revealed that automatic access to numbers is present in third graders but not in children (at the beginning) of the first grade. In this study we intended to get further insight in the ability of 5-year-old children to map numbers automatically on the mental number line. First, we asked adults to perform a symbolic and non-symbolic size congruity task by making a numerical and physical size judgment. Second, the children judged physical size in the symbolic and non-symbolic size congruity tasks. In the adult study, the presence of a SCE for non-symbolic stimuli in the physical and numerical judgment task would indicate that the non-symbolic task is a suitable measure to study automatic processing of number and physical size. The results of the child study would subsequently give further insight in the development of symbolic and non-symbolic number processing.

For the adults, a SCE effect was present for both the symbolic and non-symbolic numerical judgment task. This finding indicates that the participants were able to decide which array contained a larger number of dots, even in the incongruent condition where the visual properties (i.e. continuous variables) were misleading. This result also suggests that the participants had automatic access to physical size which is consistent with the finding of Hurewitz et al. (2006). The SCE effect was also present in the relatively easier physical size judgment tasks. Faster responses were obtained when numerosity was congruent with physical size and slower responses were obtained when numerosity was incongruent with physical size. The presence of a SCE in the non-symbolic size comparison task indicates that the participants processed numerosity automatically even though they were instructed to attend the more prominent physical size. Thus, number and physical size interfered with each other in a similar manner irrespective of the notation they were presented in. Therefore, the non-symbolic physical size and numerical judgment tasks are a suitable way to investigate numerosity processing in children.

For the children, no SCE was present in the symbolic size congruity task which is in accordance with previous studies (Berch, Foley, Hill, & Ryan, 1999; Girelli et al., 2000; Rubinsten et al., 2002). At the age of five, children are familiar with the number symbols but do not have automatic access to their meaning. However, in the non-symbolic task the children revealed a SCE, indicating that the children had direct access to non-symbolic numerosities although it was not part of the task requirement. These results also show that the children had knowledge about both, physical size and numerical value. Faster responses in the congruent and slower responses in the incongruent condition, when compared to the neutral condition, could only arise if the children did have knowledge about the two magnitudes and the fact that they can be in agreement or in conflict with each other. Therefore, the absence of a SCE in the symbolic task appears to be unrelated to a lack of mathematical or cognitive abilities necessary for the task but instead related to the relative unfamiliarity with the number symbols. In line with this result, Butterworth et al. (2001) suggested that repeated exposure to the number symbols will lead to automatic processing of numbers which in turn is considered necessary to become skilled in mathematics.

Children also revealed a larger interference effect than adults on the non-symbolic size comparison task. This finding is in agreement with the contemporary findings that children have immature inhibitory mechanisms, meaning that they are less capable of suppressing the irrelevant features of the stimulus (in the current case, numerosity) (Leon-Carrion, Garcia-Orza, & Perez-Santamaria, 2004; Schroeter, Zysset, Wahl, & von Cramon, 2004). The fact that children are less capable of suppressing the irrelevant feature should be taken into account in the paradigms used in the infants studies. Younger children will be more prone to attend to the prominent continuous variables instead of number in comparison to adults and are therefore less likely to be aware of a possible change in numerosity. The more prominent the continuous variables are the less likely it is that the child is going to perceive a change in numerosity especially when they are not instructed to attend to numerosity changes.

In contrast to Hurewitz et al. (2006), we found a SCE in the non-symbolic physical size judgment condition for both adults and children. Hurewitz et al. (2006) explained the absence of a congruency effect with the relative speed of processing account (Schwarz & Ischebeck, 2003), which states that area is processed faster and therefore not susceptible to the influence of the slower numerical processes. Hurewitz et al. (2006) concluded that the faster processing of physical size compared to numerosity might be the origin of the conflicting results in infant studies. But from the results they presented (cf. figures 3 and 4) it can be concluded that the participants were faster to judge numerosity (mean reaction times run from approximately 450 till 700) compared to area (mean reaction times run from approximately 700 till 800), which contradicts their reasoning. An alternative explanation for the lack of a SCE effect in the Hurewitz et al. (2006) study could be related to the fact that they used numerosities both above and below the subitizing range (3 till 9). For the small distance conditions this results in number pairs that are difficult to discriminate (e.g. 6-7, 8-9 and 7-8; note this is 30% of the trials). Interestingly, the large error rate that was present in the small distance, incongruent condition, of their number judgment task was 30% as well. Therefore, it appears plausible that in their study the participants were unable to judge numerosity on specific trials, which therefore did not lead to interference when physical size has to be judged.

The symbolic and non-symbolic Stroop task presented in this study is also a good paradigm to study the debate about the mechanisms underlying dyscalculia. Automatic access to symbolic numbers has been proposed to be affected in dyscalculics. Dyscalculic participants performing a physical size comparison of Arabic numbers revealed no facilitation effects (Rubinsten & Henik, 2005). Moreover, this lack of a facilitation effect is also obtained in normal subjects when the right intraparietal sulcus (IPS), the area expected to subserve number processing, was stimulated using transcranial magnetic stimulation (TMS) (Cohen Kadosh, Cohen Kadosh, Schuhmann et al., 2007). Interestingly, when the relative speed of processing of numbers and physical size are accounted for in the task, facilitation effects were obtained (Rousselle & Noel, 2007). See for an alternative explanation Mussolin & Noel (2007). These results together suggest a prominent role for automatic mapping of numbers on the mental number line in number processing. The idea of impaired automatization processes is in line with Wilson and colleagues who proposed two possible deficits that could be the cause of dyscalculia: (1) a deficit in number sense or non-symbolic representation of number or (2) a disconnection between symbolic and non-symbolic representations (Rubinsten & Henik, 2005; Wilson, Dehaene et al., 2006; Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). Cohen Kadosh and colleagues suggested that dyscalculia is not only limited to a problem in the numerical domain but instead is a deficit in general magnitude representation, meaning that also non-numerical processes can be affected (Cohen Kadosh, Cohen Kadosh, Schuhmann et al., 2007; Cohen Kadosh & Walsh, 2007). In contrast, problems in a cognitive domain have also been proposed as the source of dyscalculia (Geary, 1993). The two Stroop tasks presented in this study allow direct comparison between automatic symbolic and non-symbolic processes of numbers on one hand, and non-numerical magnitude processing on the other hand, while excluding the possibility that different outcomes on both tasks are related to distinct task requirements (e.g. mathematical or cognitive processes). In this manner, these tasks might become a valuable tool in dyscalculia research, even before children acquire a more formal education of numbers.

To conclude, we presented a non-symbolic size congruity task that gave more insight into symbolic and non-symbolic quantity processing in adults and children. Already at the age of five, children who perform well on mathematics automatically process numerosities even while they are instructed to attend to physical size. Their inability to process Arabic numerals automatically is unrelated to the mathematical abilities required for the task but instead seems to be related to an immature link between the number symbol and the magnitude it represents.

CHAPTER 3

CONFLICT PROCESSING OF SYMBOLIC AND NON-SYMBOLIC NUMEROSITY

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Submitted

ABSTRACT

It is commonly assumed that processing of magnitudes occurs independent of modality or notation. Several studies have reported similar behavioral as well as neurophysiological responses to magnitudes presented in distinct modalities as well as notations, but a direct assessment of possible interactions between different modalities and notations, using direct measures of electro-cortical processing, is lacking. In the present study we investigate whether, the neural activity underlying symbolic and non-symbolic numerosity processing interacts with the neural activity underlying physical size processing before, or proceeds independently until, selective activation of the motor system. We used a symbolic (Arabic numbers) and non-symbolic (arrays of dots) size congruency task and instructed subjects to judge either the numerical or the physical size of the stimuli, while event related potentials were recorded. Longer reaction times as well as a decrease in accuracy were obtained for incongruent compared to congruent trials. For the event related potential data, this congruency effect was also found with respect to the latency of the P3 component, reflecting an interaction at the level of stimulus evaluation. Moreover, incongruence delayed the stimulus-locked but not the response-locked lateralized readiness potential. Together, these results suggest that, irrespective of notation, the interaction between different magnitudes occurs before selective response activation.

INTRODUCTION

Modality and notation independent processing

In two influential models, The Triple Code (Dehaene, Piazza, Pinel, & Cohen, 2003) and the ATOM model (Walsh, 2003) it is proposed that distinct magnitudes are encoded in an amodal format. Evidence concurrent with these models comes from behavioral and imaging studies about the 'distance effect' and 'size effect' using distinct modalities. The distance effect refers to the faster responses obtained when discriminating between numerically far (1 and 9) compared to numerically close numbers (4 and 5) whereas the size effect refers to the longer reaction times obtained for the comparison of numerically large (8 and 9) compared to small numbers (1 and 2). Both effects have been measured at a behavioral as well as a neuronal level using modalities such as physical size (Cohen Kadosh, Henik et al., 2005; Kaufmann et al., 2005; Pinel et al., 2004; Tang et al., 2006), luminance (Cohen Kadosh & Henik, 2006b; Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh, Henik et al., 2005; Pinel et al., 2004), line length (Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003), time (Dormal, Seron, & Pesenti, 2006) and pitch (Rusconi, Kwan, Giordano, Umilta, & Butterworth, 2006; for a review and meta-analysis on this topic see: Cohen Kadosh et al. 2008).

In addition to modality independence, The Triple Code model also proposes that magnitudes are processed independent of notation. In line with this hypothesis Pinel et al. (2001) showed that number-words and Arabic numbers activate similar brain areas, the bilateral intraparietal sulci (bilateral IPS). Notation independent processing of number words and Arabic numbers was further investigated by Cohen Kadosh et al. (2007) using functional magnetic resonance adaptation as a measure. This method allows investigating stimulus related processes without the requirement of subjects responding to the stimuli presented. Since response selection activates similar areas as those expected to subserve numerosity processes (Gobel et al., 2004; Jiang & Kanwisher, 2003), this method overcomes a crucial problem in this domain of research. Cohen Kadosh et al. (2007) reported notation independent adaptation and recovery patterns in the left hemisphere as well as areas only responsive to Arabic numbers in the right hemisphere. This only partly overlapping system for Arabic numbers and number words led them to suggest that the magnitude system might not be as notation independent as previously thought. The results of two additional behavioral studies (Cohen Kadosh, 2008; Cohen Kadosh, Henik et al., 2008) further emphasized this notion.

In contrast to number words, numerosity presented in non-symbolic notation (e.g. an array of dots) is often viewed as the precursor for numerosity presented in symbolic notation (e.g. Arabic number). Infants are already capable of processing numerosity presented in non-symbolic notation (Brannon, 2002; Feigenson et al., 2004; Jordan, Suanda, & Brannon, 2008; Xu et al., 2005) and this capability is therefore commonly assumed to serve as the basis for our later acquired symbolic number system (Dehaene, 2001). Hence, numerosity presented in a non-symbolic notation might be subserved by the same processing mechanisms as symbolic notation. Consistent with this hypothesis, responses to numerosity presented in different notations (e.g. Arabic numbers versus dots) resulted in comparable electroencephalography (EEG) signals in adults (Libertus et al., 2007; Temple & Posner, 1998) as well as children (Temple & Posner, 1998). Moreover, a neural network model trained for non-symbolic notation could also process numerosities presented in a symbolic notation (Verguts & Fias, 2004). More direct evidence resulted from studies actually showing that the neural substrates subserving non-symbolic notation also becomes activated for symbolic notation (Diester & Nieder, 2007; Piazza et al., 2007). Diester et al. (2007) revealed that monkey prefrontal cortex neurons tuned for non-symbolic numerosity fired for symbolic stimuli as well after the monkey was trained on non-symbolic to symbolic number associations. Piazza et al. (2007) used functional magnetic resonance adaptation and reported adaption and recovery effects with bilateral areas responsive to arrays of dots as well as Arabic number symbols. Together, the studies presented above all suggest notation independent processing for non-symbolic number and Arabic number symbols but not for number words. Stated otherwise, interactions between different magnitudes are manifest at multiple levels of processing, but the question when precisely, is still unresolved.

Interactions between distinct magnitude-processing systems

Interactions between distinct magnitude processes are frequently investigated using congruency tasks. In contrast to comparison tasks where only one dimension is manipulated, the congruency task allows to study the interaction between two magnitudes. Here, two simultaneously presented stimuli are manipulated in two magnitude dimensions (e.g. numerical and physical size) resulting in a congruent and incongruent condition. In the congruent condition the numerically larger stimulus is also physically larger whereas in the incongruent condition the numerically larger stimulus is physically smaller compared to the stimulus presented simultaneously (e.g. congruent: 2 4; incongruent: 2 4). Generally, behavioral responses are faster for congruent (facilitation) relative to incongruent stimuli (interference). There are two hypotheses that aim to explain these interaction effects (Schwarz & Heinze, 1998). First, there is the **early interaction account**, which suggests that the processing streams of two distinct magnitudes merge at an “early” processing stage, before the response processes are initiated. At this level of stimulus processing the two magnitudes can interact as they are encoded in a similar format by the same system. In contrast, the **late interaction account** suggests that the two magnitudes are processed in two separate, independent processing streams until the stage of the response. It is only at this ‘response’ stage that the two magnitudes can interact. The behavioral and imaging results from studies investigating the interaction between physical size and Arabic numbers or distinct levels of luminance, support the early interaction account (Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh, Cohen Kadosh, Linden et al., 2007). So far, no such early interaction has been obtained for a magnitude notation (number words) other than Arabic numbers (Cohen Kadosh, 2008; Cohen Kadosh, Henik et al., 2008). A prerequisite for the commonly held view that Arabic numbers are mapped onto a non-symbolic number system as soon as the symbolic numbers are learned is the demonstration of comparable early interactions for both symbolic and non-symbolic notations. Here we specifically assess this prerequisite.

The current study

To investigate the timing of the interaction between two magnitudes, we will use a symbolic and a non-symbolic size congruency task. We specifically question whether interactions between magnitudes of distinct notation occur prior to, or only at the motor response stage. Interaction effects at an "early" stage for both the symbolic and non-symbolic size congruency task would support the hypothesis of a magnitude system that is notation independent, at least for Arabic numbers and dots (as apposed to number words). Conversely, an interaction at the response stage for either task indicates that magnitude information is processed in parallel until the response initiation or execution. Such a result would preclude the idea of a general magnitude system that is devoted to both symbolic and non-symbolic notation.

Stimulus and response complexity have additive effects on reaction time. Therefore, to discriminate between the early and late interaction accounts, the electrophysiological chronometric measures: P3 and LRP are especially useful (Lansbergen & Kenemans, 2008). The latency of the P3 component reflects stimulus evaluation and categorization processes whereas processes of response selection and execution do not affect P3 latency (Donchin, 1981; Kutas, McCarthy, & Donchin, 1977; McCarthy & Donchin, 1981; Smulders, Kok, Kenemans, & Bashore, 1995). The P3 latency can thus be used to determine whether the obtained congruency effects at the behavioral level are the result of processes leading to stimulus categorization. The LRP is a measure of selective motor activation showing larger deflections at scalp sites contralateral to the moved hand. Differential onset latencies of the stimulus locked LRP (sLRP) indicate stimulus conflict prior to motor preparation whereas differential response locked LRP (rLRP) onset latencies indicate conflict at the stage of motor preparation or execution (Smulders et al., 1995).

METHODS

Participants

Eighteen subjects participated in the experiment of which fifteen were included in the analyses (aged between 19 and 35 years M = 23.7, SD = 1.36; 13 female, 2 male). All subjects were native Dutch speakers and had normal or corrected-to-normal acuity and were paid for their participation. Written informed consent was obtained according to the Declaration of Helsinki and as approved by the Ethical Committee of the University of Utrecht.

Apparatus, stimuli and procedure

In each trial, the stimuli were displayed on a 22-inch CRT monitor using the Presentation software (Neurobehavioral Systems, Albany, CA). The paradigm was a slightly adapted version of our previous study (Gebuis, Cohen Kadosh, de Haan, & Henik, 2008).

For the *symbolic comparison task*, the stimuli consisted of Arabic numbers ranging from 1 to 9, which were presented in pairs with a small (1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, 8-9) or large numerical distance (1-6, 2-7, 3-8, 4-9). Depending on the condition numbers were presented in a small font size (height 1.7° visual angle) or a large font size (height 2.4° visual angle). For the *non-symbolic comparison task* the stimuli consisted of groups of dots ranging from 8 to 16. This relatively large number of dots is used to rule out possible subitizing effects. Depending on the condition, small (0.38° in diameter) or large dots (0.53° in diameter) were presented. In each trial, groups of dots ranging from 8 to 16 were randomly distributed within a pre-specified area (3.05° square). Again, two numerical distances were used, a small numerical distance of 4 (7-11, 8-12, 9-13, 10-14, 11-15, 12-16) and a large numerical distance of 7 (7-14, 8-15, 9-16). To exclude the possibility that the participant derived the correct answer on the basis of visual sensory properties, these were controlled for (see for details: Gebuis, Cohen Kadosh, de Haan, & Henik, 2008). The centres of the stimuli were positioned 2.0° of the left and right side of the fixation cross on a grey background and the viewing distance was approximately 57 cm.

The two comparison tasks each consisted of two judgment conditions: (1) numerical size and (2) physical size judgment. Thus a total of four tasks were administered, each consisting of (128) congruent and (128) incongruent trials, which again consisted of (64) small and (64) large numerical distance trials. The order of the four comparison tasks was counter balanced between participants. Each trial began with a fixation cross (500 ms), followed by the stimulus (until response) and a random inter trial interval (1250-1500 ms). Participants responded by pressing the button corresponding to the side at which the target (the numerically or physically largest of the two stimuli) was presented. Half of the trials was presented with the target on the left side and half of the trials with the target on the right side. Prior to each comparison task participants received instructions and performed 20 practice trials. Between each task participants could take a break.

Electrophysiological recordings

EEGs were recorded from 64 scalp electrodes according to the International 10/20 EEG system (sampling rate of 2048 Hz) using the Active Two system (BioSemi, Amsterdam, The Netherlands); for an explanation about the system see www.biosemi.com or Schutter et al. (2008). The vertical electro-oculogram (VEOG) was recorded from electrodes attached above and below the left eye and the horizontal electro-oculogram (HEOG) from the outer canthi of both eyes.

Behavioral and ERP analyses

For each subject included in the analyses, median reaction times of the correct trials were calculated for each task condition.

EEG and EOG data were analyzed using Analyzer Software (1.05). Flat and noisy electrodes were excluded from the analyses. EEG signals were referenced off-line to the average of all included electrodes and segmented into epochs from 200 ms prior to 1000 ms after the presentation of the stimulus. Epochs were filtered with a bandpass filter (0.05 Hz, 12dB octave; 40Hz, 24dB/octave) and corrected for eye movements according to the Gratton, Coles, & Donchin (1983) algorithm. Trials with artefacts (difference criterion of 100μV within an epoch; low activity criterion of 0.5μV within a 100 ms time window) or an incorrect response were rejected from further analyses. Three subjects were discarded because more than 25% of the trials contained artefacts. The baseline was defined as the mean of the 100 ms period before stimulus onset. The baseline for the response locked LRPs was -550 to – 450 ms. For both the ERPs and LRPs grand average waveforms were created for each condition and filtered at 8Hz, 12dB/octave for visualization purposes only.

For correct-response trials only, P3 latency was estimated in single trials at the Pz electrode as the largest peak within the time window of 300-800 ms after stimulus presentation (Smulders, Kenemans, & Kok, 1994). The P3 amplitude was also analysed to allow comparison with previous studies and was estimated at the Pz electrode as the largest peak within the time window of 300-800 ms after stimulus presentation. Stimulus and response locked lateralized readiness potentials (s-LRP and r-LRP, respectively) were computed by subtracting the electrode ipsilateral to the response hand from the electrode contralateral to the response hand. Subsequently, the obtained difference waves for both hands were averaged ((C3-C4 + C4-C3) / 2). Jackknife averaging was used to accurately estimate the difference in s-LRP and r-LRP onset (Miller, Patterson, & Ulrich, 1998). For each condition, averages were obtained by omitting one participant from the sample. Therefore, we had to correct the obtained F-values as follows: Fc = F/(n-1)2 (Ulrich & Miller, 2001). As recommended by Miller, Patterson, & Ulrich (1998), the relative criterion method was applied to each subsample waveform using the 50% criterion for the s-LRPs and 90% for the r-LRPs.

To compare the two distinct notations a repeated measures ANOVA was performed with Notation (symbols and dots) x Congruency (congruent and incongruent) x Distance (small and large) as within subject variables for both the physical size as well as the numerical size judgment task. If present, to further disentangle three-way interactions simple effects analyses were performed per notation condition.

RESULTS

Reaction time results (Figure 1a and b)

In the *numerosity comparison tasks* a distance effect was present [F(1,14) = 226.174, p <0.001]; subjects responded faster to large (430 ms) compared to small (477 ms) numerical distance trials. The main effect for congruency [F(1,14) = 51.886, p < 0.001] was also significant, reflecting the faster responses to congruent (429 ms) compared to incongruent trials (488 ms). Congruency and distance interacted [F(1,14) = 20.222, p = 0.001]: the congruency effect was smaller for the large (38 ms) compared to the small (82 ms) numerical distance trials. Notation and congruency [F(1,14) = 5.753, p = 0.031] interacted as well, reflecting a smaller congruency effect for dot [t(1,14) = -2.924, p = 0.011] (42 ms) compared Arabic-number notation [t(1,14) = -11.308, p < 0.001] (77 ms).

In the *physical size comparison tasks* a congruency [F(1,14) =8.987, p = 0.010] and distance [F(1,14) = 83.367, p < 0.001] effect were present. Subjects responded faster to the small (405 ms) compared to large (413 ms) numerical distance trials as well as the congruent (381 ms) compared to incongruent (436 ms) trials. In contrast to the numerosity comparison tasks, a main effect for notation [F(1,14) = 11.711, p = 0.004] was present reflecting faster responses in the dot notation compared to the Arabic-number notation condition. In addition, an interaction between distance and congruency was significant [F(1,14) = 61.090, p < 0.001] due to larger congruency effects for the large (66 ms) compared to the small numerical distance trials (44 ms). The interaction between notation and congruency [F(1,14) = 5.315, p = 0.037] also reached significance reflecting a smaller congruency effect for the dot [t(1,14) = -7.212, p < 0.001] (36 ms) compared to Arabic-number notation [t(1,14) = -7.181, p < 0.001] (74 ms).

Accuracy results (figure 1c and d)

Except for notation in the physical size comparison tasks, all main effects as well as the two and three-way interactions were significant [F(1,14) > 4.5, $p < 0.05$] for both comparison tasks. Figure 1c and 1d reveal that the differences between conditions follow the same pattern as they do for reaction time. Hence, there is no sign of differential speed-accuracy trade-offs between conditions that could complicate our chronometric analysis.

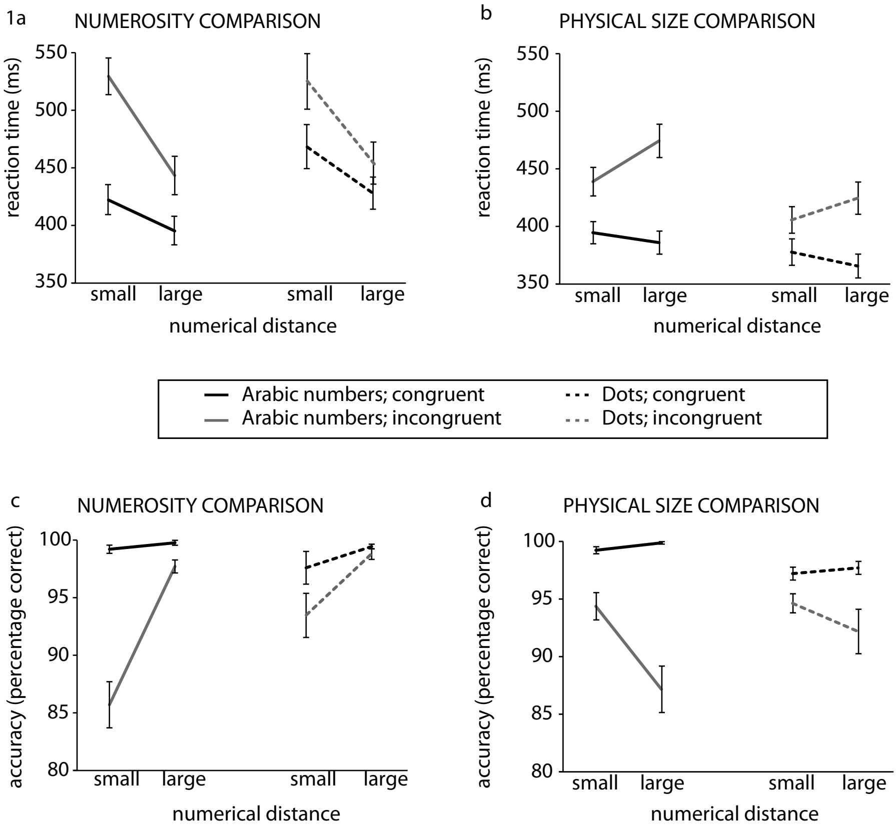

Fig. 1. Behavioral results of the four congruency tasks. The the reaction times (upper panels) and accuracy scores (bottom panels) are shown for the numerosity (left panels) and the physical size (right panels) comparison tasks. Data for Arabic numbers are shown as solid lines and those for dots as dashed lines. The results reveal a clear effect of congruency for both notation conditions on both comparison tasks as well as measures, i.e. more accurate or faster responses are given for congruent compared to incongruent trials. In addition, the small numerical distance trials show larger congruency effects for numerosity comparison, whereas the large numerical distance trials reveal the largest congruency effects in the physical size comparison tasks.

ERP results

P3 latency (Figure 2): For the *numerosity comparison tasks* the results revealed a distance [F(1,14) = 31.547, p < 0.001] as well as a congruency effect [F(2,26) = 23.976, p < 0.001]. The P3 peak appeared around a later point in time for numerically small compared to numerically large distance trials as well as incongruent compared to congruent trials. Congruency and distance interacted [F(2,26) = 23.976, p < 0.001], indicating a larger congruency effect for smaller numerical distance trials. In addition, congruency interacted with notation [F(1,14) = 12.356, p = 0.003], reflecting a smaller congruency effect for the dot notation [t(1,14) = -2.767, p = 0.015] compared to Arabic-number notation [t(1,14) = -5.692, p < 0.001].

In the *physical size comparison tasks* a distance [F(1,14) = 5.728, p = 0.031] as well as a congruency [F(1,14) = 29.456, p < 0.001] effect was present. The P3 peak appeared around a later point in time for large compared to small as well as incongruent compared to congruent trials. Moreover, distance and congruency interacted, the distance effect was larger for the large compared to the small numerical distance [F(1,14) = 8.194, p = 0.013] trials.

P3 amplitude (Figure 2): In the *numerosity comparison tasks* main effects for distance [F(1,14) = 13.053, p = 0.003], congruency [F(1,14) = 5.806, p = 0.030] and notation [F(1,14) = 8.538, p = 0.011] were present. The main effect of notation reflects the overall larger peaks obtained for the Arabic-number compared to the dot notation condition. The main effects for congruency and distance refer to the larger peak amplitude for congruent compared to incongruent and large compared to small numerical distance trials.

In the *physical size comparison tasks* the results revealed a congruency effect only [F(1,14) = 8.596, p = 0.011].

sLRP (Figure 3): In the *numerosity comparison tasks* the data revealed a trend towards significance for the effect of congruency [F(1,14) = 3.12, p = 0.09] and a significant distance effect [F(1,14) = 9.38, p = 0.008]. An interaction between notation and distance [F(1,14) = 9.45, p = 0.008] was present, as well as a three-way interaction between notation, congruency and distance [F(1,14) = 14.983, p = 0.002]. To disentangle the effects underlying the three-way interactions, simple effects analyses were performed. In the Arabic-number notation condition the results revealed a trend towards significance for congruency [F(1,14) = 3.53, p = 0.07] as well as a significant distance effect [F(1,14) = 14.054, p = 0.001] and interaction between congruency and distance [F(1,14) = 4.45, p = 0.045]. In the dot notation condition, an interaction between distance and congruency was present [F(1,14) = 9.12, p = 0.006]. In the *physical size comparison tasks* there was a significant congruency [F(1,14) = 18.14, p = 0.001] as well as a distance [F(1,14) = 13.44 p = 0.003] effect.

rLRP (Figure 4): For both the *numerosity comparison* as well as the *physical size comparison tasks*, no significant main effect or interaction was present.

DISCUSSION

In the present study we investigated at which stage in the transition from perception to action, different magnitude systems interact. Using a conflict paradigm and electro-cortical readout measures for stimulus evaluation and selective motor activation, the answer is clear cut: interactions for both symbolic and non-symbolic notation take place before the end of stimulus evaluation (P3

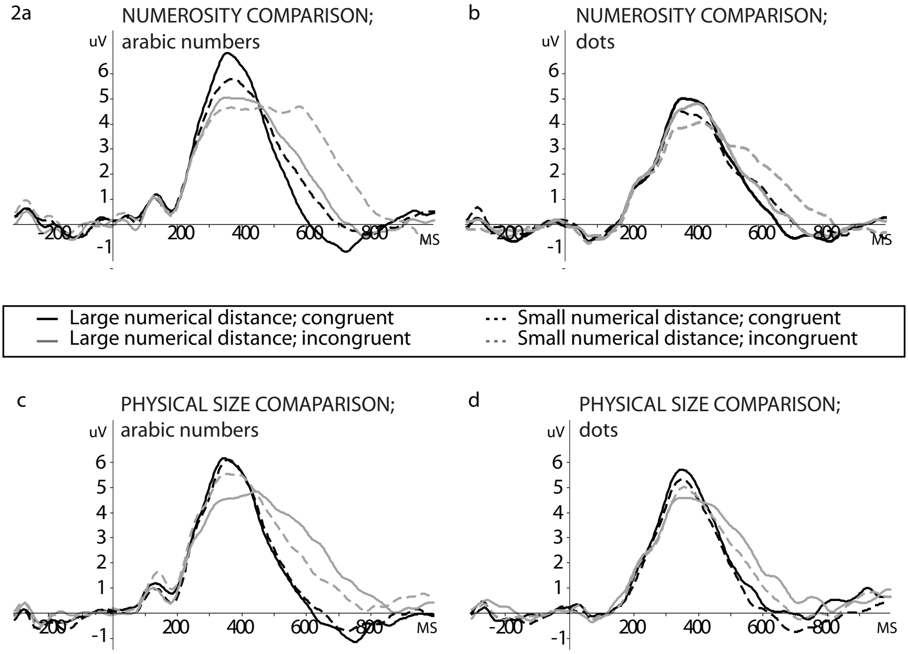

Fig. 2. Grand average ERPs at the Pz electrode. The results of the numerosity comparison (upper panels) and the physical size comparison (lower panels) of both the Arabic-number notation (left panels) and the dot notation (right panels) conditions are presented. Black lines represent congruent, gray lines incongruent trials; Solid lines represent large, dashed lines represent small numerical distance conditions. In both tasks and for both notations, a congruency effect is present in the latency (peaks appear around a later time point for incongruent trials compared to congruent trials) and peak amplitude data (peaks are larger or congruent compared to incongruent trials). Note, that the numerical distance effects for the incongruent trials are opposite for both comparison conditions. A larger delay and smaller peak amplitude are present in the physical size compared to numerosity comparison tasks for the large numerical distance trials and vice versa for small numerical distance trials.

peak latency), and before the start of selective motor preparation (LRP). These results support the early interaction account and are in line with the notion of a magnitude system that subserves numerosity presented both in symbolic and in non-symbolic notation.

The behavioral data revealed similar interaction patterns for the two notation conditions, Arabic numbers and dots, which is in perfect agreement with the results of a previous study (Gebuis, Cohen Kadosh, de Haan, & Henik, 2008). When numerosity interacted with physical size as well as the reverse, response times and the number of errors increased for the incongruent compared to the congruent trials. In addition, this congruency effect was affected by the numerical distance, though in opposite direction for the two comparison tasks. In the numerosity comparison task the effect of congruency increased with decreasing numerical distance, whereas the reverse occurred in the

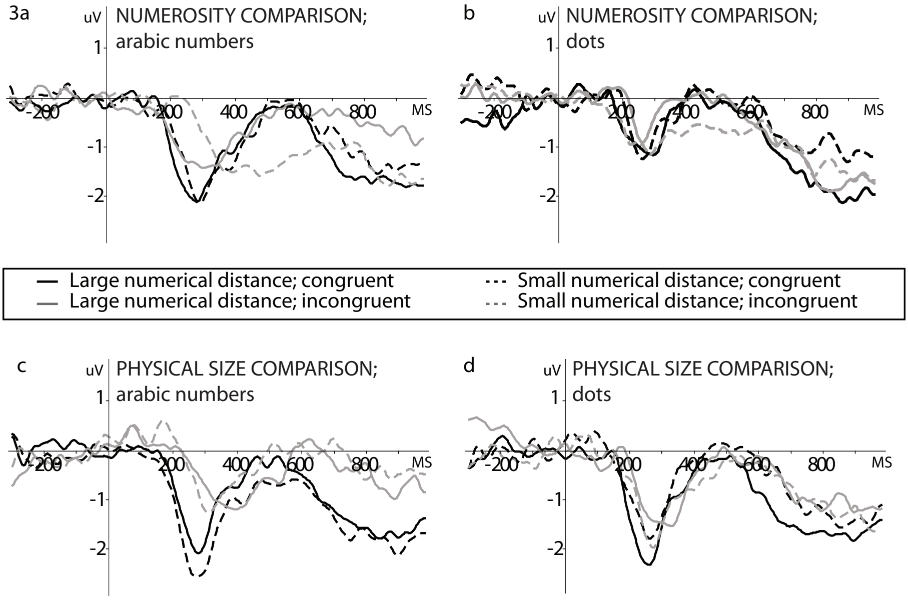

Fig. 3. Grand average stimulus-locked LRPs. The sLRPs elicited by the congruent (black lines) and incongruent (grey lines) trials of the numerosity comparison (upper panel) and the physical size comparison (lower panel) tasks and the Arabic-number notation (left panels) and the dot notation (right panels) conditions. Note, that the numerical distance effects (numerically small condition is dashed line; numerically large condition is solid line) for the incongruent trials are again opposite for both comparison conditions.

physical size comparison task, a result, also obtained in previous studies (Cohen Kadosh, Cohen Kadosh, Linden et al., 2007; Schwarz & Heinze, 1998). A tentative explanation for these results is as follows: When subjects have to judge numerical size, numbers with a large numerical distance are easier to compare than numbers with a small numerical distance. Consequently, when a number has to be judged, the relative fast responses to a large compared to a small numerical distance trials will receive less interference from the unattended physical size dimension. However, when a physical size has to be judged, the subject has to suppress the response to the incorrect numerical dimension. Since the large compared to the small numerical distance trials are still easier to discriminate and they are also less easy to suppress. Therefore, large compared to small numerical distance trials induce larger interference effects.

The comparable behavioral patterns for Arabic numbers as well as dots hint for similar timing of interaction. The behavioral results, however, cannot differentiate between the early and late interaction account. To be able to distinguish between both hypotheses we looked at the P3 component at a parietal electrode site. The results of the P3 latency nicely mimicked the behavioral congruency effects with its peaks appearing around a later point in time for incongruent compared to congruent trials. Such a congruency effect for P3 latency is indicative of conflict processing at the stimulus evaluation level (De Houwer, 2003; Schmidt & Cheesman, 2005; van Veen & Carter, 2005) and consequently is in agreement with the early interaction account. Interestingly, similar to the behavioral results, the numerical distance effect influenced the P3 latency differentially for both

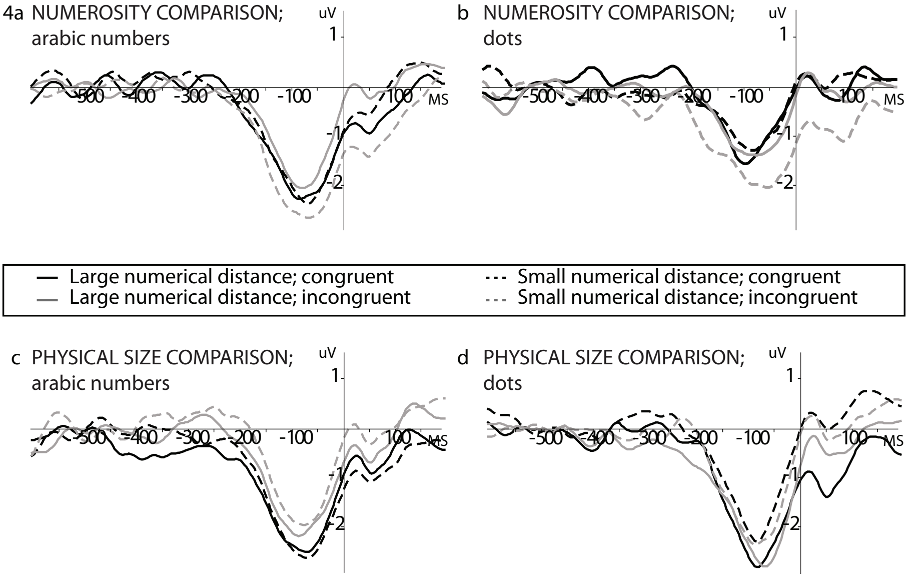

Fig. 4. Grand average response-locked LRPs. The rLRPs elicited by the congruent (black lines) and incongruent (grey lines) stimuli of the numerosity comparison (upper panel) and the physical size comparison (lower panel) tasks with Arabic-number notation (left panels) and the dot notation (right panels). In both tasks and for both notations, no congruency or distance effect was present in the onset latency.

comparison tasks; larger delays for small numerical distances in the numerosity comparison task and the reverse for the physical size comparison task were obtained.

To allow comparison with previous studies, we also investigated the P3 amplitude, which is indicative of cognitive load (for a review see: Kok, 2001). Larger P3 amplitudes were found for congruent compared to incongruent trials, suggesting an increase in cognitive load for incongruent compared to congruent trials. The result of a conflict at the level of stimulus evaluation as determined by the P3 latency (Schwarz & Heinze, 1998) as well as the effect of cognitive load as reflected by the P3 amplitude are in line with previous studies investigating the symbolic size congruency conflict (Cohen Kadosh, Cohen Kadosh, Linden et al., 2007; Szucs & Soltesz, 2007, 2008).

As hypothesized, the presence of P3 latency effects should coincide with a delayed onset of the sLRP for incongruent trials and the absence of such a delay for the rLRP. This was indeed the pattern of results obtained. Delayed onset latencies were found for incongruent compared to congruent trials for the sLRP only. These effects were present for both notation conditions when physical size was compared and only for symbolic notation when numerical size was compared. Possibly, the less accurate representation of dots in comparison to Arabic numbers could account for the absence of the sLRP onset latency effect in the dot notation condition. This idea is in agreement with Piazza et al. (2004) showing more accurate neuronal tuning for Arabic numbers compared to dots. The sLRP onset latency effects suggest that numerosity and physical size were processed in equal speed and competed before selective motor preparation started, therefore similarly to the P3 latency effect, the sLRP onset latency effects underscores the notion of an early interaction account.

Whether a general magnitude system that processes distinct magnitudes in a common code exists is a matter of debate (Cohen Kadosh, 2008). Our results demonstrate that for both symbolic and non-symbolic notation the interaction with physical size occurs before selective response activation, which is concurrent with the early interaction account and thus the notion of a general magnitude system. However, alternative explanations for the early interaction remain possible as well. Instead of being processed using a single, general code, for instance, different magnitudes can be categorized as small or large before a response code is activated (Gevers, Verguts et al. 2006; Notebaert, Gevers et al. 2006). Interactions between the distinct magnitudes could happen at this categorisation level as well.

In conclusion, in our study we elucidate the timing of the interaction between physical size and symbolically and non-symbolically presented numerosity. The presence of P3 peak and sLRP onset latency effects, together with the absence of rLRP onset latency effects suggests that these magnitudes interacted before the preparation or initiation of a response, excluding the hypothesis of a late interaction account. The fact that the early interaction account holds for both the dot and Arabic number notation adds evidence to the hypothesis of a general magnitude system that subserves both symbolic and non-symbolic magnitude, yet alternative explanations that can account for the early interaction effect remain possible.

CHAPTER 4

THE DEVELOPMENT OF AUTOMATED ACCESS TO SYMBOLIC AND NON-SYMBOLIC NUMBER KNOWLEDGE: AN ERP STUDY

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Submitted

ABSTRACT

Infants can visually detect changes in numerosity, which suggests that a (non-symbolic) numerosity system is already present early in life. This non-symbolic system is hypothesized to serve as the basis for the later acquired symbolic system. Little is known about the processes underlying the transition from the non-symbolic to symbolic code. In the current study we investigated the development of automatization of symbolic number processing in children from second (6.0 years) and fourth grade (8.0 years) and adults using a symbolic and non-symbolic size congruency task and Event Related Potentials (ERPs) as a measure. The comparison between symbolic and non-symbolic size congruency effects (SCE) allowed us to disentangle processes necessary to perform the task from processes specific to numerosity notation. In contrast to previous studies, second graders already revealed a behavioral symbolic SCE similar to that of adults. For all age groups, the ERP data showed that the two magnitudes interfered at a level before selective activation of the response system, for both notations. However, only for the second graders distinct processes were recruited to perform the symbolic size comparison task. This shift in the processes recruited for the symbolic task might reflect the functional specialization of the parietal cortex.

INTRODUCTION

A crucial aspect of arithmetic development is the acquisition of knowledge about the number symbols which, in contrast to non-symbolic number notation (e.g. arrays of dots), allows for precise and complex arithmetic. The level of automaticity in accessing the meaning of the number symbol has major implications on the ability to acquire proper mathematical skills (Butterworth, 1999). A lack of automated number knowledge results in the use of less profound strategies, e.g. finger counting. Studying the brain mechanisms that subserve the acquisition of 'number symbol knowledge' is therefore of great importance. In this study we will investigate the neural mechanisms involved in the establishment of an automatic link between the number symbol and its meaning. As a measure for automatic access to numerosity, young children as well as adults were requested to judge physical size information in a symbolic and non-symbolic size congruency task. Concurrently, event related potentials (ERPs) were measured to allow studying the neural mechanisms subserving automated numerosity processing.

A commonly held view is that humans are endowed with number sense, an innate ability to work with non-symbolic numerosity. This view is based on many studies that claim that infants can detect changes in numerosity and perform simple calculations (e.g. Brannon et al., 2007; Feigenson et al., 2002; Lipton & Spelke, 2003; Wood & Spelke, 2005). The ability to work with non-symbolic number knowledge is assumed to be a precursor for future number understanding. Children have been reported to be able to apply their non-symbolic mathematical knowledge onto symbolic math problems (Barth et al., 2005) and the accuracy with which they can discriminate numerosities has been shown to correlate with performance on arithmetics at a later age (Halberda et al., 2008). The idea of non-symbolic number knowledge as the precursor for symbolic number knowledge fits the hypothesis that the neural mechanisms that first subserve non-symbolic numerosities will become responsive to the later acquired number symbols. This merging of codes is the result of repeatedly associating a quantity with the number symbol it relates to. A strong association between the number symbol and its meaning results in the ability to automatically access number symbol knowledge is a necessary prerequisite for complex mathematical procedures. Although many studies underline the notion of a single mechanism subserving numerosities presented in distinct magnitudes in adults (for a review see: Cohen Kadosh et al., 2008), how the merging of the later acquired symbolic code with the already existing non-symbolic code develops during childhood is still unknown.

The development of automated number knowledge

Automatic access to symbolic number knowledge is often studied using the symbolic size congruency task (Algom et al., 1996; Henik & Tzelgov, 1982). In this paradigm, two Arabic number stimuli are presented simultaneously, each consisting of two stimulus dimensions (for instance numerical and physical size) that are manipulated independently resulting in congruent (e.g. 3 8), incongruent (e.g. 3 8) or neutral (e.g. 3 3 or 3 8) trials. When subjects have to respond to one dimension the unattended dimension interferes if it is automatically activated. Congruency effects obtained when subjects have to respond to the physical size of the Arabic numbers are indicative of automated number symbol meaning.

Five-year old children that have just acquired knowledge of the Arabic numbers only have automatic access to non-symbolic, but not symbolic number knowledge (arrays of dots) (Gebuis, Cohen Kadosh, de Haan, & Henik, 2008). These results implicate that the lack of automatic access to number symbol meaning cannot be attributed to premature cognitive processes (e.g. inhibitory or attentional) that are necessary to perform the task. Automatic access to number symbol knowledge may thus gradually develop with increasing age (Girelli et al., 2000; Mussolin & Noel, 2007; Rubinsten et al., 2002).

Neuroimaging studies with adults have revealed that congruency effects are associated with medial- and lateral-frontal activation, and not so much with parietal activation (except for the precuneus) (Ansari et al., 2006; Kaufmann et al., 2005; Tang et al., 2006). Activations specifically associated with numerosity-processing mechanisms have been reported in intra-parietal areas as well, sometimes more anterior to the response-selection areas (Ansari et al., 2006), but not always (Kaufmann et al., 2005). Interactions between numerosity and size (which underlie the congruency effects) take place at the level of stimulus evaluation, before response selection or preparation of competing response tendencies (Cohen Kadosh et al., 2007; Schwarz & Heinze, 1998; Szucs & Soltesz, 2008). Together these results are consistent with a functionally uniform magnitude processing system, perhaps based in posterior brain areas, on which magnitudes of different sorts would converge. Gebuis et al. (submitted a) revealed that these early interactions not only hold for symbolic but also non-symbolic notation (dots), which agrees well with the hypothesis that the neural mechanisms that at first subserve non-symbolic numerosities have become responsive to the later acquired number symbols.

A neural mechanism underlying the transition from a non-symbolic to symbolic numerosity system was suggested in a recent primate study. Rhesus monkeys were trained to learn the association between the number symbol and the number of dots the symbol represents (Diester & Nieder, 2007). At several intervals, recordings of both prefrontal and parietal cortex were made. The neurons in the prefrontal cortex were active for both the symbolic and non-symbolic code whereas the neurons in the parietal cortex only responded to non-symbolic notation. This result fitted well with the idea that the frontal cortex mediates recently acquired associations; a shift towards parietal neurons can only be expected after substantial training. Similarly, results from imaging studies, looking at functional-anatomical correlates of distinct number processes, in children that are familiar with the number symbols, revealed such a reliance on frontal instead of parietal processes (Ansari et al., 2005; Kaufmann et al., 2006; Rivera et al., 2005).

The present study

The current study compared children (2nd grade, 6.0 years) who had just become acquainted with symbolic numerosity, children (4th grade, 8.0 years) who had worked with symbolic numerosity for about 2 years, and adults, on measures of size congruency effects (SCE) for symbolic as well as non-symbolic numerosity. We included both tasks to allow disentangling task related processes from processes specific to number notation. The first question was whether especially the youngest children exhibited behavioral manifestations of automatic symbolic-number representation access, as manifest in an SCE on performance for number symbols (Gebuis, Cohen Kadosh, de Haan, & Henik, 2008). The second question was whether a behavioral SCE for children is due to the same mechanisms as for adults. Specifically, we asked whether, for these children, behavioral SCEs are paralleled by SCEs during stimulus-evaluation time and precede selective response activation. If this were the case for both symbolic and non-symbolic numerosity (as it is in adults, Gebuis, Kenemans, de Haan, & van der Smagt, submitted a), this would be consistent with an early interaction between both symbolic and non-symbolic numerosity on the one hand, and size representation on the other. A differential involvement of neural processes in the younger versus the older children or adults in the symbolic but not the non-symbolic task would reveal the neural processes involved in the initial stages of the automatization of symbolic number knowledge.

To investigate the neural mechanisms subserving the automatization process, we measured Event Related Potentials (ERPs) during both experiments. We especially looked at the P3 latency and the lateralized readiness potential (LRP). A later onset of the P3 peak as well as the stimulus locked LRP is indicative of a conflict that arises before response selection or execution. (Donchin, 1981; Kutas et al., 1977; McCarthy & Donchin, 1981; Smulders et al., 1995). Secondly, we addressed whether developmental differences in the interaction between the various numerosity dimensions reflect differences in facilitation or rather interference between dimensions. Thirdly, we explored such differences with respect to more general conflict-processing mechanisms (using the incongruent minus congruent contrast for ERP amplitude), as it may be suspected that children rely on such mechanisms in a manner different from adults.

EXPERIMENTAL PROCEDURE

Participants

Three groups of subjects participated in the experiment: (1) nineteen second grade children of which fifteen were included in the analyses (M = 6.0 years, SD = 0.26, 10 males), (2) twenty-three fourth grade children of which nineteen were included in the analyses (M = 8.1 years, SD = 0.36, 8 males) and (3) twenty adults of which seventeen were included in the analyses (M = 22,5 years, SD = 1.52, 6 males). The children and adults were recruited from the Utrecht area in the Netherlands. As indicated by school grades, the children included in this study revealed different levels of performance (from below average to excellent), and the adults had completed different levels of higher education. The children received presents for participation while the adults were paid. Only children that had symbolic number knowledge as indicated by their performance on a symbolic number comparison task, were selected. All participants were native Dutch speakers and had normal or corrected-to-normal vision. Written informed consent was obtained according to the Declaration of Helsinki and as approved by the Ethical Committee of the University of Utrecht.

Apparatus, stimuli and procedure

For the adults, the stimuli were displayed on a 22-inch CRT monitor using the Presentation software (Neurobehavioral Systems, Albany, CA). The paradigm was similar to a previous study (Gebuis, Cohen Kadosh, de Haan, & Henik, 2008). For the children we used a 17-inch Asus laptop.

For the symbolic size congruency task, the stimuli consisted of Arabic numbers ranging from 1 to 9, which were presented in pairs with a small (1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-8, 8-9) or large numerical distance (1-6, 2-7, 3-8, 4-9). Depending on the condition numbers were presented in a small font size (1.7°) or a large font size (2.4°). For the non-symbolic size congruency task the stimuli consisted of groups of dots ranging from 7 to 16, which were randomly distributed within a pre-specified area (width and height of 3.05°). This relatively large number of dots is used to rule out possible subitizing effects. Depending on the condition, small (0.38° in diameter) or large dots (0.53° in diameter) were presented. Again, two numerical distances were used, a small numerical distance of 4 (7-11, 8-12, 9-13, 10-14, 11-15, 12-16) and a large numerical distance of 7 (7-14, 8-15, 9-16). To exclude the possibility that the participant derived the correct answer on the basis of visual sensory properties, these were controlled for in several ways (see Gebuis, Cohen Kadosh, de Haan, & Henik, 2008 for details). The stimuli were presented centrally on a grey background and the viewing distance was approximately 57 cm. In order to keep the children focused, we added ten cartoon pictures, which appeared at pre-defined intervals throughout the experiment. The children were told that the task ended as soon as they "found" the tenth picture, which was always presented at the end of each task.

For both the symbolic and non-symbolic comparison task subjects were instructed to respond to the physical size of the stimuli by pressing the button corresponding to the side of the physically larger stimulus. The correct answer appeared on the left side in half and on the right side in the other half of the trials. Both tasks consisted of a congruent (96 trials), an incongruent (96 trials) and a neutral condition (48 trials). The congruent and incongruent condition consisted of (48) small and (48) large numerical distance trials. For each age group, the order of the two comparison tasks was counter balanced between participants. Each trial began with a random inter trial interval (1250-1500 ms), followed by a fixation cross (500 ms) and the stimuli (until response). Prior to each comparison task participants received instructions and performed 15 practice trials. After each comparison task participants could take a break.

Electrophysiological recordings

EEGs were recorded from 64 scalp electrodes according to the International 10/20 EEG system (sampling rate of 2048 Hz) using the Active Two system (BioSemi, Amsterdam, The Netherlands) (for an explanation about the system see www.biosemi.com or Schutter et al. (2008). The vertical electro-oculogram (VEOG) was recorded from electrodes attached above and below the left eye and the horizontal electro-oculogram (HEOG) from the outer canthi of both eyes.

ERP preprocessing

Participants were discarded from both the ERP and the behavioral analyses when more than 25% of the trials contained artefacts. This resulted in the exclusion of three second and four fourth grade children and three adults. EEG and EOG data were analyzed using Brain Vision Analyzer software (1.05). Flat as well as noisy electrodes were discarded and consequently not included in the analyses. EEG signals were off-line re-referenced to the average of all included electrodes. The continuous EEG data was segmented into epochs from 100 ms prior until 1200 ms after target presentation. Epochs were filtered with a bandpass filter (0.3 Hz, 12dB octave; 40Hz, 24dB/octave;

50Hz Notch Filter) and corrected for eye movements according to the Gratton, Coles et al. algorithm (1983). Trials with artefacts (maximum or minimum of ±125μV for the children and ±80μV for the adults) or an incorrect response were rejected from further analyses. The baseline for the stimulus locked ERPs was defined as the mean of the 100 ms period before the onset of the target stimulus. The baseline for the response locked LRPs was -550 to – 450 ms. Grand average ERPs and LRPs were created for each condition and filtered at 8Hz, 12dB/octave for visualization purposes only.

Behavioral and ERP analyses.

For the behavioral data, accuracy and the median reaction times of the correct responses were calculated. For the ERP analyses, we estimated the P3 component at the Pz electrode, which is defined as the largest peak within the time window of 300-800 ms for adults but 300-1000 ms for the children since they revealed a much larger spread in the timing of the P3 component. The stimulus and response locked lateralized readiness potentials (sLRP and rLRP, respectively) were computed by subtracting the electrode ipsilateral to the response hand from the electrode contralateral to the response hand. Subsequently, the obtained difference waves for both hands were averaged ((C3-C4 + C4-C3) / 2)[1]. As recommend by Miller, Patterson, & Ulrich (1998) the relative criterion method was applied to each subsample waveform using the 50% criterion to obtain the sLRP onset and 90% for the rLRP onset. The electrophysiological data of the second graders revealed congruency effects at left frontal electrode sites (FC3, C5, C3), which were not present for the fourth graders and adults therefore no comparable analyses were performed for the latter age groups. These positive peaks around 200 ms correspond to the P2 component and were quantified as the largest peak within the time window of 180-300 ms.

A substantial difference can be expected in the time needed to process the information in children compared to adults. One way to account for this difference in both behavioral and electrophysiological response for each age is by dividing the results of the congruent and incongruent conditions by those of the neutral condition. In this manner, any interaction with group cannot be the explained by the overall difference in the timing of the response or electrophysiological process. To test whether a congruency effect was present for each group and whether this congruency effect was distinct for symbolic compared to non-symbolic notation we performed a repeated measures ANOVA with NOTATION (symbolic / non-symbolic) x CONGRUENCY (congruent / incongruent) x DISTANCE (small / large) as within subject factors and GROUP (second grade / fourth grade / adults) as a between subjects factor. If present, three or four-way interactions were further investigated using a simple effects analyses for each task separately. The presence of congruency effects led us to perform post hoc paired samples T-tests between neutral and congruent or incongruent trials to investigate whether the congruency effect is the result of a facilitation and/or interference, respectively.

RESULTS

Results number comparison task second graders

One child responded at chance level and was discarded from further analyses. The remaining children (N=15) showed an accuracy score of 92.5%. Moreover, they responded faster to [t(1,14) = 6.397, p < 0.001] and were more accurate [t(1,14) = -3.833, p = 0.002] in large compared to small numerical distance trials (1347 ms / 98% versus 1791 ms / 87%, respectively). These results

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[1] One out of the nineteen fourth graders was not included in the LRP analyses due to a missing electrode (C4)

are indicative of the presence of number symbol knowledge. Consequently, any absence of a congruency effect in the behavioral or ERP data on the symbolic comparison task can not be due to insufficient knowledge of the number symbols. Instead, a not yet fully automated link between the number symbols and their meaning would be a more plausible explanation.

Accuracy results size congruency tasks (Figure 1a)

Repeated measures ANOVA: All main effects were significant [$F(2,48) > 14$, $p < 0.001$]. Except for the two-way interaction of notation and distance, all two and three-way interactions were significant [$F(2,48) > 3.243$, $p < 0.048$]. The three-way interactions were due to a significant congruency effect for all age groups for the symbolic [$F > 4.10$, $p < 0.05$] and only for the adults for the non-symbolic size congruency task [$F(1,16) = 4.36$, $p = 0.041$]. A trend towards significance was present for second graders [$F(1,14) = 3.91$, $p = 0.053$] and congruency effect was present for fourth graders [$F(1,18) = 3.05$, $p = 0.085$]. In addition, the results of the adults for the symbolic comparison task also revealed a distance effect [$F(1,15) = 44.28$, $p < 0.001$] and an interaction between distance and congruency [$F(1,15) = 7.69$, $p = 0.007$].

Facilitation and interference: For the symbolic task, an interference effect was present for all age groups and both numerical distances [$t > 2.4$, $p < 0.03$], but no facilitation was observed [$t < -1.0$, $p > 0.3$]. For the non-symbolic task, a significant interference effect for the large distance was present for the second graders [$t = 2.792$, $p = 0.014$] as well as the fourth graders [$t = 2.805$, $p = 0.012$]. The adults however, revealed only a trend towards significance for large numerical distance interference [$t = 1.874$, $p = 0.079$]. Again for all age groups no facilitation effects were present [$t < -1.0$, $p > 0.3$].

Reaction time results congruency tasks (Figure 1b and 1c)

Repeated measures ANOVA: Again, all main effects were significant [$F(2,48) > 4$, $p < 0.04$]: subjects were faster to compare physical sizes of number stimuli when they were separated by a small compared to a large numerical distance and congruent trials were responded to faster than incongruent trials. Distance and congruency interacted, reflecting a larger congruency effect for stimuli with a large compared to a small numerical distance [$F(2,48) = 125.792$, $p < 0.001$]. Furthermore, congruency, notation and group interacted [$F(2,48) = 11.489$, $p < 0.001$]: for symbolic notation, the congruency effect increased with age but for the non-symbolic notation, the congruency effect decreased with age (Figure 1b). Congruency, notation, distance and group interacted [$F(2,48) = 6.145$, $p = 0.004$]. Simple effect analyses revealed that a significant congruency effect was present for all age groups in the symbolic [$F > 20$, $p < 0.001$] and non-symbolic size congruency task [$F > 51$, $p < 0.001$]. However, except for the second graders, an interaction between congruency and distance was shown for the symbolic [$F > 7$, $p < 0.006$] size congruency task. On the non-symbolic size congruency task, the interaction was again present for all age groups [$F > 5$, $p < 0.025$].

Facilitation and interference: For the symbolic task, interference effects were present for the small and large numerical distances in all age groups [$t < -4.0$, $p <0.002$]. In contrast, the facilitation effect that was only significant in adults for both numerical distances [$t > 2.5$, $p < 0.02$], emerged for fourth graders as here the effect approached significance only for large numerical distances [$t = 2.077$, $p = 0.052$], and not present in second graders [$t > 1.0$, $p > 0.29$]. For the non-symbolic task, a significant facilitation [$t > 2.5$, $p < 0.03$] as well as interference effect [$t < -2.8$, $p < 0.02$] was obtained for each numerical distance and age group although facilitation in the small numerical distance condition only showed a trend towards significance [$t(15) = 1.960$, $p = 0.068$] for adults.

Surprisingly, the automatization process that becomes more apparent for symbolic notation with increasing age appears to decrease with age for non-symbolic notation (Figure 1b) as reflected by a marginal significant triple interaction between congruency, task and group [F(2,48) = 3.105, p = 0.056].

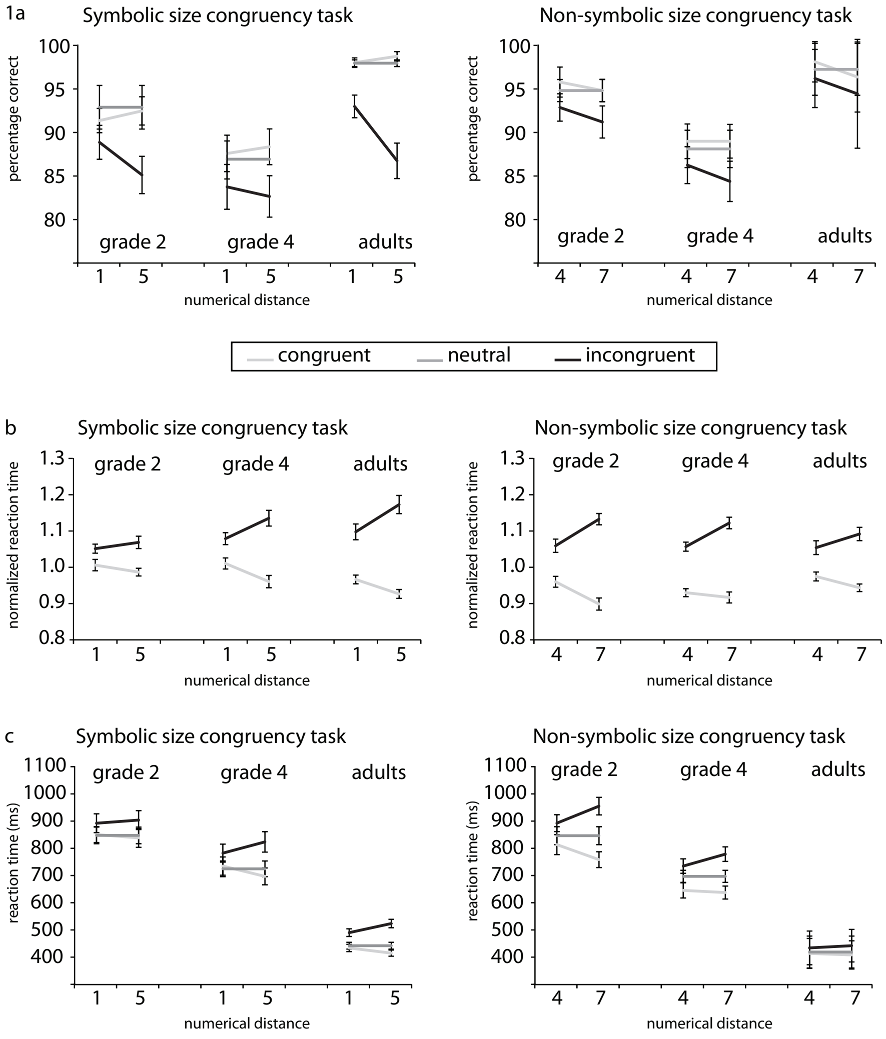

Fig. 1. The accuracy results (a), the normalized reaction time results (b) and the reaction time results (c) of the symbolic (left panels) and the non-symbolic (right panels) size congruency task. Within each panel, the results of the second and fourth grade children and adults are presented from left to right. A congruency effect is present for both tasks and each age group showing less errors (a) and faster responses (b and c) for the congruent compared to the incongruent trials. Of especial interest is the fact that the congruency effect increased with increasing age for the symbolic size congruency task but decreased with increasing age for the non-symbolic size congruency task (b).

P3 latency analyses of the congruency tasks (Figure 2)

Repeated measures ANOVA: A significant congruency main effect [F(2,48) = 69.117, p < 0.001] was obtained. The P3 peaked around an earlier point in time for congruent compared to incongruent trials. This congruency effect interacted with notation [F(2,48) = 10.921, p = 0.002], possibly as a result of the overall larger congruency effects in the non-symbolic compared to the symbolic task. A three-way interaction was present for notation, congruency and group [F(2,48) = 6.337, p = 0.004]. Similar as in the behavioral results, the congruency effect increased with age for symbolic notation but decreased with age for the non-symbolic notation. Simple effects analyses revealed a congruency effect for the symbolic task [F > 5, p < 0.03] in all groups but the second graders. In contrast, all age groups revealed a congruency effect on the non-symbolic task [F > 7, p < 0.01].

Facilitation and interference: On the non-symbolic task, the congruency effect for second graders was the result of large numerical distance interference [t(1,14) = -3.085, p = 0.008] (note that no congruency effects were present for second graders on the symbolic task thus neither facilitation nor interference can be established for this condition). For fourth graders, the origin of the congruency effect in the symbolic task was large numerical distance interference [t(1,18) = -2.892, p = 0.010] whereas in the non-symbolic task it was both large numerical distance facilitation [t(1,18) = -2.901, p = 0.010] and interference [t(1,18) = -2.991, p = 0.008]. For the adults in the symbolic task, the congruency effect was due to the small [t(1,15) = 2.146, p = 0.048] and large numerical distance interference [t(1,15) = -1.933, p = 0.071]. In the non-symbolic task there was significant small distance facilitation [t(1,15) = 2.141, p = 0.048] and large distance facilitation [t(1,15) = 1.926, p = 0.072] as well as interference [t(1,15) = -2.554, p = 0.021].

LRP onset latency analyses (Figure 3)

Repeated measures ANOVA: for the sLRP data (Figure 3a) a significant congruency effect was present [F (1,47) = 81.257, p < 0.001]. This congruency effect interacted with group [F (2,47) = 3.924, p = 0.027] suggesting that the congruency effect was of distinct size for the different age groups. Possibly due to a smaller congruency effect for symbolic notation for the children compared to adults. An interaction between notation and congruency [F (1,47) = 6.003, p = 0.018] was obtained as well indicating that the congruency effect was overall larger in the non-symbolic compared to the symbolic task. The interaction between congruency and distance was also significant [F (1,47) = 15.726, p < 0.001]: with increasing distance, the congruency effect increased. No significant results were obtained for the rLRP onset latency data [F < 2.353, p > 0.10] (Figure3b). For sLRP, simple effects analyses revealed, for the symbolic task, a trend towards significance for the second graders [F (1,14) = 3.45, p = 0.069] and fourth graders [F (1,17) = 3.09, p = 0.084] and a highly significant effect for adults [F (1,16) = 21.64, p < 0.001]. For the non-symbolic task a significant congruency effect [F > 4.03, p < 0.05] was present for all age groups.

Congruency effects at left frontal electrode sites (second grade children; Figure 4)

For the second graders only, no P3 latency effect was present for symbolic notation. sLRP onset latency effects, however, suggest that the conflict (as manifested in the behavioral data) did arise at a pre-motor level. Visual inspection of the ERP-signals revealed that the second graders recruited distinct processes as reflected by amplitude effects of the P2 component at left frontal electrode sites. A significant congruency effect [t(1,14) = 7.088, p = 0.019] for the symbolic but not for the non-symbolic task was obtained [t(1,14) = 0.275, p = 0.608].

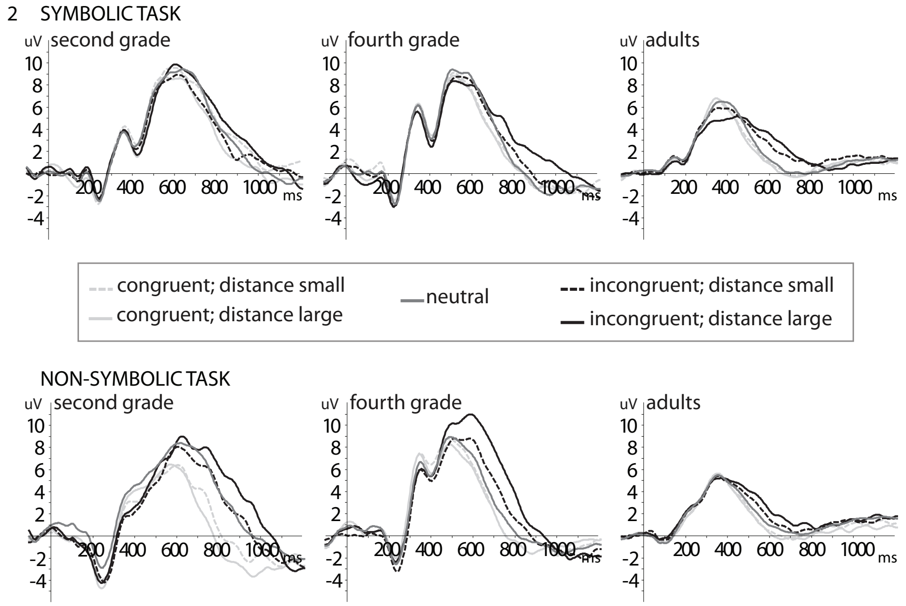

Fig. 2. The P3 component at the Pz electrode. From left to right the ERP grand average waveform at the Pz electrode is presented for second and fourth graders and adults. The upper panels reveal the results of the symbolic congruency task whereas the lower panels represent the results of the non-symbolic task. Except for second graders for the symbolic size congruency task, the P3 peaked around a later point in time in the incongruent compared to the congruent condition. Similar to the behavioural results the congruency effect as reflected by P3 latency increased with increasing age for symbolic notation but decreased with increasing age for non-symbolic notation.

DISCUSSION

In this study we sought to identify the neural mechanisms underlying the development of automated symbolic number knowledge. We first asked whether children of different age groups would show SCE effects for symbolic and non-symbolic numerosity processing. A second question was whether these SCE effects would reflect similar neural interactions for children as for adults. Thirdly, we hypothesized that children who have only just learned the Arabic number symbols recruit additional processes compared to subjects that have more experience with the Arabic numbers.

To summarize the results: on the behavioral level, (1a) for all age groups and both tasks a congruency effect was present. (1b) In the symbolic and non-symbolic task, the congruency effect consisted of both an interfering and a facilitory component of which the latter became apparent with increasing age. (1c) On the symbolic task, the congruency effect increased with increasing age but on the non-symbolic task, the congruency effect decreased with increasing age. On the electrophysiological level, (2a) *except for the second graders on the symbolic task,* all age groups

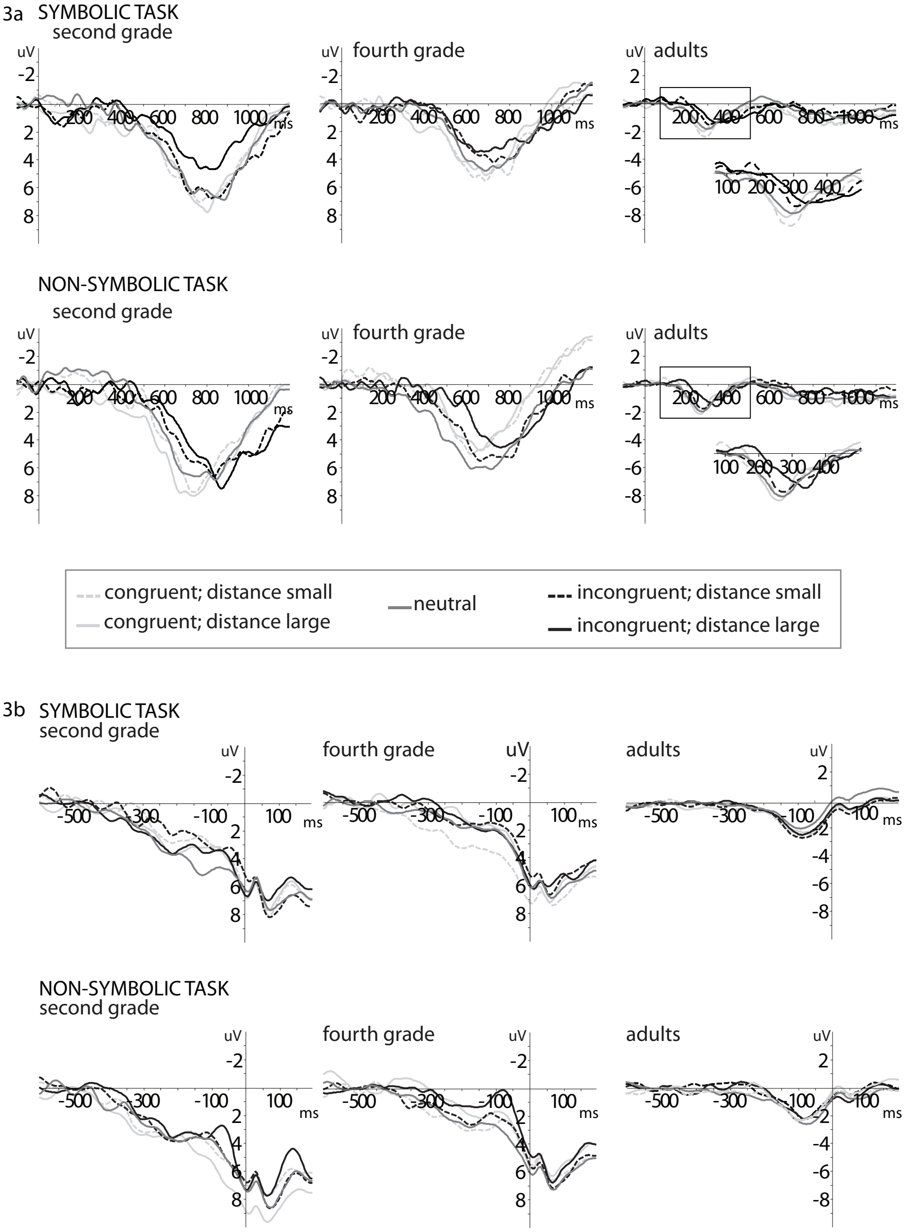

Fig. 3. The stimulus (a) and response locked (b) LRPs. The sLRPs showed an onset latency effect in both the symbolic and non-symbolic task for all age groups. For the adults a close-up of the onset latency effect of the sLRP is given as well. (a). The onset of the incongruent condition started around a later time point compared to the congruent condition. The rLRPs do not reveal an onset latency effect in the symbolic and non-symbolic task for any of the age groups (b).

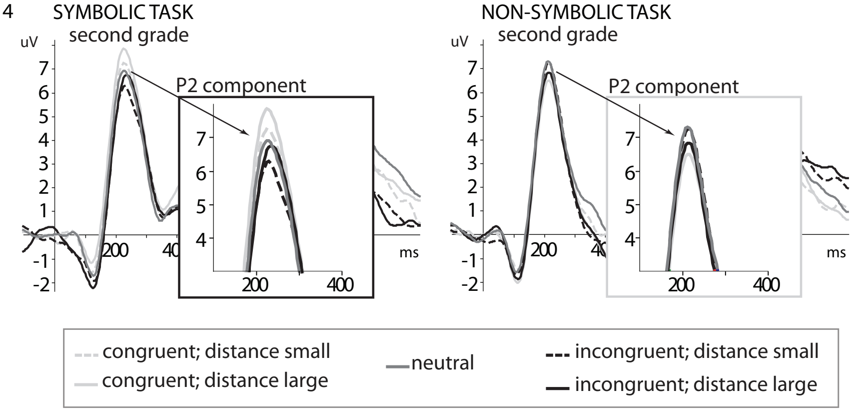

Fig. 4. The pooled data of left frontal electrodes of second grade children. For the second graders the recruitment of additional processes was apparent since only in this age group left frontal electrodes revealed congruency effects. A congruency effect was present for the peak amplitude of the P2 component for the symbolic (left panel) but not the non-symbolic task (right panel).

revealed a P3 latency effect on both tasks. (2b) The congruency effect was once more the result of both an interfering and an emerging facilitatory component, (2c) SCE effects were only present for sLRP, not for rLRP onset latencies, (3) of special interest was the recruitment of left-frontal processes by second graders. A congruency (amplitude) effect was present at the amplitude of the P2 component in the symbolic but not the non-symbolic size congruency task.

The development of the size congruency effect at the behavioral level

A behavioral congruency effect in both the symbolic and non-symbolic size congruency task suggests automated number knowledge, already for the second graders. Such an early SCE for both notations has not been reported before for European children (Gebuis, Cohen Kadosh, de Haan, & Henik, 2008 (5.6 years); Girelli et al., 2000 (8.3 years); Rubinsten et al., 2002 (7.3 years)), although it has been for Chinese children (Zhou et al., 2007 (5.8 years)). The large age range reported at which automatic access to number symbol meaning emerges has led to suggestions about the cause of this diversity. Zhou et al. (2007) proposed that Chinese children have several cultural advantages: Chinese numbers need less pronunciation time and are more incorporated in daily life (e.g. days of the week). The second graders in our current and in our previous study were recruited from the same city. In contrast to our previous study (Gebuis, Cohen Kadosh, de Haan, & Henik, 2008), the children of the current study revealed congruency effects, a discrepancy in results, which clearly cannot be explained by cultural differences. We propose instead that the differences in onset of automatic access to number symbol meaning is highly related to informal or parental schooling in addition to formal schooling; another relevant factor may be that the present second graders were on average 5 months older.

When number knowledge is fully automated, a congruency effect consists of both a facilitory and an inhibitory component. In the symbolic task, the interference component was present but the facilitory component gradually developed with age. In contrast, in the non-symbolic task, the facilitory and inhibitory effects were present from second grade onwards. The later emergence of facilitory effects in the symbolic task indicates that the link between the number symbol and its meaning is not fully automated yet in children that just gained understanding of the number symbols. This notion is further emphasized by the fact the youngest children in our study did not show an interaction between congruency and distance in the symbolic task, while this interaction was clearly apparent in the non-symbolic task. Together, even though all age groups revealed a congruency effect for both the symbolic and non-symbolic task, the lack of a facilitory effect as well as the lack of an interaction between distance and congruency for second graders hint at an automatization process that is not fully developed yet.

The neurophysiological correlates underlying the size congruency effect at distinct ages

While the children and adults revealed comparable behavioral results on the symbolic and non-symbolic numerosity task, the electrophysiological correlates revealed a clear distinction between both tasks, but again for the second graders only. For both fourth graders and adults, an SCE was present for P3 latency on both the non-symbolic and symbolic task. The second graders revealed a congruency effect for non-symbolic notation only. In addition, for all age groups, a sLRP but no rLRP onset latency effect was shown in both the symbolic and non-symbolic task implying that the conflict arose before motor processes were activated, at an “early stimulus level”. Thus, for second graders, the SCE present in the reaction time data of the symbolic task was not paralleled by P3 latency even though the conflict between both magnitudes should have arisen at a pre-response level. Instead of a P3 latency effect in the symbolic task, a congruency (amplitude) effect was present at the amplitude of the anterior P2 component. The P2 component is suggested to relate to the evaluation of task relevant stimuli but not to orienting of attention or preparation and execution of motor responses (Potts, 2004) and is as such suggested to be comparable to the P3 wave (Luck, 2005). This anterior congruency effect could only arise when number was accessed automatically explaining the congruency effects obtained at the behavioral level.

The increase in symbolic SCE but the decrease in non-symbolic SCE

Even though the behavioral and electrophysiological (P3 latency) congruency effects were present for all age groups as well as the symbolic and non-symbolic task, the effects appeared to increase with increasing age for the symbolic notation while the opposite pattern appeared for non-symbolic notation. This is a remarkable effect since it is argued that the symbolic congruency effect decreases with age as a result of developing inhibitory mechanisms (Szucs et al., 2007). These contradictory results can easily be explained. In contrast to the Szucs et al. (2007) study, we normalized our reaction times to account for the overall difference in response times between children and adults. Normalization of the data of the Szucs et al. (2007) study results in a comparable increase in interference effect as obtained in our study.

However, the question remains what caused, in our study, the opposite patterns in the development of the symbolic and non-symbolic size congruency effect. One perspective is that until the age that children are taught about the symbolic numbers they are mainly confronted with non-symbolic notation but as soon as the symbolic notation is mastered this notation is predominantly used, as it allows more precise calculations and is necessary for everyday activities. The lack of continued training and thus the decreased utilization of the structures subserving non-symbolic numerosity processing could well account for the reduction of non-symbolic SCE with increasing age. This hypothesis is in agreement with a study reporting reduced adults’ sensitivity to numerosity changes, compared to what is known from infants (Gebuis, Kenemans, de Haan, & van der Smagt, submitted b). Furthermore, as stated above, it can be suggested that the decrease in non-symbolic congruency is the result of the development of inhibitory mechanisms. Indeed, interference effects are often reported to be stronger in children than in adults, although the extent of this interaction is dependent on the type and complexity of the task (Gerstadt et al., 1994; Hanauer & Brooks, 2005; West et al., 2004; Wright et al., 2003). Children's inhibitory mechanisms develop most rapidly between 3.6 and 6.0 years (Gerstadt et al., 1994; Wright et al., 2003) and are expected to be on the same level as adults around the age of twelve (Durston & Casey, 2006). For symbolic notation then, the congruency effect would reflect the combined contributions of the increase in automatization of symbolic number knowledge, and the increase in the efficacy of inhibitory mechanisms with advancing age.

The mechanisms underlying the recruitment of additional processes

The non-symbolic size congruency task was included in the experiment to allow a direct comparison with the symbolic task; to disentangle general-task and numerosity related processes. On a behavioral level, the second graders revealed both facilitation and interference for non-symbolic notation, but only interference for symbolic notation. On the neuronal level, a P3 latency effect was present in the non-symbolic task but not in the symbolic task. Instead, in the symbolic task, the congruency effect modulated the anterior P2 amplitude suggesting the recruitment of distinct processes.

Our results are in line with previous neuroimaging studies reporting a shift from frontal to parietal areas of processes related to automated symbolic number processing (Ansari et al., 2005; Kaufmann et al., 2006; Rivera et al., 2005). Two hypotheses have been raised to explain this ontogenetic shift. First, increased automatization of Arabic symbol knowledge could result in less reliance on attentional and working memory processes (Ansari et al., 2005). Our results contradict this first hypothesis. If the second graders in our study recruited distinct resources because of the increased attentional or working memory load for the number symbols compared to the dots, it should have been reflected in prolonged reaction times or less accurate responses in the symbolic but not the non-symbolic task. Even though this was not the case[2] it could still be argued that similar behavioral responses do not exclude the recruitment of different resources for the distinct cognitive processes involved (attention or working memory) (Cohen Kadosh et al., 2008). The ERP results revealed no differences in the timing of the P3 peak or its amplitude[3] excluding the first hypothesis as a potential explanation of the results. The second hypothesis holds that the parietal cortex might not be functionally specialized for the processing of numerical magnitude in second graders yet (Ansari et al., 2005). Our results together with an earlier study revealing IPS involvement in non-symbolic numerosity processing in 4-year olds (Cantlon et al., 2006) suggest that the parietal cortex is already specialized for non-symbolic but not symbolic magnitude. This parietal functional specialization is probably directly related to the level automatization of symbolic number processes.

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[2] Post hoc analyses did not reveal a significant difference between the behavioral or accuracy results of the symbolic and non-symbolic task in the second graders (symbolic 853 ms / 94% correct; non-symbolic 860 ms / 90% correct).

[3] Post hoc analyses did not reveal a significant difference between the P3 latency or amplitude data of the symbolic and non-symbolic task in the second graders (symbolic 853 ms / 12µ; non-symbolic 860 ms / 10.5µ)

In conclusion, this study reveals the development of automated number symbol knowledge, which is contrasted with automated non-symbolic number knowledge. First, we demonstrate that automatic access to number symbol meaning can already be present in second graders (6.0 years). We propose that instead of cultural influences the diversity in informal as well as formal teaching determines the onset time of the congruency effects and thus explains the large range in onset times reported. Second, for all age groups and both tasks the magnitudes interacted at the stimulus evaluation level, before motor preparation or execution. Third, second graders recruited distinct processes in the symbolic task only. This suggests that the ontogenetic shift from frontal to parietal areas is due to increased automatization of Arabic number knowledge, which underlies the functional specialization of the parietal areas. Fourth, the demonstrated congruency effects increased in size for the symbolic but decreased for the non-symbolic task. However, further research is needed to disentangle the origins and mechanisms underlying these diverging developmental processes.

CHAPTER 5

NUMEROSITY DETECTION AND ITS NEURAL CORRELATES

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Submitted

ABSTRACT

In the present study we sought to identify electro-cortical responses related to numerosity processing in human adults. Specifically, we investigated whether these electro-cortical correlates were sensitive to proportional, rather than absolute numerosity, as is the case with infants when probed in looking-time paradigms. A visual oddball paradigm with varying ratios and set sizes between number standards and deviants was used while event-related potentials (ERPs) were recorded. In a first passive oddball experiment, a positivity at left frontal electrode sites (latency 250-300 ms) decreased with repeated presentation of the standard numerosity ('habituation'), and recovered in response to a 2.0, but not a 1.5 ratio deviant. In a second active oddball task, performance data revealed that adults could detect ratio changes of both 2.0 and 1.5. In contrast, the oddball effect on left frontal electrodes between 250-300 ms latency was again found for a 2.0 ratio deviant only. Thus, numerosity specific responses were obtained that reflected the ability to detect changes in numerosity in adults. Like in infants, adult numerosity processing is sensitive to proportional rather than absolute numerosity. Adults could actively detect numerosity changes with a ratio 1.5 and ratio 2.0. This effect however, was not reflected in the electro-cortical responses in the passive or active oddball task.

INTRODUCTION

Adults can perform complicated numerical calculations. The question of how this ability develops is at the core of the study of numerical cognition. Is there an innate magnitude system or is the acquisition of language abilities a prerequisite? A strong resemblance between the mechanisms underlying both infant and adult numerosity processing can be interpreted as evidence in favor of a magnitude system already present at infancy. Several studies have investigated numerosity processing in infants (e.g. Brannon, 2002; Feigenson et al., 2004; Jordan et al., 2008; for a review see Feigenson, 2005; Xu et al., 2005) as well as adults (e.g. Ansari, Dhital, & Siong, 2006; Barth et al., 2003; Libertus et al., 2007; Piazza et al., 2007; Pinel et al., 2004; Temple & Posner, 1998; van Oeffelen & Vos, 1982) but the paradigms used in these studies appear too distinct to enable a direct comparison between these groups. With the present study we aim to identify the electro-cortical responses specifically involved in adult numerosity processing, using event related potentials (ERPs), and investigate whether the adult numerosity system depends, similar to that of infants, on ratio and not set size information. We employ a (passive) paradigm of which the results can be more easily compared to those used in many infant studies.

A paradigm commonly used to study the infants' cognitive abilities, including their number sense, is the so-called 'looking-time' paradigm. In such tasks, a stimulus with the same numerosity content (often called a 'standard') is presented repeatedly, which results in a decrease in time spent looking at the stimulus (a phenomenon called 'habituation'). The presentation of a stimulus with a distinct numerosity, subsequently results in a looking-time increase. Such a decrease and increase in looking time can only be obtained if the infant is capable of detecting the number-deviant stimuli among the standards. Recent habituation studies revealed that six-month-old infants look longer to numerosity changes when the quantities are above the subitizing range (e.g. 16 versus 32 dots) (McCrink & Wynn, 2007; Xu & Spelke, 2000; Xu et al., 2005) suggesting that the ability to detect numerosity changes has already developed in the first months of life. This 'response' to changes in numerosity depends on the relative (ratio) but not the absolute (set size) numerical distance of the numerosity change (Xu et al., 2005) and increases in precision with age (Brannon et al., 2007; Lipton & Spelke, 2003; Wood & Spelke, 2005). Since such a magnitude system appears to be present already at infancy, it is reasonable to expect that adults detect changes in numerosity in a similar way, i.e. depending on ratio, not set size. Moreover, numerosity change detection in adults should be as accurate as, or even more accurate than that in infants.

Van Oeffelen & Vos (1982) reported that adults can discriminate large numerosities more precisely than infants can (at a ratio limit of 1.14) while Barth et al. (2003) revealed that the reaction times to numerosity judgments are related to ratio and not set size. Although these studies indeed show that the numerosity comparison mechanisms are ratio dependent and more precise than those of infants, their results cannot easily be compared to those of infant studies . First, in the study of van Oeffelen et al. (1982), the continuous variables present in the stimuli were not controlled for. Second and more importantly, these studies used two-alternative-forced-choice paradigms, in which subjects have to discriminate numerosities by means of same-different or larger-smaller judgments. In contrast, conclusions about infants' numerosity discrimination capabilities are invariably based on variations in looking time as observed in passive conditions, without any explicit task instruction. These task differences might lead to substantially different results. To be able to readily compare adult and infant results, a passive task for adult subjects appears a better alternative. Several imaging studies have indeed investigated non-symbolic numerosity processing in adults using a passive paradigm and these revealed, for instance, areas selectively active for the numerosity of arrays of dots or squares (Ansari, Dhital et al., 2006; Piazza et al., 2007; Pinel et al., 2004). However, these studies did not contrast ratio and set size.

The current study therefore employed an oddball paradigm that included both set size and ratio conditions. Event-related potentials (ERPs) were used as a direct index of electro-cortical numerosity processing without the requirement of an overt response. During the experiment the subjects viewed a constant stream of stimuli consisting of squares (standards) that change in numerosity in 10% of the trials (number-deviants). If adult numerosity processing is comparable to that of infants we expect the following results: First, there should be electro-cortical activity that decreases with repeated presentation of the standard ("habituation") and increases in response to a number deviant stimulus ("recovery"). Second, similar to the looking-time performance in nine-month-old infants, the recovery effect is expected to be present for ratios 1.5 and 2.0. Third, the recovery effect should depend on ratio between the standard and deviant numerosity but not on absolute numerosity (i.e. set size, whether the deviant numerosity is larger or smaller than the standard numerosity).

While we think it more useful to compare adult results to those of infants when such a 'passive' paradigm is used, these results are less informative about adult numerosity processing capabilities as such, and the influence task demands (the usage of a detection instead of discrimination task) have on their performance. Therefore, the subjects performed the same experiment a second time but now instead of passive viewing (passive paradigm) they had to respond to the number deviant stimuli (active paradigm). The behavioral results of the active experiment are expected to be in line with the ERP results of the passive paradigm. The comparison of the ERPs of the two experiments will specifically reveal the effect of task instruction.

METHODS

Participants

Twenty subjects participated in the study. Eleven (aged between 21 and 29 years; M = 23, SD = 2.53; 6 female) participated in both the passive and active experiment and had less than 25% of trials containing artifacts. From six out of the eleven remaining subjects we were able to also record the EEG during the active experiment. All subjects were native Dutch speakers and had normal or corrected-to-normal vision. Written informed consent was obtained according to the Declaration of Helsinky and as approved by the local Ethical Committee of Utrecht University.

Apparatus, stimuli and procedure

The stimuli were presented on a 22-inch CRT monitor using the Presentation software (Neurobehavioral Systems, Albany, CA). The viewing distance was approximately 57 cm.

In this study we employed an oddball paradigm. The standards consisted of 12 squares and the number-deviant stimuli consisted of 6, 8, 18 or 24 squares. In this manner, we created two ratio conditions: ratio 1.5 (8 and 18) and ratio 2.0 (6 and 24) as well as two set size conditions: small set size (6 and 8) and a large set size (18 and 24). The squares were presented in black against a grey background and could appear on a random location, 3 degrees from the center of the screen. Both standards and number-deviant stimuli were presented for 200 ms and followed by a random inter trial interval of 1250 to 1500 ms (see Figure 1). In total, each experiment consisted of 1200 stimuli of which 10% was a number-deviant stimulus. The number-deviant stimuli were randomly presented and separated by at least three standard stimuli.

We controlled for the extensive (accumulated area and density) as well as the intensive parameters (individual item size and inter item spacing) (see Figure 1). To control for the extensive parameters we equaled the accumulated area of the number-deviant stimulus to the average accumulated area of the sequence of standards preceding it. This means that similar to previous studies (Cantlon et al., 2006; Izard, Dehaene-Lambertz, & Dehaene, 2008; Pinel et al., 2004), the more numerous deviant stimuli (18 and 24) consisted of physically smaller individual item sizes and smaller inter item spacing whereas the less numerous deviant stimuli (6 and 8) consisted of physically larger individual items and inter item spacing (these are the intensive parameters) when compared to the standards. However, the range of the intensive parameters used for the number-deviant stimuli still falls well within the range used for the standards. Consequently the only novel dimension in the number-deviant stimuli is number. We can therefore exclude that extensive or intensive parameters can explain results related to ratio or set size effects. On the contrary, if subjects do not process number information but instead the change in extensive or intensive parameters, this would yield null results. Dependence on the extensive parameters would result in similar responses across of stimulus conditions, since the extensive parameters change for each standard and number deviant stimulus. As a consequence, neither habituation nor recovery will be observed. Conversely, attending the intensive parameters would result in the absence of any habituation effect (since the intensive parameters change for each standard) and a reversed size effect (since the item size, when compared to those of the standards, is on average smaller for number-deviant stimuli of the large set size and larger for the number-deviant stimuli of the small set).

In the passive experiment, subjects were instructed to respond with the right index finger when the fixation cross changed from green to red (200 ms duration, random in 10% of the trials) to make sure the subjects focused on the screen during the experiment (Cantlon et al., 2006). In the active experiment subjects were instructed to respond with the right index finger when a change in numerosity was detected.

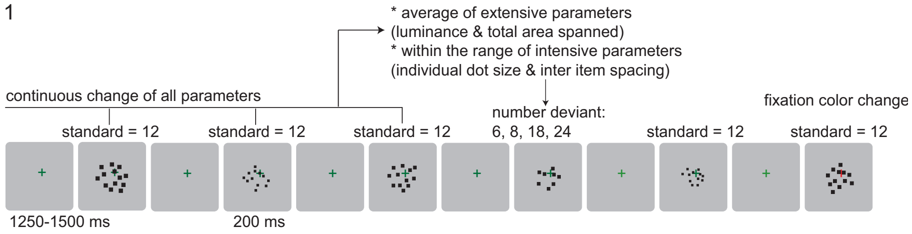

Fig. 1 Schematic representation of a stimulus sequence of the passive oddball paradigm. The active oddball paradigm was identical, except for the occasional change in color (from green to red) of the fixation cross. For the standards the extensive and intensive parameters continuously changed. The extensive parameters of the number-deviant stimulus were equated to the average of the extensive parameters of the sequence of the standards preceding it. The intensive parameters of the number-deviant stimulus were within the range of those of the preceding standards.

Electrophysiological recordings

The electroencephalogram (EEG) was recorded from 64 scalp electrodes according to the International 10/20 EEG system (sampling rate of 2048 Hz) using the Active Two system (BioSemi, Amsterdam, The Netherlands) (for an explanation about the system see www.biosemi.com or see methods section Schutter, de Weijer et al. 2008). The vertical electro-oculogram (VEOG) was recorded from electrodes attached above and below the left eye and the horizontal electro-oculogram (HEOG) from the outer canthi of both eyes.

Electrophysiological preprocessing

Participants were discarded from the ERP analyses when more than 25% of the trials contained artifacts. This resulted in the exclusion of seven subjects mainly as a result of large amounts of alpha activity. Two subjects were excluded because they did not participate in the second experiment. EEG and EOG data were analyzed using Brain Vision Analyzer software (1.05). Flat or noisy electrodes were discarded from further analysis. EEG signals were off-line re-referenced to the average of all electrodes. The continuous EEG data was segmented into epochs from 300 ms prior until 1000 ms after the presentation of the stimulus. Epochs were filtered with a bandpass filter (0.03 Hz, 12dB octave; 40Hz, 24dB/octave) and corrected for ocular artifacts according to the Gratton, Coles et al. (1983) algorithm. Trials with artifacts (difference criterion of 100μV within an epoch; low activity criterion of 0.5μV within a 100 ms time window) were rejected from further analyses. In the passive paradigm, the trials where the fixation color changed or a response related to this color change was given were discarded to exclude interference with the processes of interest. The baseline of the ERPs was defined as the mean of the 100 ms period before the onset of the standard or number-deviant stimulus. Grand average ERPs were derived for the first and the last standards of each sequence of standards as well as the ratio and set size conditions separately. The ratio conditions were pooled across set sizes whereas the set sizes were pooled across ratio conditions to increase power. For visualization purposes only the grand averages were subsequently filtered at 8Hz, 12dB/octave.

Analyses passive experiment

Scalp maps portraying the difference waves of the habituation effect (first standard – last standard), the ratio related oddball effect (ratio 2.0 deviant - last standard and ratio 1.5 deviant - last standard) and the set size related oddball effect (small set size deviant - last standard and large set size deviant - last standard) were used to select electrodes as well as the time periods of interest (see Figures 2 and 3). Mean activity amplitude per condition within each time window was calculated and subjected to a paired samples T-Tests to test the habituation, as well as ratio and the set size effects.

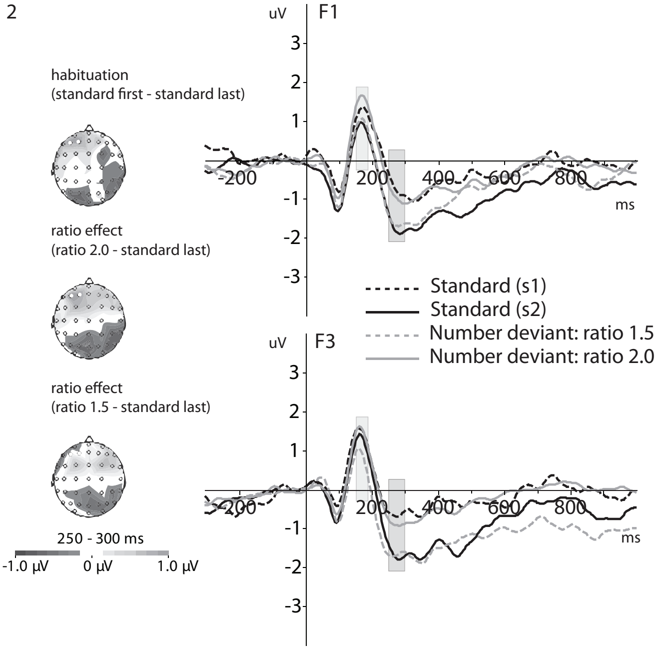

Fig. 2. (left panel): The difference waves of the scalp maps reveal a habituation effect (decreased activation for the last compared to the first standard) at the left frontal electrode sites F1 and F3 (white dots). (right panel): The electrophysiological responses at these electrode sites are presented revealing the habituation effect (compare bright line to dashed bright line) as well as an oddball effect (compare dark dashed line to bright line) for the large ratio condition (2.0). No significant oddball effect was found for the small ratio condition (1.5; compare dark line to bright line).

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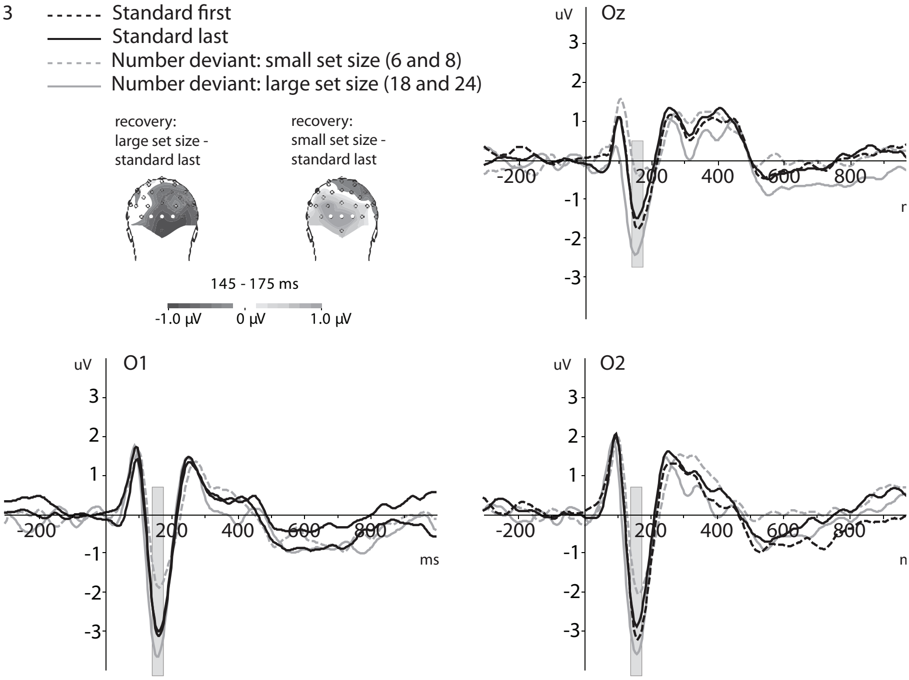

Fig. 3. The scalp maps reveal an early (oddball) effect at the occipital electrode sites (O1,Oz and O2; white dots) with larger peaks for the large set size conditions and smaller peaks for the small set size conditions when compared to the standard(s). No habituation effect was present in this time window at these electrode sites.

Analyses active experiment

For the ERP analyses we used the same electrodes and time windows as in the passive experiment to allow direct comparison between both experiments (see Figures 4 and 5). For the behavioral analyses we calculated the percentage of false positives (responses to the standards divided by the number of standards present in the study) and the percentage of hits (the number of correctly identified number-deviant stimuli divided by the total number of number-deviant stimuli) per ratio and set size condition (see Figure 6). To indicate whether subjects detected the number-deviant stimuli on the basis of ratio or set size we performed repeated measures ANOVA with ratio (2.0 and 1.5) and set size (small and large) as within-subjects factors.

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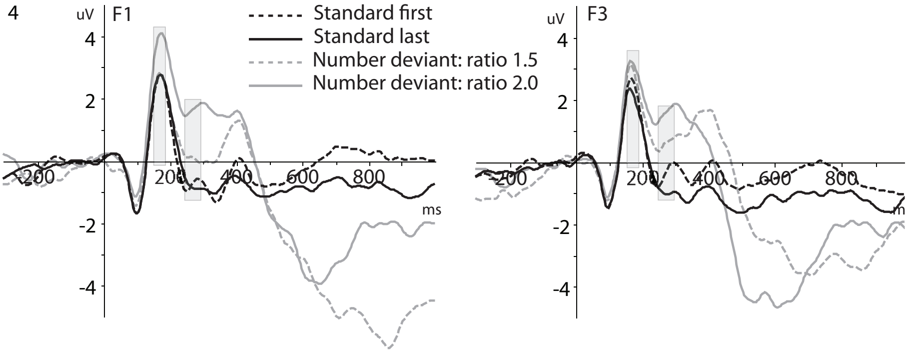

Fig. 4. The electrophysiological results for the active paradigm at the same left frontal electrode sites and time window as in the passive paradigm (Figure 2, right panels). An oddball effect is apparent for the large (2.0) ratio condition, but not for the small (1.5) ratio condition.

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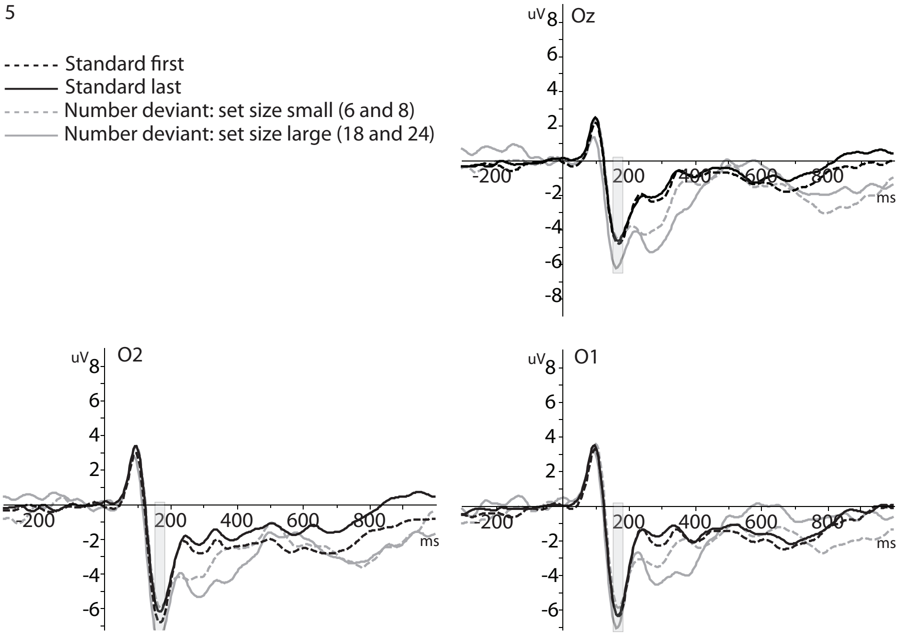

Fig. 5. The electrophysiological results for the active paradigm at the same occipital electrode sites and time window as in the passive paradigm (Figure 3) reveal the absence of habituation as well as set size (or spatial frequency) related effects.

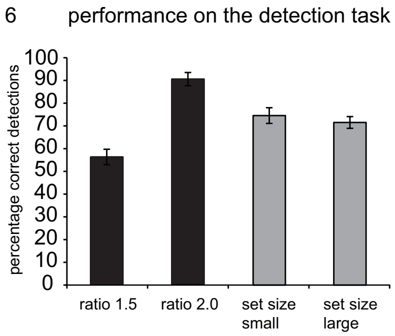

Fig. 6. The behavioral results of the active paradigm reveal a significant difference between the accuracy scores of the ratio (black bars) but not for set size conditions (grey bars).

RESULTS

Passive experiment

On the basis of scalp maps reflecting the difference waves of the first standard in the sequence – the last standard in the sequence before a number deviant stimulus was presented (first standard – last standard), a left frontal (electrodes F1 and F3) positivity was obtained implicating habituation to the standards (see Figure 2). Inspection of the grand average waveforms reveals that this habituation effect was present in an ‘early’ (150-190 ms) as well as a ‘late’ (250-300 ms) time window. This habituation effect was significant in both the early [t(10) = 2.325, p = 0.042] as well as the late time window [t(10) = 2.614, p = 0.026] implicating that independent of the continuous change in extensive and intensive parameters a decrease in activation was present as a result of repeated presentation of the same numerosity.

The scalp maps portraying the difference waves of the oddball effect of the ratio condition (ratio 1.5 deviant - last standard and ratio 2.0 deviant - last standard) revealed an oddball effect for the large ratio condition (2.0) in the late time window [t(10) = -2.940, p = 0.009]. No significant oddball effects were found for either ratio condition in the early time window or for the small ratio condition (1.5) in the late time window.

The scalp maps portraying the difference waves for set size (small set size deviant - last standard and large set size deviant - last standard) revealed a dependence on set size condition. Specifically, a differential positivity was observed for small, and a differential negativity for large set sizes, in an early time window (145-175 ms) on the occipital electrodes (O1, O2, Oz). This effect was significant for the large set size [t(10) = -3.011, p = 0.013] and tended to significance for the small set size [t(10) = 2.112, p = 0.061] (see Figure 3). This early effect on the occipital electrodes suggests that visual cues (the intensive parameters, for instance) induce the set size effect.

Active experiment

The ERP results showed no habituation effect on the early or the late time window. However, (as in the passive experiment) the oddball effect for the large ratio condition (2.0) was still observed on the late time window [t(5) = 3.688, p = 0.014], while no significant oddball effects for either ratio condition in the early time window, or ratio 1.5 in the late time window were present (see Figure

4). In contrast to the passive experiment, no significant oddball effects were obtained for the set size condition for both comparisons (see Figure 5). The behavioral results revealed that subjects detected number-deviant stimuli with a ratio of 2.0 on average in 90 % of the trials and with ratio 1.5 in 56 % of the trials. Number-deviant stimuli with a small set size were, on average, detected in 75 % of the trials while those with a large set size in 72 % of the trials (see Figure 6). Since the percentages of correctly identified number-deviant trials are much larger than the negligible number of false positives (0.015 %), this indicates that subjects could detect the number-deviant stimuli among the standards, although performance was significantly worse for the small (1.5) compared to the large (2.0) ratio [$t(10) = 9.711$, $p < 0.001$]. Moreover, the repeated measures ANOVA revealed a significant effect of ratio [$F(2,20) = 99.473$, $p < 0.001$], but no set size effect [$F(2,20) = 1.016$, $p = 0.337$]. These results implicate that the detection of number changes depends on ratio.

DISCUSSION

In this study we sought to identify the neural correlates of numerosity processing in adults. We reasoned that electro-cortical responses to stimuli that occasionally change in numerosity should exhibit habituation and oddball effects only if they purely reflect numerosity processes. The usage of a passive paradigm consisting of both ratio and set size conditions allowed the comparison with results known from infant studies. If adults' numerosity detection performance depends on ratio and is as accurate as infants', this is evidence in line with the hypothesis of an innate magnitude system.

Neural correlates of numerosity detection

In infant studies, looking time decreases after repeated exposure to the same stimulus and increases again after a number-deviant stimulus is perceived. Similar to these results for the infants' looking time (McCrink & Wynn, 2007; Xu & Spelke, 2000; Xu et al., 2005), the adult ERP data revealed a decrease in activity when the standard was repeatedly presented and an increase in activity when a number-deviant stimulus was presented. Both this decrease and increase of the ERP signal occurred at the same left frontal electrodes suggesting that for the habituation and oddball effect similar processes are involved. However, the increase in activation was present only for ratio 2.0, and not for ratio 1.5. This is a striking result since nine-month-old infants show sensitivity to changes in numerosity differing with a ratio of 2.0 as well as 1.5 (Lipton & Spelke, 2003; Wood & Spelke, 2005). Moreover, a recent study even revealed EEG effects for ratio 1.5 in three-month-old infants using EEG (Izard et al., 2008). One could argue that these contradictory results relate to the level of attention directed towards the stimuli. Infants might find dots appearing on a screen more interesting than adults and are subsequently more prone to numerosity changes. This however, is inconsistent with the electrophysiological results of the second experiment (active paradigm), which show, similar to the first experiment (passive paradigm), a (left frontal) oddball effect for the large (2.0) ratio condition but not for the small ratio condition (1.5). Thus the level of attention directed to the stimulus can be excluded as an explanation for this (lack of) an effect. Yet the lack of an effect in the small ratio condition might relate to the significantly poorer behavioral performance on detection of the number deviant stimuli compared to the large ratio condition.

From the behavioral results we can also conclude that the kind of task (two-forced-choice-discrimination versus detection) has a major influence on the behavioral results. The subjects in the two-forced-choice-discrimination study of Van Oeffelen et al. (1982) performed around 90%

correct when 12 versus 16 (ratio 1.3) or 12 versus 8 (ratio 1.5) dots were compared whereas in our detection experiment, a percentage of 90% correct was only obtained in the ratio 2.0 condition (6 vs. 12 or 12 vs. 24 dots), ratio changes of 1.5 lead to 56% correct identifications. These results clearly reveal that the performance of infants in passive detection tasks cannot be readily compared with the performance of adults on two-forced-choice-discrimination tasks.

A ratio or a set size dependent process?

In infant studies, set size did not influence the infants' numerosity detection abilities whereas ratio did. In the present experiments we manipulated set size while keeping ratio constant and vice versa. As mentioned above, in the passive experiment an oddball effect for ratio 2.0 was present at the same left frontal electrodes that revealed habituation effects. In contrast, the set size condition revealed early occipital effects. The co-occurrence of the habituation and oddball effects on the left frontal electrodes suggests ratio-dependent processes underlying numerosity detection, a result confirmed by the behavioral results of the active experiment, which also revealed a main effect for ratio but not set size. Together, it can be concluded that, as is the case in infants, a ratio dependent process subserves a response to changes in numerosity in adults.

The involvement of visual properties

Even though we carefully controlled for the continuous variables of the stimuli, an early occipital oddball-effect was present in the set size condition of the passive experiment. In comparison to the standard, a larger negative peak amplitude was observed for the large set size condition, and a smaller negative peak amplitude for the small set size condition. This occipital effect is probably the result of the individual item sizes used for the stimuli. The stimuli in the large set size condition were smaller on average whereas in the small set size condition they were larger than the standards. In concurrence with other studies that used comparable controls for the visual cues present in the stimuli (Cantlon et al., 2006; Izard et al., 2008; Pinel et al., 2004) we reasoned that subjects do not process the individual item sizes of the number-deviant stimuli when they are within the range of the item sizes used for the standards. However, the presence of the occipital effect in the passive paradigm suggests that in fact individual item size does affect the processing of the presently used stimulus displays. Large items contain relatively more low(er) spatial frequencies than small items (Kenemans, Baas, Mangun, Lijffijt, & Verbaten, 2000), which might explain these early set size effects. Note however, that they cannot explain the later ratio effects since both ratio conditions consisted for 50% smaller and 50% larger items compared to the average item size.

Interestingly, the early occipital effects present in the passive experiment were absent in the active experiment. Apparently, the more prominent visual cues are attended to when subjects are passively viewing the stimuli. When specifically requested to attend the numerosity of the stimuli (i.e. in the active task), the focus of attention will probably have shifted towards the numerosity changes instead of irrelevant visual properties. This result is consistent with the reports of the subjects. After participating in the passive experiment the subjects retrospectively reported to have seen the changes in location or physical size of the stimuli but not numerosity.

In summary, the results of the present study reveal the electro-cortical processes underlying numerosity detection. Second, we show that these processes are affected by task awareness. The neurophysiologic correlates of the passive and active oddball paradigm differed significantly. Third, we reveal that a detection task can lead to substantially different results compared to studies using a discrimination task (Barth et al., 2003; van Oeffelen & Vos, 1982). Subjects are apparently better at discriminating numerosities differing with a specific ratio than detecting the deviant numerosities when presented in a sequence of standard numerosities differing with the same ratio. Therefore, studies intending to link the results from adult or children to that of infants should use numerosity detection instead of discrimination tasks. Fourth, we show that, similar to infants, the mechanisms underlying adults' ability to respond to changes in numerosity depends on ratio, not set size. This result adds evidence to the innate number sense hypothesis but before accepting it, more detailed information should be obtained about the development of numerosity detection at different ages. Possibly the influence of schooling can explain the increase in precision in numerosity detection and should therefore be included in the design.

CHAPTER 6

NUMBER-LUMINANCE CONGRUENCY EFFECTS AND THEIR ORIGINS

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Submitted

ABSTRACT

To investigate the proposition of a common neural substrate for magnitude processing, irrespective of its origin, congruency tasks are a commonly used instrument. They have provided support for an amodal magnitude system for magnitudes that have a 'spatial' character, but conflicting results have been obtained for magnitudes that do not (e.g. luminance). In this study we extricate the factors that underlie these number-luminance congruency effects and test alternative explanations: (unsigned) luminance-contrast and saliency. We adapted the number-luminance congruency task by manipulating the (luminance) contrast between stimulus and background, and adding extra comparison conditions. When luminance had to be compared under specific task conditions, we revealed for the first time, a true interaction between number and *luminance*: numerically larger stimuli were consistently associated with darker stimuli and the reverse was true for numerically smaller stimuli. However, when number had to be compared *luminance-contrast*, not luminance per se, interacted with number. Apparently, associations exist between number and luminance as well as luminance-contrast of which the latter is stronger. The distinct results for both tasks imply that before or even instead of a mapping onto the mental number line (MNL), the stimuli are categorized according to task. Future studies should choose their task conditions in such a manner that alternative explanations can be excluded.

INTRODUCTION

Shared neural mechanisms or shared processing mechanisms.

Magnitudes can be expressed in many distinct notations and formats, but irrespective of their representation or modality, they all appear to result in similar behavioral and neuronal responses (for a review and meta analyses see: Cohen Kadosh, Lammertyn et al., 2008). For instance, studies reported similar behavioral results for magnitudes expressed as number of dots (Gebuis, Cohen Kadosh, de Haan, & Henik, 2008; Hurewitz et al., 2006; Zhou et al., 2007), pitch (Rusconi et al., 2006), time (Xuan, Zhang, He, & Chen, 2007), physical size, line length (Fias et al., 2003) and luminance (Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh & Henik, 2006b). Concurrently, imaging studies revealed support for similar processing mechanisms underlying distinct magnitudes such as number, physical size, line length (Fias et al., 2003) as well as luminance (Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh, Henik et al., 2005). fMRI-Adaptation paradigms have revealed cross-notation adaptation for numbers and number words (Cohen Kadosh, Cohen Kadosh, Kaas et al., 2007) as well as numbers and dots (Piazza et al., 2007), and electroencephalography (EEG) studies demonstrated the time courses for processing of distinct magnitudes to be highly comparable (Libertus et al., 2007). The observation of similar behavioral and neuronal responses to distinct magnitudes served as a basis for the ATOM model, which states that magnitudes that have a similar (often spatial) metric are encoded by the same amodal magnitude system (Walsh, 2003). Similarly the Triple Code model (Dehaene et al., 2003) entails number encoding independent of its notation.

Spatial versus non-spatial

Notwithstanding the general level of consensus on an amodal magnitude system, how stimuli that do not have an explicit spatial component are encoded remains controversial. Pinel, Piazza et al. (2004) manipulated number, physical size and luminance within a single stimulus and subjects were required to judge each dimension in separate blocks, a task often referred to as the Stroop or congruency task (Algom et al., 1996; Henik & Tzelgov, 1982). Pinel et al. (2004) demonstrated a congruency effect on the behavioral level only when subjects had to make numerical judgments but could not find a congruency effect in the imaging results, neither for the numerical nor for the luminance judgment task. In contrast to these null results, two recent studies did find congruency effects between number and luminance on a behavioral (Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh & Henik, 2006b) as well as the neuronal level (Cohen Kadosh, Cohen Kadosh et al., 2008). The authors reasoned that the lack of an effect in the Pinel et al. (2004) study was due to the manipulation of three distinct magnitudes in one stimulus, which probably resulted in the masking of the underlying interaction effects. The results of the studies of Cohen Kadosh and colleagues suggest that the amodal magnitude system is not limited to magnitudes with a spatial component. However, on closer inspection, their results appear contradictory: faster responses were obtained for stimuli that are numerically larger and darker (Cohen Kadosh & Henik, 2006b) but also for stimuli that are numerically larger and brighter (Cohen Kadosh, Cohen Kadosh, Kaas et al., 2007; Pinel et al., 2004). These contrasting results are intriguing especially when considering the metaphor that is often used to describe our magnitude representations: the mental number line (Dehaene, 1992). In this metaphor, all magnitudes are represented from small to large, from left to right. This idea has gained support from spatial cueing tasks, where small numbers appear to facilitate left hand responses or responses to left sided targets whereas the opposite pattern occurs for large numbers (Dehaene, Bossini, & Gireaux, 1993; Fischer, Castel, Dodd, & Pratt, 2003; but for a different opinion see: Santens and Gevers 2008). Can we reconcile the mental number line with the contradictory findings with luminance? Are numbers represented from bright (small, left) to dark (large, right) or the other way around? Or might a different explanation for these seemingly contradictory findings be more plausible?

The current study

In this study we specifically focus on the *origin* of the number-luminance congruency effects. Apart from the prevalent hypothesis that luminance is associated with number, two alternative hypotheses for the interaction effects are plausible as well. Moreover, these can account for the contradictory findings introduced above.

The first hypothesis states that it is not luminance per se but (unsigned) **luminance-contrast** (the brightness of the stimulus in relation to the brightness of the background) that explains these interaction effects. In the study where numerically large and dark stimuli led to the fastest responses (Cohen Kadosh & Henik, 2006b) a bright background was used, whereas the study that revealed fastest responses for numerically large and bright stimuli employed a background darker than the stimuli (Cohen Kadosh, Cohen Kadosh et al., 2008). In essence, faster responses were always obtained for the stimuli that were numerically larger and had a larger luminance-contrast.

The second (more unorthodox) hypothesis stems from the idea that there might not be any magnitude association at all, yet subjects simply respond to the most **salient** stimulus. The term salient here means the stimulus that directly draws attention due to its stimulus characteristics, be it size, position, color or in the above case luminance (contrast). For example: on a white background, black stimuli are more salient than grey stimuli, while the reverse is true for the same stimuli on a black background.

In summary, there are (at least) three possible hypotheses about the luminance-congruency task: (1) if number is associated with *luminance*, numerically larger stimuli should consistently be associated with either darker or brighter stimuli and the reverse for numerically smaller stimuli, (2) if number is associated with *luminance-contrast*, numerically larger stimuli should consistently be associated with larger luminance-contrast and numerically smaller stimuli with smaller luminance-contrast, and (3) if the congruency effects are the result of *saliency*, the stimulus with the largest luminance-contrast is always responded to fastest irrespective of its numerical size.

To specifically test these three distinct hypotheses, we created a modified version of the luminance-congruency task by adding two manipulations: a '*contrast*' manipulation and a '*task instruction*' manipulation. Instead of a black or white background we used an intermediate grey background and stimuli that were brighter than the background in half of the trials and darker than the background in the other half of the trials. This stimulus-background contrast manipulation was incorporated to be able to distinguish the luminance from the luminance-contrast and saliency hypotheses. These contrast manipulations led to trials where the numerically larger stimulus is darker but has a ***small*** **luminance-contrast** and is ***less*** **salient**, and trials where the numerically larger stimulus is darker and has a ***large*** *luminance-contrast* and is ***more*** **salient** (Figure 1). On the other hand, the instruction manipulation allowed distinguishing between the luminance-contrast and the saliency hypotheses. Instead of two, we used four instruction conditions: respond to (1) the numerically larger, (2) the darker as well as (3) the numerically smaller and (4) the brighter stimulus. The trials in which the subject had to respond to the numerically larger or darker stimulus had a ***large*** **luminance-contrast** and were ***more*** **salient**, but the trials in which the subject had to respond to the numerically smaller or brighter stimulus had a ***small*** **luminance-contrast** and were ***less*** **salient** (Figure 1). In both these cases luminance-contrast and numerical size are congruent (larger number has a larger luminance-contrast / smaller number has a smaller luminance-contrast) but the targets are not always the most salient. Therefore a similar effect for responses to the numerically larger or smaller stimulus implicates luminance-contrast to be the underlying factor, whereas distinct responses for both instruction conditions suggest that saliency induced the congruency effects. Note, that for the luminance comparison tasks, the background manipulation already allows to distinguish between the three possible underlying factors. Saliency is either congruent or incongruent with the target condition therefore if subjects respond to saliency instead of luminance or contrast, null results are expected.

METHODS

Participants

Eight students (aged between 20 and 25 years M = 22.47, SD = 2.31; 6 female, 2 male) from the University of Utrecht took part in the experiment. All participants were right-handed, native Dutch speakers and had normal or corrected-to-normal vision. For their participation, they received course credits.

Stimuli

All stimuli were displayed on a 22-inch monitor using the Presentation software (Neurobehavioral Systems, Albany, CA). On each trial the participants were presented two Arabic numbers (height 2° visual angle), one presented on each side of the fixation cross. Manual responses were recorded using a response box.

Eight Arabic numbers (1 to 9 except for 5) and eight luminance levels (photometric values: 48, 63, 76, 95, 142, 172, 207 and 250 cd/m2) were used. The luminance levels were chosen such that they yielded four equal (Michelson) contrast steps with respect to the background (117 cd/

m2) in either direction. Consequently, half of our stimuli were brighter and half were darker than the background, producing our *stimulus-background contrast manipulation*. Number and luminance values together constituted the three congruency conditions, resulting in the following pairs: (1) the numerically larger stimulus is darker and the numerically smaller stimulus is brighter, (2) both stimuli are the same number but have distinct luminance levels or the reverse (3) the numerically larger stimulus is brighter and the numerically smaller stimulus is darker. These three congruency conditions were further divided over three number and three luminance distances with the number distances being: distance 1 (1-2, 3-4, 6-7, 8-9), distance 2 (1-3, 2-4, 6-8, 7-9) and distance 3 (1-4, 6-9) and the luminance distances being: distance 1 (48-63, 76-95, 142-172, 207-250 cd/m2), distance 2 (48-76, 63-95, 142-207, 172-250 cd/m2) and distance 3 (48-95, 142-250 cd/m2) .

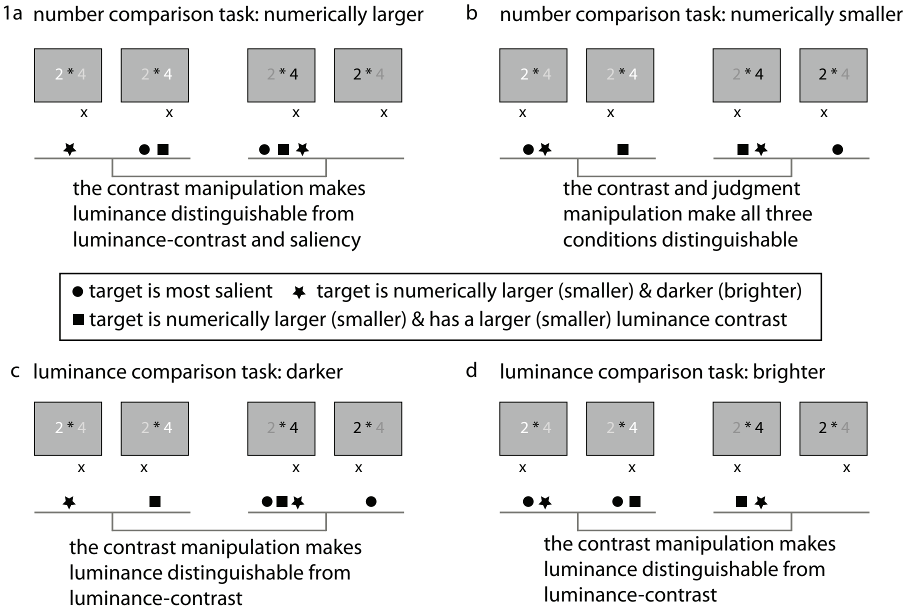

Fig. 1. The distinct stimulus conditions. The upper row represents the number comparison conditions and the lower row the luminance comparison conditions. The left side represents the instruction conditions: numerically larger and darker whereas the right side represents the instruction manipulation conditions we added: numerically smaller and brighter. For each task and instruction combination we created (besides the neutral conditions) four number-luminance stimulus pairs with on the left side the stimuli brighter than the background and on the right side the stimuli darker than the background (our stimulus-background manipulation). Underneath each stimulus condition we show which of the three hypotheses (luminance (star), luminance-contrast (square) or saliency (circle)) is in agreement with a faster response to the target (the side of the 'x').

Procedure

The paradigm consisted of two tasks: (1) a **number comparison task** where subjects had respond to the numerical size of the stimulus and (2) a **luminance comparison task**, where subjects had to respond to the brightness of the stimulus. Both tasks consisted of two instruction conditions: our instruction manipulation. In the number comparison task, subjects had to respond either to the numerically larger or the numerically smaller stimulus, while in the luminance comparison task subjects had to respond to either the darker or the brighter stimulus. Subjects made their judgment by pressing the button on the side corresponding with the target location (the stimuli were blocked for each instruction condition). The target was presented equally often on the left and right side of fixation. Together, the experiment consisted of two comparison tasks that consisted of two instruction conditions (288 trials per instruction condition), each consisting of three congruency conditions (96 trials per congruency), which again consisted of three luminance distances (48 trials per distance) and three number distances (19 trials per distance). The order of the four tasks was counter balanced between participants. Before the experimental trials started the subjects received instructions and performed 15 practice trials. Each trial began with a fixation cross (250ms), followed by the stimulus (which remained on the screen until the subject gave a manual response) and an inter-trial interval (500ms).

Analyses

For each subject median reaction times of the correct responses were calculated. To investigate the presence of a congruency effect and its origin, we performed, for each comparison task separately, a repeated measures ANOVA with stimulus-background contrast manipulation (stimuli brighter or darker than the background) x instruction manipulation (numerically larger/smaller stimuli; darker/brighter stimuli) x congruency (neutral, congruent, incongruent) as within subject variables. Thus we had a 2 x 2 x 3 factorial design for each comparison task.

RESULTS

For both comparison tasks accuracy was above 95%, and therefore not further analysed.

The reaction time analyses revealed a main effect for congruency [$F(1,7) = 4.171$, $p = 0.038$] for the **number comparison task**, suggesting that the unattended dimension (either luminance, luminance-contrast or saliency) interacted with the number judgment. In addition, an interaction was present for congruency and the stimulus-background contrast manipulation [$F(1,7) = 15.985$, $p < 0.001$], but not for the instruction manipulation [$F(1,7) = 2.466$, $p = 0.121$]. Therefore the congruency main effect appeared the result of luminance-contrast interference with number: faster responses occurred for stimuli that were numerically larger (or smaller) and had a large (or small) luminance-contrast (Figure 2, top panels).

For the **luminance comparison task**, a main effect was obtained for both congruency [$F(1,7) = 4.802$, $p = 0.026$] and the stimulus-background contrast manipulation [$F(1,7) = 18.963$, $p = 0.003$]. The main effect for congruency indicates that number processing interacted with luminance or luminance-contrast (but not saliency, see above). Congruency did not interact with the stimulus-background contrast [$F(1,7) = 0.547$, $p = 0.590$] or task instruction manipulation [$F(1,7) = 1.648$, $p = 0.228$]: faster responses occurred for stimuli that were numerically larger (or smaller) and darker (or brighter) (Figure 2 bottom panels).

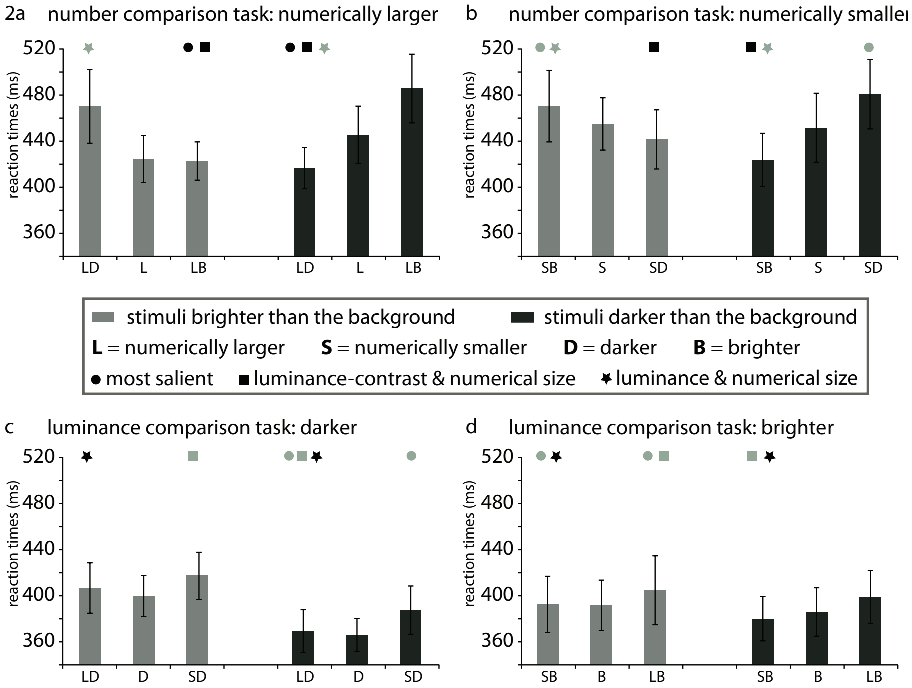

Fig. 2. The reaction time results of the number comparison tasks (top panels) and the luminance comparison tasks (bottom panels). The brighter bars show the results of the stimuli brighter than the background and the darker bars show the results of the stimuli darker than the background. In the number comparison tasks, this stimulus-background contrast manipulation influenced the results revealing opposite congruency effects. This effect was absent in the luminance comparison tasks. The instruction manipulation did not affect the results; the right panels show congruency effects similar to those in the left panels. The black symbols above the bars denote which factor induced the congruency effect. For 'number comparison: larger' (top-left), this can be both luminance-contrast and saliency, for 'number comparison: smaller' (top-right) this is luminance-contrast, for 'luminance comparison: darker' (bottom-left) as well as 'brighter' (bottom-right) this is luminance. The error bars denote the standard error of the mean.

DISCUSSION

Previous studies (Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh & Henik, 2006b; Pinel et al., 2004) generated conflicting results on the luminance-congruency task. We hypothesized that these conflicting results can be explained in alternative ways. Instead of luminance information per se, luminance-contrast or even saliency might have induced the congruency effects. To further disentangle the processes underlying number-luminance congruency effects we expanded the luminance-congruency paradigm with two extra conditions, namely stimulus-background contrast and response instruction.

The results of the **number comparison task** revealed a congruency effect that was induced by either luminance-contrast or saliency when subjects had to respond to the numerically larger stimulus but when subjects had to respond to the numerically smaller stimulus, only luminance-contrast could account for the congruency effects. Therefore, it appears plausible that the interaction effects obtained for both tasks are induced by luminance-contrast, not saliency. Large luminance-contrast stimuli were thus associated with numerically larger stimuli and vice versa. For the **luminance comparison task** number induced a congruency effect: subjects associated numerically larger stimuli consistently with darker stimuli and vice versa.

From our results we conclude that two distinct factors, namely luminance-contrast and luminance, interacted with number. Though seemingly contradictory, this result is easily explained by differential strength of these interactions and the task conditions chosen. First, in the **number comparison task** a luminance-contrast instead of a luminance effect was apparent. This suggests that the association between luminance-contrast and number is stronger than that between luminance and number and thus the previously found luminance-number interactions (Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh & Henik, 2006b) should be attributed to luminance-contrast effects only. Second, our targets were brighter than the background in half of the trials and darker than the background in the other half (our contrast manipulation), in the **luminance comparison task**, responding to luminance-contrast (or saliency; be it explicitly or implicitly) would lead to chance performance. In this case a relatively small but significant interaction between number and luminance emerged. Thus, when luminance-contrast is not controlled for, it overrules the association between luminance and number. Controlling for luminance-contrast and saliency in a similar manner as has been employed in our study is therefore a prerequisite for investigating pure luminance-number interactions.

The finding that luminance-contrast as well as luminance can be associated with number is intriguing. The fact that the same stimulus, a number with a certain level of brightness, can be 'mapped onto the mental number line' based on both the level of its brightness and the level of its luminance-contrast, implies that the stimuli are categorized prior to or even instead of this mapping on the mental number line. The latter hypothesis was recently introduced to account for the spatial numerical association of response code (SNARC) effect (Gevers, Verguts et al., 2006; Santens & Gevers, 2008).

Furthermore, our results put constraints on the hypothesis that luminance is a "special" magnitude, since 'bright' and 'dark' cannot be categorized as 'small' or 'large', which is straightforward with for instance number or physical size (Cohen Kadosh & Henik, 2006b). In the luminance-congruency task this hypothesis would yield two distinct response codes: small and large for number, but dark and bright for luminance. The present finding of luminance-contrast interference reveals that we do categorize the luminance stimuli similar to number and physical size (e.g. large or small number, or size, or luminance-contrast) in the standard luminance-congruency task (since here luminance-contrast not controlled for). Therefore, the use of a luminance-congruency task does not necessarily exclude response code mapping as an explanation of the congruency effects.

In summary, we demonstrate that numbers can be associated with luminance-contrast as well as luminance. However, the latter was only obtained when luminance-contrast or saliency were controlled for, and was only demonstrated in a single direction (number interferes with luminance). Whether the interaction occurs in the opposite direction (luminance interferes with number) as well remains an open question. Our results explain previous contradictory findings, and give a valuable insight in possible factors that can induce luminance-number interferences. Those inclined to use the luminance-congruency task in the future should pick their stimuli and task conditions in such a manner that multiple explanations, of which some are unrelated to magnitude, can be excluded.

CHAPTER 7

OF COLORED NUMBERS AND NUMBERED COLORS; INTERACTIVE PROCESSES IN GRAPHEME-COLOR SYNESTHESIA

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ABSTRACT

Grapheme-color synesthetes experience a specific color when they see a grapheme but they do not report to perceive a grapheme when a color is presented. In this study, we investigate whether color can still evoke number-processes even when a vivid number experience is absent. We used color-number and number-color priming, both revealing faster responses in congruent compared to incongruent conditions. Interestingly, the congruency effect was of similar magnitude for both conditions and a numerical distance effect was present only in the color-number priming task. In addition, a priming task in which synesthetes had to judge the parity of a colored number, revealed faster responses in parity congruent compared to parity incongruent trials. These combined results demonstrate that synesthesia is indeed bi-directional and of similar strength in both directions. Furthermore, they illustrate the precise nature of these interactions and show that the direction of these interactions is determined by task demands, not the more vividly experienced aspect of the stimulus.

INTRODUCTION

Synesthesia is the phenomenon where a percept in one sensory modality can lead to the elicitation of a sensation in another sensory modality or within one modality. As an example of the latter, in grapheme-color synesthesia (a relatively common form of synesthesia), a letter or number leads to a vivid and robust experience of a color. The synesthetic color experience is often subjectively reported as being helpful in for example remembering names or telephone numbers (Smilek, Dixon, Cudahy, & Merikle, 2002). That synesthetic color can indeed be helpful in experimental settings has been shown with visual search (Laeng, Svartdal, & Oelmann, 2004; Palmeri, Blake, Marois, Flanery, & Whetsell, 2002) and with figure-ground segregation experiments (Ramachandran & Hubbard, 2001). In the visual search paradigm, for instance, participants have to search for a target embedded among distracters (e.g. a two embedded among fives). The speed with which the target is detected is related to the number of distracters; with an increasing number of distracters, the time needed to detect the target increases. In such experiments, synesthetes detect the target faster than control participants when the target elicits a synesthetic color distinct from the distracters, yet this advantage disappears when targets and distracters elicit similar synesthetic colors. In other words, synesthetic color clearly induces a pop-out effect.

Besides being advantageous, the induced color experience can also interfere with the process at hand, for instance in a Stroop task (Stroop, 1935), where color names are printed either in a congruent color (the word RED printed in red), or in an incongruent color (the word RED printed in blue). Participants have to name the color aloud while ignoring the meaning of the word. Since reading is an automatic process and cannot be suppressed, the naming latencies are shorter in the congruent compared to the incongruent condition. In a Stroop like paradigm, synesthetes respond faster when they have to name the ink color of a grapheme that matches the synesthetic color (experience) induced by the grapheme than when these colors differ. Based on these results it has been concluded that synesthesia might be an involuntary and automatic process (Cohen Kadosh & Henik, 2006a; Dixon, Smilek, Cudahy, & Merikle, 2000; Mattingley, Rich, Yelland, & Bradshaw, 2001; Mills, Boteler, & Larcombe, 2003).

The processes involved in the elicitation of a synesthetic color experience when a grapheme is perceived, has been studied extensively in recent years (Hubbard & Ramachandran, 2005; Rich &

Mattingley, 2002), but the reverse, the elicitation of a grapheme after having seen a color, only gained interest recently (Cohen Kadosh, Cohen Kadosh & Henik, 2007; Cohen Kadosh & Henik, 2006c, 2006a; Cohen Kadosh, Sagiv et al., 2005; Johnson, Jepma & de Jong, 2007; Knoch, Gianotti, Mohr & Brugger, 2005). This is probably related to the fact that synesthetes report no vivid experience of a grapheme when they perceive a color (Cytowic, 1989). Interestingly, the studies by Cohen Kadosh et al. suggest that a (synesthetic) color that is associated with numerical information can interact with number processes. They revealed that magnitude judgments of congruently or incongruently colored numbers results in significantly delayed responses on the incongruent trials. They also used a more indirect paradigm to reveal that the color interference remained when instead of numbers, line lengths or triangle sizes were used. This result of a bi-directional interaction is of importance, as it has major implications for the interpretations of previous studies (Cytowic, 1989; Esterman, Verstynen, Ivry, & Robertson, 2006; Mattingley et al., 2001; Mills et al., 2003) that only took into account the possibility that a number can elicit color processes and not vice versa. In the often used Stroop paradigm (Cytowic, 1989; Esterman et al., 2006; Mills et al., 2003), for instance, where the presented grapheme is either congruently or incongruently colored, it is unclear whether stimulus color or its form and meaning elicited the synesthetic process that induced the congruency effect. Yet, in order to gain insight in the bi-directional nature of the interaction between the inducer and its synesthetic experience in grapheme-color synesthesia, such dissociation is paramount. Moreover, such dissociation enables the parametric study of the magnitudes of these interactions in both directions.

In the present study, we chose number stimuli to investigate bi-directionality, because number processes interfere with each other in a manner that is distinguishable from interactions between color processes. It has been shown that participants are faster to compare numbers that are numerically further apart (e.g. 1 and 9), compared to numerically closer numbers (e.g. 5 and 6), the so-called numerical distance effect (Moyer & Landauer, 1967). The numerical distance effect has also been demonstrated in priming studies, in which numerically close prime-target pairs led to faster responses compared to prime-target pairs that were numerically more distant (Bodner & Dypvik, 2005; Reynvoet & Brysbaert, 2004; Reynvoet, Brysbaert, & Fias, 2002). We designed both a color-number and a number-color priming task, in which participants had to name aloud the target (the number in the color-number priming task and the color in the number-color priming task) of a congruent (i.e. prime and target match) or an incongruent condition (i.e. prime and target do not match). The trials of the incongruent condition were divided into three numerical distance groups. Therefore, the number related to the printed (synesthetic) color and the number presented in the same trial were either one, two or three numerical distances apart (e.g. the number 3, primed with the synesthetic color of number 4, 5 or 6, and vice versa). We reasoned that if synesthesia is uni-directional (numbers can elicit colors, but colors cannot elicit numbers), the number prime will elicit a synesthetic color process in the number-color priming task, which interferes with naming the target color (see Figure 1a). Similarly, in the color-number priming task, the color prime is congruent or incongruent with the vivid color experience elicited by the number target (see Figure 1b). Thus, a congruency effect would be the result of interacting color processes. However, if synesthesia is bi-directional, the number elicits color processes and the ink color elicits number processes. Therefore, it is unclear whether a congruency effect is the result of color congruency or number congruency (or both). To determine the underlying process(es), we will specifically analyze the numerical distance effect, which only arises when two number processes interact. Hence, if such a numerical distance effect is found in the number-color priming task, the number prime interacts with the number process elicited by the color target (see Figure 1c). A numerical distance effect in the color-number priming task will be the result of the color prime eliciting a number process that interacts with the number target (see Figure 1d).

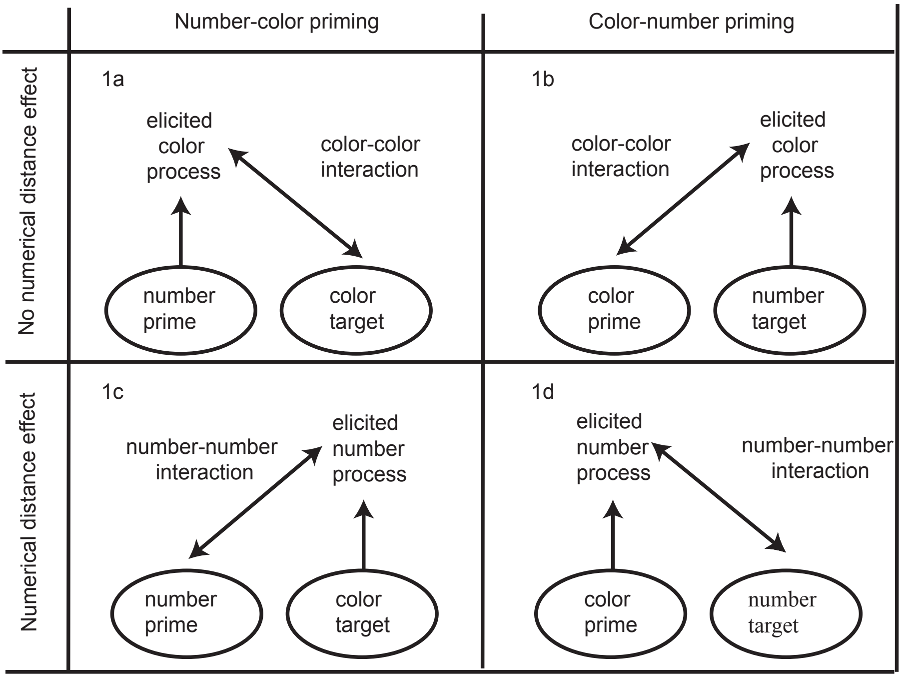
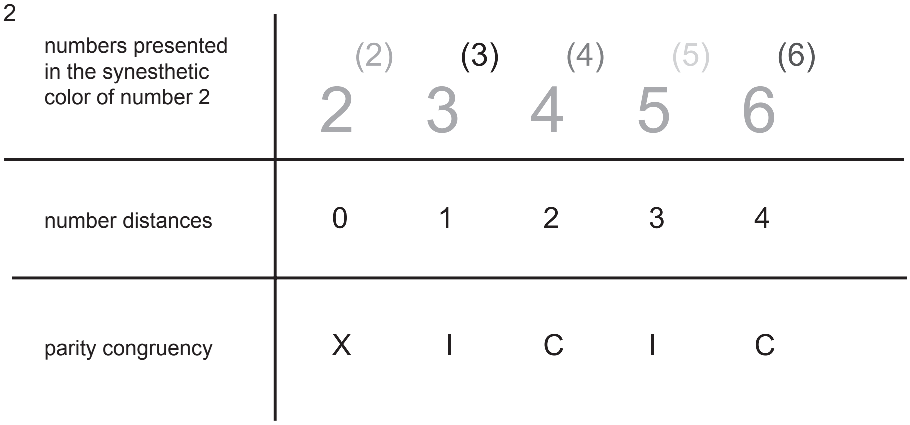


Fig. 1. Possible outcomes of the color-number and the number-color priming task are presented. The upper row represents the two outcomes without a numerical distance effect (a and b) and the bottom row represents the two outcomes with a numerical distance effect (c and d). It is expected that only the prime elicits its related synesthetic process and interacts in both direction with the target process (a and d).

In a second experiment, we investigated the effect of synesthetic color on numerical processes with a parity judgment task. Participants had to judge the parity of a number, by pressing the button corresponding to even or odd. A recent number-number priming task in which participants had to judge parity, has revealed shorter reaction times when both prime and target were of the same parity in contrast to pairs of distinct parity (Bodner & Dypvik, 2005). The occurrence of a parity congruency effect in the present experiment would conclusively demonstrate that the numerical process elicited by the ink color of the stimulus affects the response pattern. The number presented in each trial was thus colored in its related synesthetic color (congruent condition) or a color that was (by the synesthete) associated with a different number (incongruent condition). In addition, the incongruent color condition consisted of four numerical distance groups. Because four numerical distances were used, the trials could be separated in two parity congruent (distance two and four, e.g. the even number 4 or 6 presented in the synesthetic color of the even number two, see Figure 2), and two parity incongruent (distance one and three, e.g. the odd number three or five presented in the synesthetic color of the even number two, see Figure 2) conditions. Faster responses were of course expected in the congruent trials compared to the incongruent trials, which would (again) indicate that color and number processes interact. In addition, a parity congruency effect is expected and would indicate that it was the numerical process elicited by the ink color of the stimulus that determined the response pattern.

It should be noted that most studies on synesthesia have either been single case studies, or studies with only a limited number of participating synesthetes. We were in the position of testing a group of 19 synesthetes, 16 of which are included in the analyses of the priming task and 14 in the analyses of the parity judgment task, thus enabling us to more conclusively determine the underlying mechanisms of color-number (as well as number-color) interactions.



2					
numbers presented in the synesthetic color of number 2	(2) 2	(3) 3	(4) 4	(5) 5	(6) 6
number distances	0	1	2	3	4
parity congruency	X	I	C	I	C

Fig. 2. The upper row represents the numbers two till six colored in the synesthetic color of number two, the colors between the brackets represent the synesthetic color one of the synesthetes experienced with those numbers. The second row represents the number distances and the bottom row the parity congruent conditions (C) and the parity incongruent conditions (I). The number two colored in its synesthetic color is color congruent and parity congruent and is therefore marked with an "x".

METHODS

Participants

Nineteen grapheme-color synethetes (aged between 21 and 54 years M = 35.5, SD = 11.7; 18 female, 1 male), two of which were classified as projectors (Dixon et al, 2004) participated in both experiments. 16 Non-synesthetic controls participated in the priming task (aged between 20 and 32 years M = 26.2, SD = 3.9; 13 female, 3 male) and 14 in the parity judgment task (aged between 21 and 32 years M = 27.3, SD = 3.7; 11 female, 3 male). All participants were native Dutch speakers and had normal or corrected-to-normal vision. All synesthetes had to color the numbers 2 till 9 prior to and after the behavioral tests in the color they experience when seeing the number. The colors were chosen from the custom color palette available in Microsoft Office 2000. All synesthetes colored the numerals almost identical in both instances. The colors chosen in the prior test were used in the priming and parity judgment tasks. Each control participant performed the tasks with a different set of colors that was identical to the colors of one of the synesthetes (included in the analyses).

Apparatus and stimuli

In each trial, the prime and target were displayed centrally on a 22 inch monitor using the Presentation software (Neurobehavioral Systems, Albany, CA). The stimuli consisted of black Arabic numbers ranging from 2 till 9 and color patches in the synesthetic colors that were related to the numbers 2 till 9 (width = 1.6°, height = 2°). The stimuli were presented centrally on a grey background at a distance of approximately 57 centimeter from the monitor. Verbal reaction times were recorded with a voice key.

The priming task consisted of two tasks, (1) number-color priming, where the participant had to respond by naming aloud the color of the color patch and (2) color-number priming, where the participant had to respond by naming aloud the number presented. In addition, each task consisted of congruent and incongruent conditions. The incongruent conditions consisted of three numerical distance groups. For the color-number priming task this means that the number related to the color prime had a numerical distance of one, two or three from the number target. For the number-color priming task this means that the number prime had a numerical distance of one, two or three from the number related to the target color. Thus, the experiment consisted of two priming tasks (240 trials in each task), each again consisted of two congruency conditions (120 trials), of which the incongruent condition consisted of 3 number distances (40 trials per distance). The order of the two priming tasks was counter balanced between participants. Before the experimental trials started participants received instructions and performed 15 practice trials. Each trial began with a fixation cross (500ms), followed by the prime (500ms), an inter stimulus interval (500ms), the target (which remained on the screen until the participant gave a verbal response) and an inter trial interval (500ms).

The parity task consisted of a congruent condition (the color of the number matched the synesthetic color associated with that number) and an incongruent condition (the color differed from the synesthetic color associated with that number). In the latter case, the color used was the color of a number that was one, two, three or four numerical distances apart from the number presented in that trial. The incongruent trials thus consisted of 2 parity congruent conditions (numerical distance 2 and 4) and 2 parity incongruent conditions (numerical distance 1 and 3) meaning that the parity of the number belonging to the presented color and the parity of the number presented were not of the same kind (even/odd; see Figure 2 for an example). Size of the stimuli was equal to that in the priming task.

Half of the participants started responding with the right hand to even and the left hand to odd numbers, while the other half of the participants started with the reversed order, to correct for possible contamination of the data by stimulus-response related effects, which have been demonstrated before with these paradigms (Dehaene, Bossini, & Giraux, 1993). All participants performed the task with both response formats. Before the experimental trials started participants received instructions and performed 20 practice trials. Thus, the experiment consisted of color-number congruent and incongruent trials (each 320 trials), the incongruent trials again consisted of parity congruent and parity incongruent trials (each 160 trials), and both parity congruent trials and incongruent trials consisted again of distance small and distance large (each 80 trials). Each trial began with a fixation cross (500ms), followed by the target (200ms), a backward mask (which remained on the screen until the participant gave a manual response) and an inter trial interval (500ms).

Analyses

For the priming task, three synesthetes were excluded due to voice key problems and in the parity judgment task five synesthetes were excluded because they had less than 70% of the trials correct. For the parity judgment task, the data was grouped over both response formats (left even and right odd and vice versa). For each remaining participant, median reaction times of the correct trials were calculated per condition.

RESULTS

Priming task

For the 16 included synesthetes, a repeated measures (two-way) ANOVA was performed on the reaction times for the different conditions in the two priming tasks, which revealed a significant main effect for task [F(1,15) = 70.41, $p < 0.001$], the synesthetes responded significantly faster in the color-number compared to the number-color priming task. A significant main effect for congruency was also present [F(1,15) = 12.27, p = 0.003] with faster responses for the congruent compared to the incongruent condition. No significant interaction effect between task and congruency [F(1,15) = 0.56, $p > 0.464$] was found. Post-hoc paired t-tests showed that synesthetes responded faster in the congruent compared to the incongruent trials in both the number-color [t(15) = -3.5, p = 0.003] and the color-number priming task [t(15) = -2.4, p = 0.025] (see Figure 3a). In addition, we compared the ratio's (the median reaction time of the congruent condition divided by the incongruent condition) of both priming tasks to investigate whether the larger priming effect in the color-number (44ms) compared to the number-color priming task (33ms) was due to the overall faster responses in the color-number priming task. Interestingly, no significant difference was obtained between both the ratio's [t(15) = .319, $p > 0.754$] (congruent = 0.91%; incongruent = 0.95%) and the absolute values [t(15) = .751, $p > 0.464$] (congruent 53.5ms; incongruent = 28.86ms) indicating that the priming effect was indeed of the same relative magnitude in both tasks. Besides the reaction time data we also investigated the effect of congruency on task accuracy. The synesthetes did not reveal a congruency effect for color-number priming [t(15) = 0.8, p = 0.425] (congruent = 0.951%, incongruent = 0.929%) nor for number-color priming [t(15) = 1.2, p = 0.234] (congruent = 0.953%; incongruent = 0.926%). This result indicates that the congruency effects present in the reaction time data could not be the results of a speed accuracy trade off.

Because a priming effect was present in both tasks, we further explored whether a numerical distance effect was present within the incongruent conditions. A repeated measures ANOVA was performed for both tasks separately with the three numerical distance conditions as independent factors. A significant numerical distance effect (for distance 1 till 3) was present in the color-number priming task [F(2,30) = 4.63, p = 0.018], but no significant numerical distance effect was present in the number-color priming task [F(2,30) = 0.58, $p > 0.566$] (see Figure 4a and b). For the color-number priming task we performed Bonferroni corrected post hoc comparisons, a significant difference between distance distance 1 and 2 (t(15) = -4.286, p = 0.001) but not between distance 2 and 3 (t(15) = 1.135, p = 0.274) in the color-number priming task. The lack of a distance effect between distance 2 and 3 indicates that priming is effective up to a number distance of 2. A lack of a priming effect for distances 3 and larger is in agreement with the results presented in a numerical priming study performed by Roggeman, Verguts et al. (2007) (see Figure 2a). The presence of a numerical priming effect is in agreement with the expectations as depicted in the models 1a and

1d in Figure1. In order to ascertain whether the effects present in the results of the synesthetes can indeed be attributed to their synesthetic experience we also tested 16 control participants. The repeated measures ANOVA revealed a significant difference for task [F(1,15) = 21.39, $p < 0.001$] with faster responses for the color-number compared to the number-color priming task. Yet, no significant difference for congruency [F(1,15) = 0.182, $p > 0.297$] nor an interaction effect [F(1,15) = 0.207, $p > 0.656$] was found (see Figure 3b).

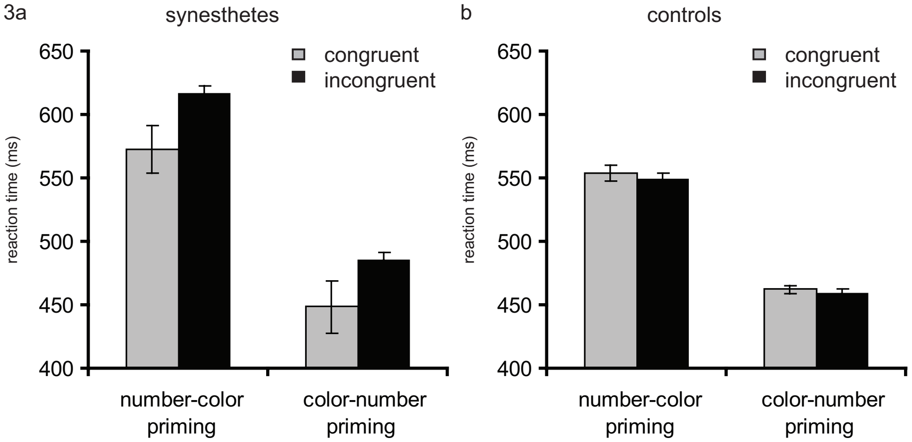


Fig. 3. The results of the synesthetes revealed a congruency effect with faster responses for the congruent (color and number matched) compared to the incongruent (color and number did not match) condition in both the priming tasks, indicating an effect of numbers on colors, as well as of colors on numbers (a). In contrast, the results of the controls revealed a congruency effect in neither priming tasks (b). The error bars represent the 95% confidence interval (Loftus, 1994).

Parity task

For the remaining 14 included synesthetes a paired T-tests revealed significantly faster responses for congruent compared to incongruent conditions [t(13) = -4.68, $p < 0.001$]. No congruency effect was present for accuracy [t(13) = -0.38, p = 0.713]. (congruent = 86% incongruent = 85%). Because a congruency effect was present for the reaction times, a repeated measures ANOVA was performed with parity congruency (parity congruent and incongruent) and distance (distance small and large) as separate factors to reveal whether a parity or a numerical distance effect was present within the incongruent condition. A significant parity congruency effect [F(1,13) = 5.14, p = 0.041] but no distance effect [F(1,13) = 1.37, $p > 0.262$] nor an interaction effect was present [F(1,13) = 0.03, $p > 0.859$] (see Figure 5a). This finding is in agreement with our expectations and indicates that that the ink color of the stimuli elicited number processes that interfered with the number stimulus. Not very surprisingly, for the 14 controls, T-tests revealed no significant difference in the reaction times for the congruent compared to incongruent conditions [t(14) = -0.207, $p > 0.839$] (see Figure 5b).

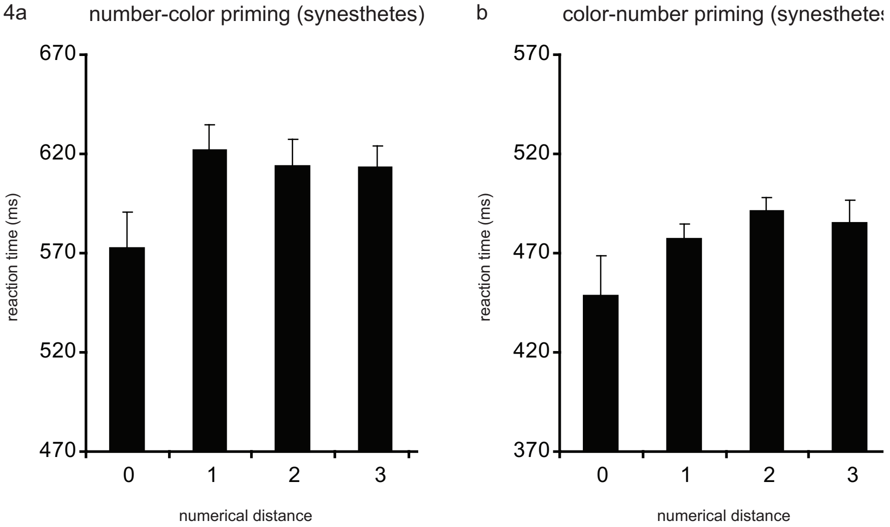


Fig. 4. The results of the number-color priming task does not reveal a numerical distance effect (a) while the results of the color-number priming task do reveal a numerical distance effect with faster responses for distance 0 compared to 1 (29ms) and for distance 1 compared to 2 (14ms) (b). The error bars represent the 95% confidence interval (Loftus, 1994). Note that the scales of graphs are different.

DISCUSSION

Grapheme-color synesthetes describe a vivid experience of a color when they see (for instance) a number, but the reverse, the experience of a number when a color is perceived has not been reported. It has been suggested that even in the absence of a vivid number experience, color still elicits numerical processes (Cohen Kadosh & Henik, 2006c, 2006a; Cohen Kadosh, Sagiv et al., 2005; Johnson et al., 2007; Knoch et al., 2005). In this study, we investigated whether color can indeed elicit number processes and how the interaction between color and number processes is established. To this end, synesthetes and controls performed two priming tasks and a parity judgment task, each of which contained congruent (color and number matched) as well as incongruent (color and number did not match) conditions. For synesthetes faster responses were obtained for the congruent compared to the incongruent conditions, indicating that an interaction between both sensory processes occurred in both experiments. This finding is consistent with previous findings in Stroop-like paradigms (Cohen Kadosh & Henik, 2006a; Dixon et al., 2000; Mattingley et al., 2001; Mills et al., 2003). Moreover, the present experimental design enabled us to determine which process caused this interaction by comparing the different numerical distance groups within the incongruent conditions.

In the priming task, a numerical distance effect was present in the color-number priming task, which indicates that the color prime elicited number processes that interacted with the number target (see Figure 1d). In the number-color priming task no numerical distance effect was found,

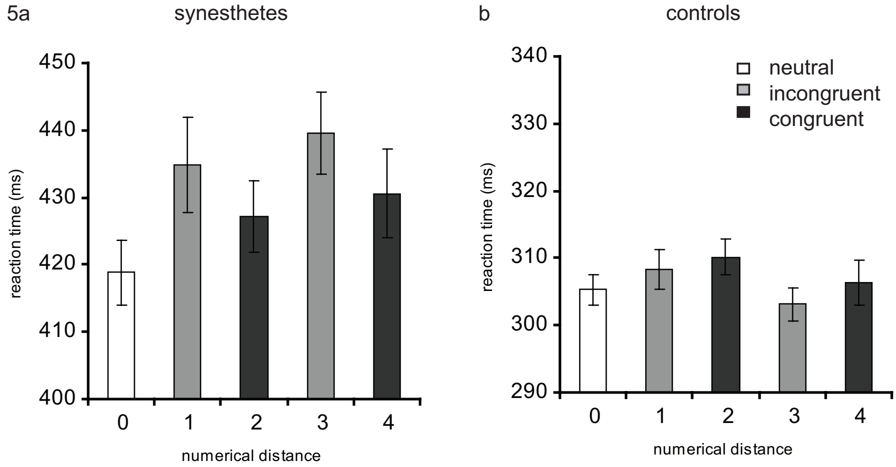


Fig. 5. The results of the synesthetes for the priming task reveal faster responses for the congruent (distance 0) compared to the incongruent conditions (distance 1, 2, 3 and 4). Moreover, faster responses are obtained for parity congruent trials (distance 2 and 4) compared to parity incongruent trials (distance 1 and 3). No significant difference was present between the small versus the large distances (distance 1 compared to 3 and distance 2 compared to 4) (a). The results of the controls revealed neither a color-number congruency nor a parity congruency effect (b). The error bars represent the 95% confidence interval (Loftus, 1994). Note that the scales of the graphs are different.

which indicates that the faster responses in the congruent compared to the incongruent condition were a result of interacting color processes only (see Figure 1a). More specifically, the number prime induced a color experience that interacted with the color target. Thus, a congruency effect arises for the process that is addressed in the task (i.e. color in the number-color priming task and number in color-number priming task). The results of both priming tasks indicate that the interaction between graphemes and colors in grapheme-color synesthesia is bi-directional. An additional interesting finding is that the difference in response times between congruent and incongruent conditions is of similar magnitude in both tasks. This indicates that, although colors do not elicit vivid numerical experiences, the percept of ink color (and thus the induced number process) primes numerical processes to a similar extent as numbers (and thus the induced color process) prime color processes. It could be argued that color-color priming across or within trials can account for the results in the color-number priming task. We think this very unlikely for the following reasons: first, a large number of different prime-target combinations was used (each combination of the incongruent trials was presented only once or twice). If one of these combinations led to color-color priming its effect would be marginal. Moreover, any effect of such a combination would not be systematic, since incongruent prime-target combinations almost never consisted of color within a single color category. Second, our large population of synesthetes revealed a large variety in the colors elicited by the numbers, which again reduces the chance that color-color priming could have induced systematic effects.

The results of the parity task revealed a parity congruency effect, with faster responses for the conditions where the parity of the number related to the ink color of the stimulus was the same as the number stimulus presented in the same trial. Apparently, a parity congruency effect could arise even though color and number were presented simultaneously. One would expect that when a color and number are present as a single stimulus that the most vivid experience, the color experience elicited by the number, would induce the interaction effect. Instead, we found a numerical interaction effect, suggesting that even in the presence of the vivid color experience, number processes are elicited by the ink color that interacts with the number perceived. Since the synesthetes were instructed to respond to the number and not the color of the stimulus we suggest that the interaction effect is not related to the more vivid aspect of the stimulus (the synesthetic color experience) per se, but is related to the stimulus property that is responded to (in this case the number). This finding underlines the results of the priming study where a priming effect was only present for the stimulus format the subject responded to (e.g. color or number naming; see also Figure 1a & 1d). The presence of a parity congruency effect instead of a numerical distance effect (as in the priming task) is in agreement with the results of Bodner and Dypvik (2005). In their number-number priming study subjects had to make either a parity or a magnitude judgment. In the former case a parity congruency effect was obtained while in the latter a numerical distance effect was obtained. It was reasoned that the results were directly related to the task instruction.

Besides the main finding of bi-directionality in both experiments, the result that the priming effect was of similar strength in both priming tasks is intriguing. The grapheme-color synesthetes that participated in this experiment told us to have a vivid experience of a color when a number is perceived but no vivid experience of a number when a color is perceived. We speculate that this could be related to the fact that color information has access to many associated objects in memory (e.g. yellow can be associated with a banana, sunflowers, the sun, etc.) (Nijboer, van Zandvoort, & de Haan, 2006) whereas a number is only associated with the amount it refers to. If a color process is elicited, not one object in particular but many associated objects are primed (at the same time). The fact that a number is only one of the many associated objects for synesthetes, could be the reason why no vivid number experience is present when a color is perceived. Yet, the percept of a number will only lead to the elicitation of a single association in grapheme-color synesthesia: a color, and as a result it can more easily lead to a vivid experience of that color. This idea complements that of Ramachandran and Hubbard (2003), who proposed that the induced color experience when a number is perceived can be superimposed on that number form but the other way around, the percept of a color can not be ascribed to a number form since this number form could have distinct sizes or fonts. Instead of a distinct format for one particular number we suggest that there are more associations besides number form that are linked to color.

How the interaction between number and color is established is directly related to the cortical areas involved in synesthesia. There are two main hypotheses that describe the underlying structure that subserves the synesthetic experience. First, synesthesia might arise from long range connections between lower visual areas V4/V8 and higher cortical areas. Second, synesthesia might arise from close connections between adjacent areas at a lower perceptual level (e.g. the fusiform gyrus) (Ramachandran and Hubbard, 2001; see for a review Hubbard and Ramachandran, 2005). However, a recent study investigating bi-directionality revealed that brain activation is modulated by task (Cohen Kadosh, Cohen Kadosh, & Henik, 2007). In this study a number comparison task led to effects in the IPS while a triangle comparison task led to effects in the fusiform gyrus. In addition, close connections between adjacent areas at a higher, more conceptual stage have also been suggested (Ramachandran & Hubbard, 2001). Two psychophysical studies that investigated bi-directionality hint at cross wiring at a higher more conceptual level. These studies revealed that color influenced both number (Cohen Kadosh & Henik, 2006a; Cohen Kadosh, Sagiv et al., 2005) and line length judgments (Cohen Kadosh & Henik, 2006a; Cohen Kadosh, Sagiv et al., 2005) in synesthesia, and that this effect is comparable to the effect of physical size on number judgments as has been found frequently in number studies (Besner & Coltheart, 1979; Henik & Tzelgov, 1982). Together with the notion that the Intra Parietal Sulcus (IPS) is considered to process different magnitudes such as numbers, physical sizes or line lengths (Cohen Kadosh, Henik et al., 2005; Fias et al., 2003; Pinel et al., 2004), these findings resulted in the suggestion that the synesthetic colors in synesthetes are scaled ordinal according to their numerical value (Cohen Kadosh, Sagiv et al., 2005) and that synesthesia might be a result of cross wiring within the IPS (Cohen Kadosh & Henik, 2006a). The interaction between number and physical size, however, occurs similarly in both directions (i.e. size interferes with number and number interferes with size) (Henik & Tzelgov, 1982). In the two studies mentioned above only the influence of color on number processes was tested and not vice versa. On the basis of the results of our priming tasks, in which the influence of color on number as well as the influence of number on color were tested, we can conclude that this interaction occurs in a dissimilar fashion in both directions. Therefore, we suggest that synesthetic colors are not ordered in an ordinal manner like numbers (or processed in the IPS). Instead we propose that color activates number processes (possibly in the IPS), which in turn interfere with the number processes evoked by task demands. Three architectural models that underlie synesthetic processes have been proposed. These are the local cross-activation model (e.g. Ramachandran and Hubbard, 2003), the re-entrant model (e.g. Smilek, Dixon et al., 2001) and the disinhibited feedback model (e.g. Grossenbacher and Lovelace, 2001). Our results can not differentiate between the three architectural models but do constrain possible models, as outlined above.

To conclude, we report more conclusive evidence about the bi-directional interaction between color and number in grapheme-color synesthesia. It appears that color and number processes in grapheme-color synesthesia interact in both directions and that this bi-directional interaction is of similar strength. Moreover, the task demand determines the direction of the interaction, not the aspect of the stimulus that is more prominent.

CHAPTER 8

MULTIPLE DIMENSIONS IN BI-DIRECTIONAL SYNESTHESIA

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ABSTRACT

Grapheme-color synesthetes report seeing a specific color when a number is perceived. The reverse, the synesthetic experience of a specific grapheme after the percept of a color is extremely rare. However, recent studies have revealed these interactions at both behavioral and neurophysiological levels. We investigated whether similar neuronal processes (i.e. perceptual and/or attentional) may underlie this bi-directional interaction by measuring Event Related Potentials (ERPs) during both a number-color and color-number priming task. In addition, we investigated the unitarity of synesthesia by comparing two distinct subtypes of synesthetes, projectors and associators, and assessed whether consistencies between measures (i.e. behavioral and electrophysiological) were present across synesthetes. Our results show longer reaction times for incongruent compared to congruent trials in both tasks. This priming effect is also present in the P3b latency (parietal electrode site) and P3a amplitude (frontal electrode site) of the ERP data. Interestingly, projector and associator synesthetes did not reveal distinct behavioral nor electrophysiological patterns. Instead dissociation was found when synesthetes were divided in two groups on the basis of their behavioral data. Synesthetes with a large behavioral priming effect revealed ERP modulation at the frontal and parietal electrode sites, whereas synesthetes with a small effect revealed a frontal effect only. Together, these results show, for the first time, that similar neural mechanisms underlie bi-directional synesthesia in synesthetes that do not report a synesthetic experience of a grapheme when a color is perceived. In addition, they add support for the notion of the existence of both 'lower' and 'higher' synesthetes.

INTRODUCTION

Bi-directional synesthesia

Synesthesia is the phenomenon in which one sensory modality automatically activates an experience in another sensory modality. For instance, grapheme-color synesthetes experience a color when a number or a letter is perceived. The reverse, the experience of a number when a color is perceived, is extremely rare; only a single case has been reported ('explicit' bi-directional synesthesia) (Cohen Kadosh, Cohen Kadosh, & Henik, 2007). Recently, it has been suggested that colors can activate number processes in synesthetes, even though a synesthetic number experience is absent at the phenomenological level ('implicit' bi-directional synesthesia) (Knoch et al., 2005). This bi-directionality in synesthesia was more comprehensively investigated by Cohen Kadosh and colleagues (Cohen Kadosh, Cohen Kadosh, & Henik, 2007; Cohen Kadosh & Henik, 2006c, 2006a). Their results revealed an influence of color on task performance even when different magnitudes, such as line lengths and triangle sizes, were used instead of numbers. The elegance of the above studies lies in that they eliminated the possibility of number processes being triggered by the mere presence of number stimuli. Another way to overcome this confound is to present numbers and colors at different moments in time as is common in, for instance, priming studies. In a recent priming study, a bi-directional interaction (i.e. from number to color as well as from color to number) of equal magnitude for both directions, was revealed with grapheme-color synesthetes (Gebuis, Nijboer, & van der Smagt, 2009). This result is surprising given the clear distinction present at the phenomenological level (i.e. the lack of reporting the presence of a number experience when a color is perceived) and hints at a similar mechanism underlying both directions of information flow.

To date, only a single study investigated the underlying processes of bi-directional interactions in synesthesia using imaging techniques (Cohen Kadosh, Cohen Kadosh, & Henik, 2007). In this study, distinct activation patterns and time courses were found for both directions of information flow (grapheme to color and the reverse), suggesting the recruitment of different mechanisms. It is important to note, however, that the synesthete participating in that study experienced colors when numbers were presented but the reverse as well: the experience of numbers when colors were perceived. This is (to the best of our knowledge) the only reported case, and thus extremely rare. Therefore, we will investigate (using both behavioral and ERP measures) whether synesthetes who do not experience this explicit bi-directionality (thus showing the more common form of grapheme-color synesthesia) also have distinct neurophysiological patterns when performing in a bi-directional synesthetic priming experiment.

Bi-directionality and homogeneity within synesthesia

Synesthetes have been classified in two groups based on their subjective experience and response patterns (Dixon et al., 2004): synesthetes who see their synesthetic color experience projected onto the grapheme (called ‘projectors’), and synesthetes who see the synesthetic color experience in their ‘mind’s eye’ (called ‘associators’). Differences between projectors and associators have been reported on behavioral (Dixon et al., 2004) and physiological levels (Rouw & Scholte, 2007). A different classification of synesthetes was proposed by Ramachandran & Hubbard (2001), who classified synesthetes into ‘higher synesthetes’, for whom the number *concept* is critical, versus ‘lower’ synesthetes, for whom the *percept* of the physical grapheme is necessary to elicit the synesthetic experience. This distinction recently gained support from a behavioral and imaging study (Hubbard et al., 2005). Although Dixon & Smilek (2005) have suggested that these classifications overlap to a large extent, this claim is yet to be substantiated. Therefore, we will also investigate whether these classifications of synesthetes (projector versus associator – higher versus lower) are equivalent or dissociable using behavioral and neurophysiological techniques.

The above raised issues are addressed using a number-color (Mattingley et al., 2001) as well as a color-number priming task (Gebuis, Nijboer, & van der Smagt, 2009). Faster responses are expected for congruently compared to incongruently primed targets as a result of correctly activated processes prior to target presentation. Event related potentials were used as a neurophysiological measure since its accuracy in the temporal domain gives an insight in the timing of the distinct processes involved. The P3b latency is generally thought to be related to the processing time needed to evaluate a stimulus (e.g. perceptual processes; Luck, 2005). Therefore longer P3b latencies are expected for the incongruent compared to the congruent trials. Based on the results of previous studies, effects of early perceptual or orthographic processing (N170 component) at the parietal-occipital electrodes (Cohen Kadosh, Cohen Kadosh, & Henik, 2007; Sagiv & Ward, 2006) and possibly inhibitory frontal effects (Schiltz et al., 1999) are expected as well. Whether distinct time courses for both priming tasks (as found with an ‘explicit’ synesthete (Cohen Kadosh, Cohen Kadosh, & Henik, 2007)) will be obtained in (subtypes of) ‘implicit’ synesthetes remains a matter of scrutiny.

EXPERIMENTAL PROCEDURE

Participants

Eighteen grapheme-color synesthetes participated in the experiment. Before participation synesthetes who applied to attend the study received a questionnaire that included a large variety of questions about their synesthetic experiences as well as their history of neurological disorders or substance abuse. Only synesthetes with no history of substance abuse, neurological disorders and the presence of grapheme-color associations were included. Furthermore, the specific color associations that were tested prior to and after the experiment (see below) should be consistent between them as well as with the colors reported in the questionnaire. Due to artifacts in the EEG data only 14 synesthetes (aged between 18 and 53 years; M = 33.9, SD = 3.24; 13 female; 12 right-handed) were included in the analyses. Out of the 14 synesthetes, six reported to perceive the synesthetic color projected onto the grapheme (projectors) and eight reported to perceive the synesthetic color in their 'mind's eye' (associators). Fifteen controls that did not report any grapheme-color or other synesthetic associations participated in the experiment of which fourteen (aged between 19 and 35 years M = 23.7, SD = 1.36; 13 female; 13 right-handed) were included in the analyses. All participants were native Dutch speakers and had normal or corrected-to-normal visual acuity. They reported no color blindness or a history of neurological disorders. Written informed consent was obtained according to the Declaration of Helsinki and as approved by the Ethical Committee of the University of Utrecht.

Apparatus, stimuli and procedure

In each trial, the prime and target were displayed on a 22-inch CRT monitor using the Presentation software (Neurobehavioral Systems, Albany, CA). The paradigm was a slightly adapted version of our previous study (Gebuis, Nijboer, & van der Smagt, 2009) (Figure 1). Prior to and after the experiment, all synesthetes had to color the numbers 1 to 9 in the specific hues they experience when seeing the number. The colors were chosen from the custom color palette available in Microsoft Office 2000 (32 bit color-depth; hue, saturation and brightness could be set independently). All synesthetes colored the numbers almost identical in both instances, indicating that good color/hue matches could be obtained. Pair-matched controls used the color-number pairs of each synesthete.

The stimuli consisted of black Arabic numbers ranging from 3 to 6 and color patches in the synesthetic colors that were related to the numbers 3 to 6 (width = 1.6° visual angle, height = 2° visual angle). None of the synesthetes participating in the experiment had similar synesthetic colors for the distinct numbers, therefore cross-priming can be excluded as a factor causing congruency effects. 14 Prime-target combinations were used (3-3, 3-4, 3-5, 4-3, 4-4, 4-5, 4-6, 5-3, 5-4, 5-5, 5-6, 6-4, 6-5, 6-6). The stimuli were presented centrally on a grey background and the viewing distance was approximately 57 cm. The study consisted of two tasks (384 trials each), each consisting of both congruent and incongruent trials (192 trials each).

The two tasks were (1) a number-color priming task in which participants had to press the button of a response box that corresponded to the color target presented on the screen (Figure 1a) and (2) a color-number priming task in which participants had to press the button of the response box that corresponded to the number target presented on the screen (Figure 1b). The order of the two priming tasks was counter-balanced between participants. Each trial began with a fixation cross (500 ms), followed by the prime (500 ms), an inter-stimulus-interval (500 ms), the target (500 ms) and a random inter-trial-interval (1250-1500 ms). Participants responded with the left middle finger to the number 3, the left index finger to the number 4, the right index finger to the number 5 and the right middle finger to the number 6 (or the synesthetic color corresponding to that particular number). Prior to each experiment, 20 practice trials were completed. In addition, the buttons on the response box were marked with the colors or numbers they corresponded to.

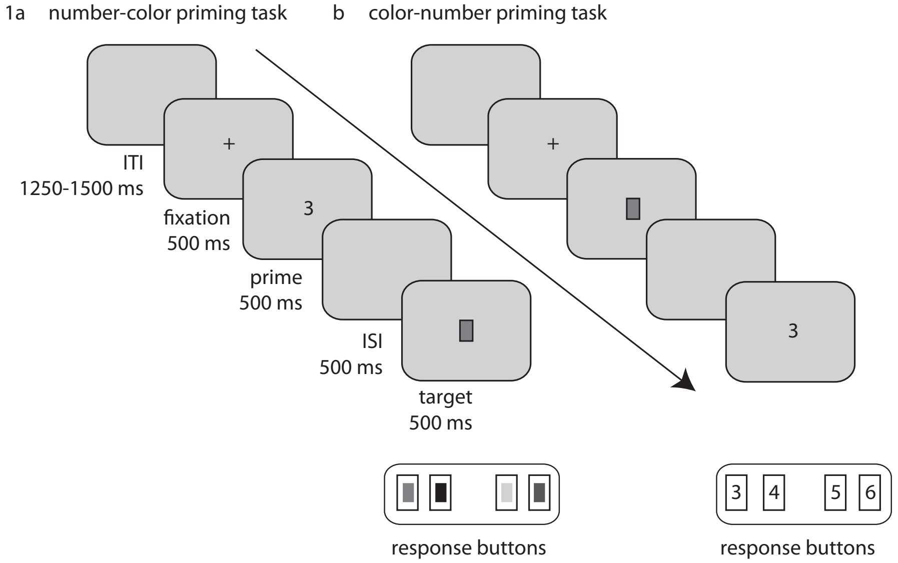

Fig. 1. Schematic representation of a trial of the number-color priming task (a) and the color-number priming task (b) where subjects had to manually respond to the target stimulus by pressing the corresponding button.

Reaction time analyses

All participants reached our criterion of 80% correct responses. For each participant, median reaction times for these correct responses were calculated per congruency condition. All statistical analyses were performed on these median reaction times.

Electrophysiological recordings

EEG and EOG activity were recorded using an Electrocap with 58 tin electrodes, referenced to the right mastoid. The ground electrode was placed within the cap between Fpz and Fz. Vertical electro-oculogram (VEOG) was recorded from electrodes attached above and below the left eye and the horizontal electro-oculogram (HEOG) from the outer canthi of both eyes. Electrode impedance was kept below 5kΩ. EEG and EOG were amplified with a Brain-Amp amplifier (Brain Products GmbH, Germany) with a bandwidth of 0.04-100 Hz. The sampling rate was 500 Hz.

ERP analyses

Participants were discarded from both the ERP and the behavioral analyses when more than 25% of the trials contained artifacts. This resulted in the exclusion of four synesthetes and one control participant. EEG and EOG data were analyzed using Brain Vision Analyzer software (1.05). Data from noisy or flat electrodes were discarded (this never concerned more than 2 electrodes per subject); the electrodes included in the rest of the analyses were not among them. EEG signals were off-line re-referenced to the average of all electrodes. The continuous EEG data was segmented into epochs from 300 ms prior to the prime until 1000 ms after the presentation of the target (in total an epoch comprised 2000 ms). An artifact of any kind during the prime might severely influence the response to the target. Including the prime in epoch allowed rejecting the segment when an artifact was present during the presentation of the prime. Epochs were filtered with a bandpass filter (0.05 Hz, 12dB octave; 40Hz, 24dB / octave) and corrected for eye movements according to the Gratton et al. algorithm (1983). Trials with artifacts (difference criterion of 100μV within an epoch; low activity criterion of 0.5μV within a 100ms time window) or an incorrect response were rejected from further analyses. The baseline for the ERPs was defined as the mean of the 100ms period before the onset of the target stimulus. Grand average ERPs were created for each congruency condition. These were filtered at 8Hz low pass, 12dB / octave for visualization purposes only.

On the basis of scalp maps of the synesthetes reflecting the difference waves (incongruent-congruent), a frontal positivity and a parietal negativity were obtained (Figure 2a and b). Inspection of the grand average waveforms revealed that the frontal positivity reflects a difference in amplitude (Figure 4a and b), whereas the parietal negativity reflects a latency difference (Figure 4c and d). The frontal-central priming effect started around 280-450 ms post stimulus, which corresponds to the component commonly referred to as the P3a. The parietal priming effect started around 300-500 ms post stimulus and corresponds to the component commonly referred to as the P3b. Peak amplitudes were estimated for each subject separately at the Fz electrode in the 280-450 ms time window and peak latencies at the Pz electrode in the 300-600 ms time window. We also estimated the peak latencies of the P1 (80 – 180 ms) and N2 (150 – 220 ms) components at the Pz electrode to investigate whether the peak latency effect was already apparent at an earlier stage. Moreover, even though no early perceptual effects were apparent from the difference waves, the N170 component (a component related to orthographic processing) was estimated at the occipital and parietal-occipital electrodes as well. Specifically, it was estimated as the largest negative deflection at 150-200 ms at the electrode sites Oz, PO7 and PO8. This allowed us to ascertain whether early perceptual effects are present in subtypes of synesthetes that are not apparent at group level.

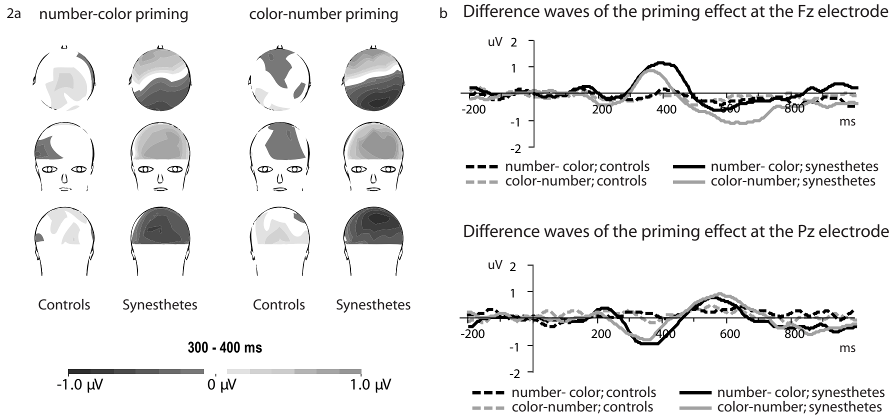

Fig. 2. Scalp maps portraying the priming effects (incongruent-congruent) for both controls and synesthetes and both priming tasks (a). Difference waves portraying the priming effect (incongruent-congruent) of both controls (dashed lines) and synesthetes (solid lines) and both priming tasks at the electrode Fz (upper figure) and electrode Pz (lower figure) (b)

Behavioral results

To test whether priming effects were present in the number-color and the color-number priming task of the synesthetes and controls independent of the direction of information flow, we performed a repeated measures ANOVA with TASK (number-color and color-number priming) x CONGRUENCY (congruent and incongruent) as within subjects factors and GROUP (controls and synesthetes) as a between subjects factor. A significant main effect of Group [F(2,26) = 16.128, $p < 0.001$] as well as an interaction between Congruency and Group was present [F(2,26) = 12.380, p = 0.002], indicating that a significantly larger congruency effect was present for synesthetes compared to controls in the number-color (132.6 ms versus 12.7 ms) and in the color-number priming task (135.7 ms versus 5 ms) (Figure 3). Post hoc T-tests revealed a significant congruency effect within the group of synesthetes with increased reaction times for the incongruent compared to the congruent condition for both the number-color priming [t(13) = -3.782, p = 0.002] and the color-number priming [t(13) = -3.537, p = 0.004] task. Post hoc paired samples T-tests for the control group showed a significant congruency effect of the color-number priming task only [t(13) = -2.625, p = 0.021]. Even though the congruency effect of the controls was significant, it was only 5 ms and was, as described above, significantly smaller compared to the synesthetic priming effect (135.7 ms; ~41 standard deviations away from that of the controls). Moreover, even when the group of synesthetes was split, based on the strength of the priming effect (see below), the group with the smallest priming effect revealed a priming effect that was more than 5 times larger than that of the controls (26.4 ms; ~8 standard deviations from that of the controls; see Table 1). Therefore, we consider this outcome coincidental.

Having established that a congruency effect was present for synesthetes in both the number-color and color-number priming task, we subsequently analyzed whether these synesthetic congruency effects were of similar magnitude. To this end we performed paired T-tests on the relative and absolute congruency effects of the synesthetes, which were calculated by dividing the incongruent by the congruent condition or subtracting the congruent from the incongruent condition, respectively. Both relative [t(13) = 0.164, p = 0.872] and absolute [t(13) = 0.032, p = 0.975] congruency effects did not differ significantly, suggesting that colors primed numbers equally well as numbers primed colors.

In addition, we compared the results of projector and associator synesthetes to test for potential differences between subtypes. A second repeated measures ANOVA was performed with TASK (number-color and color-number priming) x CONGRUENCY (congruent and incongruent) as within subjects factors and SUBTYPE (projectors and associators) as a between subjects factor. No significant main effect or interaction was present.

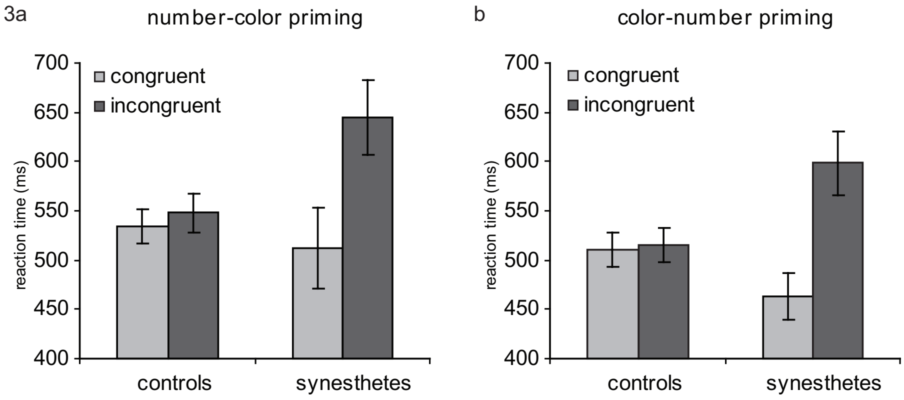

Fig. 3. In contrast to the results of the controls, the results of the synesthetes reveal a congruency effect with faster responses for the congruent (color and number matched) compared to the incongruent (color and number did not match) condition in both the priming tasks, indicating an effect of number on color processes (a), as well as of color on number processes (b).

ERP results: bi-directionality

Difference waves (incongruent-congruent) for both tasks are shown in Figure 2, from which a substantial effect of priming in both directions is apparent, but only for synesthetes. As stated in the methods, the frontal positivity reflects a difference in amplitude, whereas the parietal negativity reflects a latency difference (Figure 4). To test the frontal amplitude and the parietal latency effects we performed a repeated measures ANOVA with TASK (number-color and color-number priming) x CONGRUENCY (congruent and incongruent) as within subjects factors and GROUP (controls and synesthetes) as a between subject factor for both the P3a amplitude at Fz as well as the P3b latency at Pz. [1]

For P3a peak amplitude, a significant effect of Congruency was present [F(2,26) = 6.35, p = 0.018], as well as an interaction between Congruency and Group [F(2,26) = 7.81, p = 0.010], which suggests that the congruency main effect was modulated by Group. Post hoc paired samples T-tests revealed a significant congruency effect (larger amplitudes for incongruent compared to congruent trials) for the number-color [t(13) = -3.064, p = 0.009] as well as the color-number [t(13) = -3.206, p = 0.007] priming task (Figure 4a and b), but only for the synesthetes. Post hoc paired T-tests of the congruency effect of the P3a amplitude (incongruent-congruent) revealed that the effect was of similar magnitude in both priming tasks [t(13) = 0.691, p = 0.502], which concurs with the behavioral data (see above).

For P3b peak latency, the results revealed a significant congruency effect [F(2,26) = 12.426, p = 0.002] with longer latencies for incongruent compared to congruent trials. This congruency effect interacted with Group [F(2,26) = 7.05, p = 0.013], indicating a significantly larger congruency effect for synesthetes (45 ms for the number-color and 61 ms for the color-number priming task) compared to controls (11 ms for the number-color and 4 ms for the color-number priming task). Paired samples T-tests underlined these results: a significant congruency effect on the number-color priming [t(13) = -3.408, p = 0.005] as well as color-number priming task [t(13) = -2.578, p = 0.023] was present for synesthetes only (Figure 4c and d). Post hoc paired T-tests of the congruency effect of the P3b latency (incongruent-congruent) revealed that the congruency effect was of similar

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[1] No statistical main or interaction effects were found for P3a latency at Fz or P3b amplitude at Pz.

magnitude in both priming tasks [t(13) = 0.769, p = 0.456] as was the case for the behavioral and P3a amplitude data (see above).

A latency effect of the P3b component is the result of processes leading up to stimulus evaluation (i.e. processes that happen before the P3b peak; Luck, 2005). To test whether these P3b latency effects can be explained by processes starting before P3b onset, we performed a repeated measures ANOVA with TASK (number-color and color-number priming) x CONGRUENCY (congruent and incongruent) as within subjects factors and GROUP (controls and synesthetes) as a between subject factor for the earlier components at Pz (P1 and N2) and ERP measures (latency and amplitude). No significant Congruency or interaction of Congruency and Group was obtained suggesting that the latency effect of the P3b could not directly be related to effects present at earlier components (P1 and N2) at Pz.

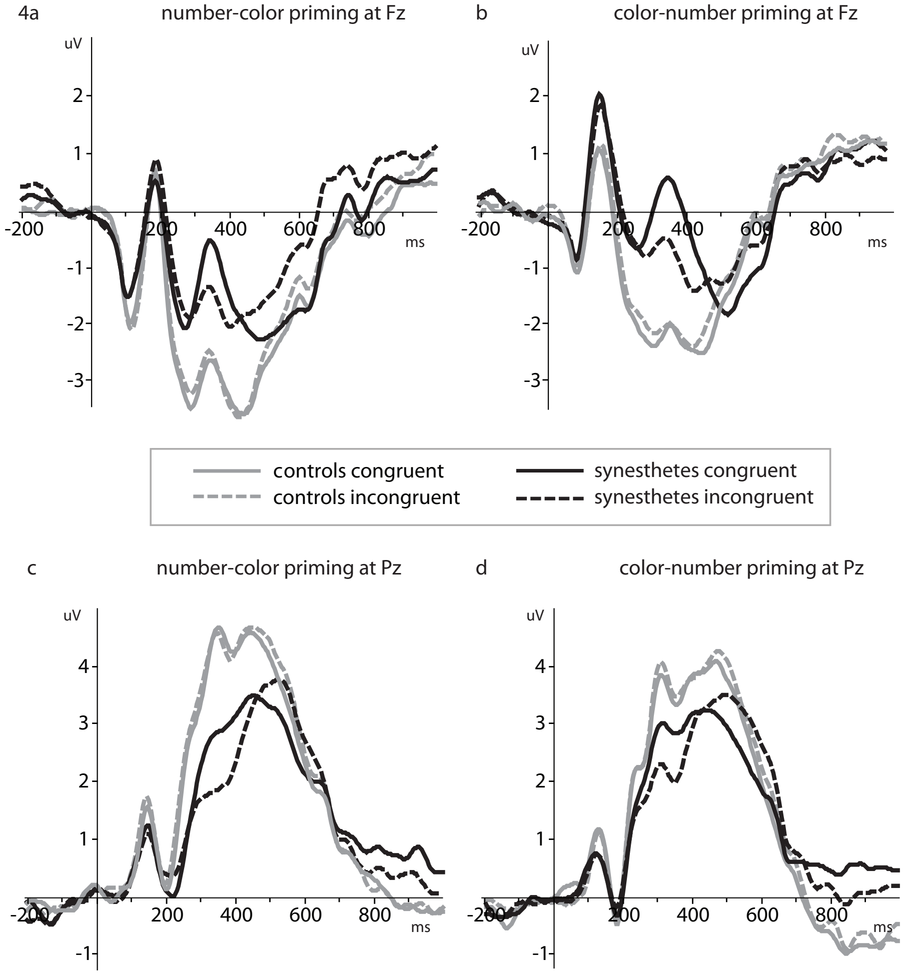

Fig. 4. The ERPs revealing the congruent and incongruent priming condition of the controls (grey lines) and the synesthetes (dark lines) in the number-color priming task (a and c) and the color-number priming task (b and d) at the Fz (upper row) and the Pz electrode (lower row).

ERP results: Projector – associator versus lower- higher synesthetes

Since the inclusion of distinct subtypes of synesthetes might have obscured synesthetic subtype specific effects, we performed a repeated measurements analyses with TASK (number-color and color-number priming) x CONGRUENCY (congruent and incongruent) as within subjects factors and GROUP (projectors and associators) as a between subject factor for the distinct ERP components and measures presented above. No significant interaction between Congruency and Group was present for the P1, N2 and P3b component at Pz, for the P3a component at Fz, or for the N170 component at the electrodes PO7, PO8 and Oz.

In addition to the phenomenological classification into projector and associator synesthetes, Hubbard et al. (2005) showed that synesthetes appeared to be distinguishable on the basis of their behavioral results. In this study, they demonstrated a strong correlation between their behavioral effect and a physiological (fMRI) measure. Consistent with their reports, in our study, two distinct groups of synesthetes were dissociable on the basis of the behavioral results as well: one containing the synesthetes with a small, and one containing the synesthetes with a large priming effect (see Table 1). In our sample, these groups were equal in size (n=7, for both groups[2]). Even though the priming effects were small in the former group they were significant for both the number-color [t(6) = -4.871, p = 0.003] and the color-number [t(6) = -2.052, p = 0.046] priming task. Not surprisingly, significant behavioral results were obtained for the group with the large priming effects as well for the number-color [t(6) =-3.592, p = 0.011] and for the color-number priming task [t(6) = -6.603, p = 0.001]. We subsequently tested whether this division is mirrored by any of our physiological measures. Therefore, a repeated measures ANOVA was performed with TASK (number-color and color-number priming) x CONGRUENCY (congruent and incongruent) as within subjects factors and GROUP (small and large behavioral priming effect) as a between subjects factor for both the P3a amplitude as well as the P3b latency data. For the P3a amplitude, no interaction between Congruency and Group was present [F(2,6) = 2.486, p = 0.141]. However, a significant interaction between Congruency and Group was obtained for the P3b latency [F(2,6) = 15.734, p = 0.002]. Post hoc paired T-tests revealed that a significant congruency effect was present in the group with large behavioral effects for both the number-color [t(6) = -2.462, p = 0.049] and the color-number [t(6) = -3.435, p = 0.014] priming task. In contrast, no significant congruency effects for the number-color [t(6) = -1.225, p = 0.266] or the color-number priming task [t(6) = -1.709, p = 0.138] were present in the group with small behavioral effects. Together, these results indicate that within the group of synesthetes, two classes can be distinguished: synesthetes revealing congruency effects at the frontal and parietal electrode sites and a group displaying a modulation at the frontal electrode site only. Within the group of controls we found no dissociable congruency effect. Therefore, no comparable statistical analysis was performed on the control data.

Finally we also investigated whether the congruency effect of the P3b latency and P3a amplitude was of similar magnitude in both priming tasks for the two dimensions of synesthetes. No significant results were obtained suggesting that the task at hand did not influence the size of the congruency effect for both the projector and associator as well as higher and lower synesthetes.

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[2] Coincidentally, both groups contained 3 projectors and 4 associators.

Table 1 The behavioral and neurophysiological priming effects

	number-color priming task					
	RT		P3a amplitude		P3b latency	
	M	SD	M	SD	M	SD
synesthetes (small behavioral priming effect)	49.1	12.2	0.3	0.7	18.0	14.7
synesthetes (large behavioral priming effect)	216.1	60.2	1.0	0.5	73.7	29.9
controls	12.7	4.8	0.0	0.2	11.4	13.4

	color-number priming task					
	RT		P3a amplitude		P3b latency	
	M	SD	M	SD	M	SD
synesthetes (small behavioral priming effect)	26.4	14.9	0.6	0.3	27.4	16.0
synesthetes (large behavioral priming effect)	245.0	37.1	1.5	0.6	94.0	27.4
controls	5.0	3.3	-0.1	0.1	3.6	10.6

Table 1. The three measures (reaction time, P3a amplitude and P3b latency) are given for two groups of synesthetes separately. The two groups were distinguished on the basis of their behavioral priming effect (incongruent – congruent). The upper part shows the means (M) and standard deviations (SD) for the number-color priming task, the lower part shows the means and standard deviations for the color-number priming task.

GENERAL DISCUSSION

Bi-directionality

In this study, our main aim was to investigate the time course of bi-directional interactions in synesthesia using a number-color and a color-number priming task. The reaction time data revealed a priming effect (present only for the synesthetes) that was of similar magnitude in both directions, thus replicating the results of our previous study (Gebuis, Nijboer, & van der Smagt, 2009). This outcome already hints at similar neural correlates underlying both directions of information flow in synesthesia, yet more conclusive evidence was derived from the ERP components affected. For both priming tasks, the congruency effect modulated the same ERP components. The incongruent trials resulted in larger P3a amplitudes at frontal and longer P3b latencies at parietal electrodes for the incongruent compared to the congruent trials. The P3a amplitude reflects orienting of attention (Polich & Comerchero, 2003; Schroger & Wolff, 1998) or the inhibition of response processes (Goldstein, Spencer, & Donchin, 2002), whereas the P3b latency effect is thought to be related to processes leading up to stimulus evaluation such as lower-level sensory processes (Donchin, Miller, & Farwell, 1986; Luck, 2005). Consequently, both early perceptual as well as later attentional or inhibitory processes appear to play a role in synesthesia.

Our results concerning the influence of number on color processes are consistent with previous studies (Mattingley, Payne, & Rich, 2006; Mattingley et al., 2001; Schiltz et al., 1999). The presence of the modulation of attentional processes in synesthetes is in line with the results of Mattingley et al. (2001) who reported the necessity of overt recognition of the prime in synesthetic priming. In their study, priming effects were obtained only after initial processing of visual form. In addition Schiltz et al., (1999) found amplitude differences at the frontal electrodes and large positive peaks at the parietal electrodes as well. They suggested that the frontal amplitude effects were related to inhibitory mechanisms that modulated the parietal activation, an idea that is most consistent with the disinhibited feedback model (Grossenbacher & Lovelace, 2001). This model postulates that feedback of information is inhibited in normal subjects but not in synesthetes resulting in synesthetic experiences.

Our results concerning bi-directional processing suggest that similar mechanisms subserve both directions of information flow in synesthesia, extending the results of Cohen Kadosh et al. (2007). In their study, an explicit synesthete revealed bi-directional congruency effects at the perceptual as well as a late attentive stage. As these authors already suggested, the usage of an explicit synesthete could lead to distinct results when compared to the implicit form of bi-directional synesthesia, which is consistent with the results presented here. The results of the implicit synesthetes revealed that the same processes were affected independent of the direction of information flow.

Multiple dimensions in synesthesia

Synesthetes have been classified along two dimensions: (1) projectors versus associators and (2) higher versus lower synesthetes. Dixon & Smilek (2005) recently suggested that both dimensions might be equivalent. The neurophysiological responses obtained during the priming tasks allowed us to dissociate distinct processes in time, which together with the inclusion of projector and associator synesthetes made it possible to differentiate between these two dimensions.

For the projector-associator dimension, a significant difference was found neither at the behavioral, nor at the neurophysiological level. The absence of a significantly larger priming effect in the reaction time data for projectors is at odds with results obtained by Dixon et al. (2004). They reported that projectors were more hindered by the elicited color experience compared to associators in a synesthetic Stroop task. In such a paradigm graphemes are presented in an ink color congruent or incongruent with the synesthetic color experience. The difference in (either grapheme- or color-) naming latency of the incongruent and congruent trials is referred to as the congruency effect and is indicative of automatic interference of the unattended dimension (e.g. the elicited synesthetic color or the ink color). Johnson et al. (2007) reported a similar finding. The results of the projector in their study revealed the largest congruency effect on a color-naming task and belonged to one of the three synesthetes with the largest effect in the digit-naming task. As already suggested by Cohen Kadosh et al. (2007), task differences (in this particular case priming versus conflict processing) might underlie these different outcomes. In the synesthetic Stroop task, for instance, the color and a number are presented at the same time, which might result in a visual conflict leading to longer reaction times in the incongruent condition. It is not surprising that in this case projectors suffer more from the visual conflict induced compared to associators. In contrast, in our study, both stimulus properties were presented sequentially, which prevented such a visual conflict.

For the higher-lower synesthesia dimension we applied a similar method of analyses as Hubbard et al. (2005). They demonstrated that consistent patterns within two groups of synesthetes were present between two measures (behavioral and fMRI data). In our study, the synesthetes could be divided into a group with small and a group with large behavioral priming effects. Interestingly, as was the case in the Hubbard et al. (2005) study, these two groups of synesthetes partly differed in their physiological responses as well. The group with large behavioral priming effects revealed priming effects at both frontal and parietal electrodes, whereas the group with small behavioral effects revealed frontal effects only[3].

Together, these results are indicative of the existence of distinct groups of synesthetes. Synesthetic experiences can apparently arise as a result of both bottom up (perceptual) and top-down (attentional/inhibitory) processes, or as a result of top-down (attentional/inhibitory) effects only. Our results fit well with the classification proposed by Ramachandran & Hubbard (2001), who suggested that besides the classification of synesthetes on the basis of their phenomenological experience, synesthetes could be classified on the basis of the inducers or the triggers of the synesthetic experience. They referred to synesthetes that reveal effects at lower perceptual processes as 'lower' synesthetes and to synesthetes with higher cognitive effects as 'higher' synesthetes. Our results indicate that attentional or inhibitory processes appear to play a role in bi-directional priming in all synesthetes, whereas only some (possibly 'lower') synesthetes reveal a priming effect at a lower, possibly perceptual level, as well.

Dixon & Smilek (2005) already emphasized the necessity of scrutinizing effects at the single subject level. They stated that if synesthesia is not a unitary phenomenon, possible patterns might be masked when all synesthetes are grouped together, resulting in conflicting reports or erroneous conclusions. Our results underline this suggestion and might explain some of the conflicting results reported concerning the stage at which the synesthetic experience arises. Involvement of both early pre-attentive as well as later attentional processes have been demonstrated in psychophysical (see for a critical review: Gheri, Chopping, & Morgan, 2008) as well as imaging research (Barnett et al., 2008; Beeli et al., 2008; Brang, Edwards, Ramachandran, & Coulson, 2008; Elias, Saucier, Hardie, & Sarty, 2003; Nunn et al., 2002; Paulesu et al., 1995; Rich et al., 2006; Schiltz et al., 1999; Weiss et al., 2005). In accordance with the study of Hubbard et al. (2005), the present study demonstrated that (grapheme-color) synesthesia is far from a unitary phenomenon.

CONCLUSIONS

Our results demonstrate, for the first time, that the same mechanisms underlie bi-directional interactions in synesthesia, at least for implicit synesthetes. At the group level, the priming effect for number to color as well as color to number were present at parietal (possibly perceptual processes) as well as frontal electrode sites (possibly attention or inhibitory processes). The ERP-components affected did not differ between the often-described synesthetic subtypes (projectors and associators). Instead, when subjects were classified according to their behavioral performance, a dissociation between 'lower' and 'higher' synesthetes emerged. It is tempting to suggest that the attentional or inhibitory processes are important for higher and lower synesthetes alike, while for lower synesthetes perceptual processes play a role as well."

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[3] Although stimulus categorization processes can be reflected in both the P3b latency and reaction time, suggesting a close relation between both measures (Luck, 2005), the presence of significant priming effects in both groups of synesthetes combined with an absence of a P3b latency effect in one group only, implies that there is no direct causal relationship between our behavioral and electrophysiological measure. Rather it suggests that the behavioral results of the group with small priming effects but no P3b latency effects are induced by the processes underlying the frontal amplitude effects.

CHAPTER 9

DISCUSSION AND PERSPECTIVES

DISCUSSION

This thesis consists of three parts. The first entails the development of automated symbolic and non-symbolic numerosity processing. The second concerns the mechanisms underlying the interactions between distinct magnitudes while the third deals with the mechanisms underlying interactions between arbitrary associations. Using behavioral and electrophysiological measures hypotheses surrounding these topics were investigated in children, adults and synesthetes and discussed in chapters 2 to 8. Below I will give a concise summary of the results and consider future perspectives.

Automated symbolic and non-symbolic numerosity

The behavioral studies that have previously investigated the development of Arabic number processing revealed that automated access to symbolic number knowledge arises around the age of 7 or 8 (Girelli et al., 2000; Rubinsten et al., 2002). In chapter 2 we questioned whether this rather late onset of automated access to symbolic number meaning was the result of the child's relative unfamiliarity with the number symbols or the result of not yet fully developed cognitive abilities. To disentangle both hypotheses we designed a non-symbolic size congruency task and administered it together with the symbolic size congruency task to adults. The results revealed similar behavioral congruency effects for both numerosity notations. Consequently, the task was considered suitable to directly compare symbolic and non-symbolic numerosity processes in second graders. The behavioral results of the children's responses to the physical size of the stimuli revealed congruency effects for non-symbolic but not symbolic notation. It was therefore concluded that the link between the number symbol and its meaning is still premature in second graders.

In chapter 3 we employed the same size congruency tasks as in chapter 2. Adults had to respond to both physical as well as numerical size while electrophysiological recordings were made. Chronometric analyses of the event related potentials (ERPs) showed that both tasks are not only comparable on a behavioral level but also affect the same neural correlates.

In chapter 4 the development of neural processes involved in the automatization of symbolic numerosity processing was addressed. Children that just learned the number symbols (second graders), children that worked with the number symbols already for two years (fourth graders) and adults were tested. All subjects had to perform physical size judgments in the symbolic and non-symbolic size congruency task while electrophysiological recordings were made. The behavioral and the ERP data revealed several interesting results. First, the children of the youngest age group revealed congruency effects at the behavioral level for the non-symbolic but also the symbolic notation. This is remarkable since the second graders tested in chapter 2 did not reveal such a behavioral congruency effect for symbolic notation. The second graders that participated in the experiment of chapters 2 and 4 were recruited from the same area in Utrecht. Consequently, the currently held hypothesis that cultural differences underlie the large variety in onset time of automatic symbolic number knowledge can be rejected (Zhou et al., 2007). A tentative explanation for the contradictory findings is a difference in both formal as well as informal schooling. Second, the same neural correlates subserved automatic processing of magnitude in fourth graders as well as adults. This is intriguing since previous studies reported that children around eight to fourteen years still recruit distinct processes when symbolic number meaning has to be accessed (Ansari et al., 2005; Kaufmann et al., 2006; Rivera et al., 2005). Again the differences in formal and informal schooling, the children received, might explain these relative early onsets of automated number processing. Third, second graders recruited distinct processes in the symbolic but not the non-symbolic task. This ontogenetic shift in the processes recruited for symbolic number processing might relate to the automatization of number processes or the functional specialization of the parietal cortex (Ansari et al., 2005). Fourth, the effect of interference for symbolic notation increased while that for non-symbolic notation decreased with age. We proposed two putative explanations for this result. On the one hand increased reliance on symbolic and decreased reliance on non-symbolic processes when the symbolic notation is learned could explain these effects. On the other hand developing inhibitory processes could lead to decreased congruency effects for non-symbolic notation while increased automatization of the number symbols could lead to larger congruency effects for symbolic notation.

Chapters 2 to 4 focused on the automatization of symbolic numerosity using non-symbolic numerosity processing as a control. These studies relied on the embedded assumption that the adults non-symbolic numerosity system derived from the rudimentary number sense present at infancy. In Chapter 5 it is questioned whether this is indeed the case. To address this issue it is fundamental to use a paradigm comparable to those used in infant studies therefore we developed a habituation like paradigm and used electrophysiology as a measure. In the first part of the experiment, the subjects were not informed about the numerosity changes in the task as to mimic the infant's unawareness of the task at hand (passive paradigm). The ERP results revealed that, similar as in infants, the ability to "detect" numerosity changes in adults depended on the relative and not the absolute difference of the numerosity changes. However, adults appeared less prone to numerosity changes compared to what could be expected on the basis of the results of the infant studies. In a second study, this controversy was addressed. We informed the adults about the numerosity changes and instructed them to make a button press as soon as they detected a numerosity change (active paradigm). Contrary to the expectations, the electrophysiological effects were comparable to those obtained in the passive paradigm. However, the behavioral results could explain this effect, adults appeared significantly worse in detecting the small compared to the large ratio changes. Apparently, adults are less prone to numerosity changes than infants are. These novel results are in agreement with the outcomes of chapter 4.

Early or later interaction account

Chapter 3 revealed that the timing of the interaction between distinct magnitudes is similar for distinct numerosity notations and occurs prior to response selection or initiation. On the basis of these results an interaction at the level of stimulus evaluation was proposed. Even though the result of an "early" interaction at the stimulus processing level is in line with a general magnitude system (Dehaene, 2003; Walsh, 2003), alternative explanations remain. For instance, instead of integrating the distinct codes into a common code they could be processed in parallel and interact at a stimulus categorization level. As a result of the task requirements the stimulus could be categorized into "small" or "large" number, physical size, line length etc. The relative extent to which each of the two alternative categories is activated determines the direction and the magnitude of the conflict, which is subsequently expressed in the reaction times. Chapter 6 further elucidated the origins of such magnitude interactions using a number-luminance congruency paradigm. Contradictory results, in previous studies employing this paradigm, have been reported (Cohen Kadosh, Cohen Kadosh et al., 2008; Cohen Kadosh & Henik, 2006b; Pinel et al., 2004) therefore we proposed three alternative explanations for the origins of the number-luminance interaction. To be able to distinguish between the three hypotheses we added two conditions to the original number-luminance congruency task. The results revealed that both the level of luminance of the stimulus itself as well as the contrast of luminance and the background is associated with numerical size. It should be noted that the stimuli were identical. Thus even though the stimuli were alike luminance was differentially associated with numerical size suggesting that a categorization process preceded response processing.

Arbitrary associations

As revealed in chapters 2 to 4 and 6, interactions between distinct magnitudes can arise even when the magnitudes have been learned later in life. Similarly, in synesthetes, associations between distinct sensory experiences and the later acquired graphemes can establish. In contrast to, for instance, numerical and physical size interactions synesthetic experiences are not bi-directional. Arabic numbers evoke color experiences in synesthetes but there is only one study that reported the reverse (Cohen Kadosh, Cohen Kadosh, & Henik, 2007). In chapters 7 and 8 we investigated the possibly implicit bi-directional interaction between numbers and colors in grapheme-color synesthetes. Previous studies mostly relied on paradigms where both the “explicit” as well as the “implicit” inducer were present in the same stimulus (e.g. synesthetic Stroop task). The direction of the interaction is consequently not controlled for. To overcome this problem we presented the stimuli sequentially (priming paradigm). From number priming studies it is known that the priming effect decreases with increasing distance between the prime and the target (Roggeman et al., 2007). The presence of a numerical distance effect in the color-number priming task and the absence of it in the number-color priming task would implicate that the color prime elicited number processes. The results revealed a numerical distance effect in the color-number priming task only supporting the notion of bi-directional synesthesia. In the second part of this study we used a parity judgment paradigm. Subjects viewed numbers presented in the color that matched the synesthetic experience of that number or in a color that did not match the synesthetic color experience. The synesthetes responded faster to the trials where the parity of the synesthetic color and the number matched. This result underlined the findings of the first part of the experiment by adding evidence to the notion of bi-directional interactions in synesthesia. In chapter 8 synesthetes performed, similar as in chapter 7, a priming task but now we also recorded the ongoing neural activity. One of the two neural correlates that were affected by the priming task was the same parietal component as obtained for number-size interactions in chapters 3 and 4. The other component involved was present at a frontal electrode site and is often associated with attentional or working memory processes. Interestingly, dividing the group of synesthetes in two on the basis of the behavioral results revealed a dissociation in the neural components affected. The frontal component only was affected in the group of synesthetes with a small but significant behavioral priming effect whereas both the frontal and parietal component were affected in the group of synesthetes with a large behavioral priming effect. No such dissociation was present for the projectors and associators, suggesting that multiple dimensions of synesthesia exist.

PERSPECTIVES

The findings reported in this thesis show that the mechanisms underlying the development of number processes are only roughly understood. This present thesis provides some basic insight in these mechanisms. However, questions remain concerning the ontogenetic shift in processes recruited to process Arabic numbers (chapters 2 and 4), as well as the observed decreased reliance on non-symbolic numerosity processes in adults compared to infants or children (chapters 4 and

5). Furthermore, the results concerning the second theme of the thesis, the interactions between distinct magnitudes, revealed support for the “early interaction account”. However, it does not necessarily implicate the existence of a general magnitude system (chapters 3 and 6). I have emphasized the possibility of an alternative explanation, which might advance the ongoing debate about the neural representation of magnitudes. Finally, my results concerning the last theme of this thesis, about aberrant interactions, showed that bi-directional interactions can arise in synesthetes on an ‘implicit’ level and that synesthesia is not a unitary phenomenon (chapters 7 and 8). It could be argued, however, that these interactions that are only present at the implicit level, are the result of long-term learning.

The experimental paradigms implemented in our studies about the development of number processes and the interactions between magnitudes were all variants of Stroop paradigms. Even though this is a frequently used paradigm to study automated access to magnitude representations, it is not the only one that can give an insight in these processes. The numerical priming paradigm, for instance, might be a good alternative. This paradigm does not rely on conflict or inhibition processes, which are still under development in children. Therefore, the use of such a priming paradigm might be particularly suited to study the differences in the onset of automated number processing, the mechanisms underlying the ontogenetic shift, as well as the interactions between magnitudes.

The priming paradigm already appeared a fruitful technique to study aberrant connections. Even though this part of the thesis did not address the development of these aberrant connections per se, the use of this paradigm and the study of synesthesia, can have major implications for synesthesia research but also studies on number processes in the non-synesthetic population. First, studying the development of synesthetic experiences could reveal whether the activation of number processes when colors are perceived are due to long-term learning. Second, this association of colors and numbers might reflect the automatization of Arabic number symbols. Since synesthetes explicitly perceive these color associations when this process becomes automated, this automatization of associations between distinct entities can be studied more explicitly. To be able to include children that are on the brink of having these aberrant associations is of course a major problem. A possible strategy is to search for children that already have synesthesia with non-symbolic numerosities or, since synesthesia is suggested to be inheritable, initially children can be included in the study that have one or more synesthetic family members.

Together, in the field of numerical cognition, the study of the neural processes underlying the development of distinct magnitude representations is of fundamental importance. Knowledge about how these processes develop in the normal population is a necessary prerequisite before conclusions can be drawn about children or adults with mathematical difficulties. In the end, this could lead to a better guidance of teachers and thus a better education.

EPILOGUE

The studies reported in this thesis are part of the Educational Neuroscience project, supported by the Netherlands Organization for Scientific Research (grant nr: 051.04.050). This project aimed to combine perspectives from the field of neuroscience and education research to study the processes subserving mathematical development. Mathematics is one of the main topics provided in education. The necessity to reach a sufficient proficiency in mathematical abilities is reflected in the many encounters in daily life that require mathematical reasoning. Currently, there is not much consensus about the problems that cause mathematical difficulties in children or adults, and therefore the Educational Neuroscience project aimed to provide new tools to assess mathematical difficulties. From neuroscience it is suggested that there is a core mechanism, the number sense, which is necessary for numerical reasoning but that there are also processes that aid or facilitate these numerical skills such as spatial reasoning. By combining the neuroscience results with knowledge derived from what is observed during daily activities in the classroom, a more thorough picture of the processes necessary for proper mathematical development can be provided.

However, developing a single task that is useful for both disciplines proved difficult, since both disciplines are very distinct, both in methods and scientific mores. Education research uses qualitative methods by assessing the child's strategies in an interactive manner whereas neurosciences relies more on quantitative methods using carefully controlled designs and larger populations. Consequently, in this project neuroscience focused upon one part of the research aim entailing the mechanisms necessary to develop proper mathematical skills, whereas education research focused on the necessity of spatial skills that were proposed to aid mathematical processing. In this manner the results from both disciplines were additive. The reported results about processes subserving mathematical development and the problems faced in combining both fields of research are of great value for mathematics research as well as future studies intending to conduct interdisciplinary research. We propose that future interdisciplinary studies, investigating mathematical processes, should not intend to create a single task or methodology but instead use the results of the education research to classify the mathematical abilities of children based on their strategies used. Additionally, the neuroscience methodologies should be used to identify whether these distinct strategy groups also reflect differences at the neuronal level.

SAMENVATTING IN HET NEDERLANDS

Dit proefschrift bestaat uit 3 delen. In het eerste deel wordt de ontwikkeling van geautomatiseerde symbolische en niet symbolische numerieke processen besproken. Het tweede deel gaat over de mechanismen die betrokken zijn bij de interacties tussen verschillende grootheden en het derde deel gaat over de processen die betrokken zijn bij de interacties van arbitraire associaties. Met behulp van gedragsmaten en elektro-encefalografie (EEG) bestudeer ik hypotheses over deze onderwerpen in kinderen, volwassenen en synestheten in hoofdstukken 2 tot en met 8.

De ontwikkeling van numerieke processen.

Met behulp van kijktijd paradigma's is vastgesteld dat baby's van een paar maanden oud al in staat zijn om aantallen te onderscheiden. Nadat een baby herhaaldelijk een scherm met eenzelfde aantal stippen heeft gezien neemt zijn/haar aandacht af, waardoor de baby minder lang naar het scherm zal kijken. Zodra een scherm met een ander aantal wordt gepresenteerd kijkt de baby weer langer naar het scherm. Baby's van 6 maanden oud laten zo'n kijktijd-effect zien als het verschil tussen beide scènes minimaal met een ratio van 2.0 verschilt. Dit 'aantal'-mechanisme is afhankelijk van het relatieve en niet het absolute verschil tussen de aantallen en wordt nauwkeuriger met het ouder worden. In tegenstelling tot baby's van 6 maanden laten baby's van 10 maanden al kijktijd-effecten zien bij bij ratio veranderingen in aantal van 1.5.

Het al vroeg aanwezige vermogen om een onderscheid te kunnen maken tussen aantallen wordt gezien als de basis voor het later aangeleerde symbolische cijfersysteem. Rond het 5de levensjaar leren we de cijfer symbolen die ervoor zorgen dat we niet alleen nauwkeuriger kunnen gaan rekenen, maar ook complexere berekeningen kunnen gaan uitvoeren. Deze symbolen worden geleerd door associaties te leggen met het aantal dat het symbool representeert. Als deze associaties voldoende geautomatiseerd zijn, dan hoeft het kind niet meer stil te staan bij de betekenis van het symbool maar is deze kennis direct en impliciet aanwezig. Het volledig automatiseren van de link tussen het cijfersymbool en zijn betekenis duurt enkele jaren en kan onderzocht worden met de zogenaamde numerieke-Stroop-taak. In deze taak worden steeds twee cijfers aangeboden die kunnen verschillen op 2 dimensies, de fysieke grootte en de numerieke grootte. Hierdoor ontstaan er 3 verschillende condities. De congruente conditie waarbij het numeriek grotere cijfer fysiek groter is, de incongruente conditie waarbij het numeriek grotere cijfer fysiek kleiner is en de neutrale conditie waarbij alleen de numerieke of juist de fysieke grootte verschilt. Als de beoordeling van fysieke grootte van het cijfer resulteert in langzamere reacties in de incongruente conditie en in snellere reacties in de congruente conditie, vergeleken met de neutrale conditie, dan kan men concluderen dat cijferkennis geautomatiseerd is. Recent onderzoek heeft laten zien dat automatisering pas rond het 7de of 8ste levensjaar aanwezig is.

In hoofdstuk 2 van dit proefschrift beschrijven we een studie waarin we kijken waardoor het komt dat kinderen pas 2 of 3 jaar na het leren van de cijfersymbolen deze kennis geautomatiseerd hebben. Komt deze relatief late ontwikkeling van automatische cijferkennis doordat de taak gerelateerde processen zoals aandacht en werkgeheugen nog niet voldoende ontwikkelt zijn of doordat kinderen inderdaad moeite hebben met het automatiseren van cijferkennis? Om deze vraag te kunnen beantwoorden hebben we een niet symbolische Stroop taak ontwikkelt. In deze taak worden in plaats van cijfers van verschillende grootte groepen stippen van verschillende grootte gebruikt. De aanwezigheid van congruentie-effecten in de niet-symbolische en de afwezigheid in de symbolische taak kan nu alleen toegeschreven worden aan de notatie van aantal niet aan taak gerelateerde processen. Nadat we de taak gevalideerd hadden bij volwassenen lieten we kinderen uit groep 2 (die de cijfers die in de taak voorkwamen kenden) de fysieke grootte van de cijfers en aantallen in de symbolische en de niet symbolische Stroop taak beoordelen. De resultaten lieten geautomatiseerde kennis van aantallen maar niet van cijfers zien. Kortom de relatief late automatisering van cijfers is niet toe te schrijven aan taak gerelateerde cognitieve processen die zich nog moeten ontwikkelen maar aan een nog niet voldoende ontwikkelde automatische kennis van cijfersymbolen.

In hoofdstuk 2 lieten de volwassenen op de symbolische en niet-symbolische Stroop taak dezelfde gedragseffecten zien. Dit bewijst nog niet dat de symbolische en niet-symbolische hoeveelheden ook op eenzelfde wijze in ons brein verwerkt worden. Dit hebben we onderzocht in hoofdstuk 3. Terwijl volwassenen een fysieke of een numerieke beoordeling van cijfers en aantallen stippen maakten nam ik het EEG signaal op. Het EEG signaal liet zien dat de interactie tussen grootheden op eenzelfde moment in de tijd plaats vond onafhankelijk van de notatie. In hoofdstuk 4 keek ik hoe deze neurale correlaten van numerieke verwerking zich ontwikkelen. Daarvoor heb ik kinderen gemeten die net de cijfers geleerd hebben, kinderen die al meer kennis van de cijfers hebben en volwassenen die cijferkennis al volledig geautomatiseerd hebben. Deze studie liet veel verschillende resultaten zien. Ten eerste vond ik, in tegenstelling tot hoofdstuk 2, dat kinderen uit groep 2 al wel automatische cijferkennis kunnen hebben. De kinderen uit beide studies kwamen uit dezelfde regio, daarom kunnen culturele verschillen uitgesloten worden en is het waarschijnlijk dat de tegengestelde resultaten komen door verschillen in (in)formeel onderwijs. Ten tweede, bleken deze kinderen andere hersenprocessen te gebruiken om de taak uit te voeren. De oorzaak hiervan zou kunnen zijn, dat de hersengebieden die deze numerieke processen bij kinderen uit groep 4 of volwassenen aansturen in kinderen uit groep 2 nog niet functioneel gespecialiseerd zijn. Ten derde bleek de grootte van het automatisering effect met leeftijd toe te nemen voor cijfers, maar juist af te nemen voor stippen. Dit zou kunnen komen doordat men na het leren van cijfers minder gebruik gaat maken van aantallen. Ook zou het kunnen komen doordat kinderen beter worden in het onderdrukken van de verkeerde reactie. Hierdoor laten ze minder grote congruentie-effecten zien op de niet symbolische stroop taak, terwijl de toename van automatisering van cijferkennis juist zorgt voor een groter congruentie-effect op de symbolische stroop taak.

In de bovengenoemde studies gebruikte ik steeds de niet-symbolische Stroop taak als basis waartegen ik de effecten op de symbolische Stroop taak afzette. Hierbij ging ik er steeds van uit dat aantallenkennis de basis vormt voor de later geleerde cijferkennis. In hoofdstuk 5 heb ik gekeken of deze hypothese kan kloppen door te kijken of volwassenen inderdaad gebruik maken van hetzelfde niet symbolische systeem als baby's. Als volwassenen inderdaad eenzelfde mechanisme gebruiken dan zouden zij net als baby's aantallen onderscheiden op basis van een relatief en niet een absoluut verschil in aantal en zouden ze even nauwkeurig of misschien wel nauwkeuriger moeten zijn in het onderscheiden van aantallen. In plaats van kijktijd (zoals bij baby's) heb ik EEG gebruikt bij de volwassenen. Op deze wijze kreeg ik een indirecte uitleesmaat voor aantalverwerking. Uit de resultaten bleek dat de volwassenen eigenlijk niet beter presteerden dan de baby's van 6 maanden oud. De volwassenen lieten alleen een effect op ratio 2.0 maar niet op ratio 1.5 zien. Uit de gedragsresultaten van een tweede taak waarbij de volwassenen wisten en zelfs geïnstrueerd werden te reageren zodra ze een aantalsverandering zagen bleek dat de volwassen veel slechter zijn in ratio 1.5 dan 2.0. Gemiddeld hadden ze maar 56% van veranderingen opgemerkt, hetgeen het gebrek aan een EEG effect kan verklaren. Ondanks het feit dat de volwassenen een stuk minder nauwkeurig leken te zijn in het onderscheiden van aantallen dan baby's, bleek het effect wel afhankelijk van het relatieve en niet het absolute verschil tussen de aantallen. Dus het onderliggende mechanisme zou wel gelijk kunnen zijn aan dat van de baby's.

De interactie tussen verschillende grootheden.

In het brein wordt een systeem verondersteld dat grootheden verwerkt, ongeacht de notatie of modaliteit waarin de grootheid aangeboden is. Zodra men een grootheid waarneemt wordt deze vertaald naar een algemene code die voor elke grootheid gelijk is. Hierdoor kan informatie van die verschillende grootheden met elkaar interacteren. Twee hypotheses omtrent dit idee zijn geponeerd: De eerste is de vroege interactie hypothese waarbij beide grootheden al vrij snel nadat ze zijn waargenomen gecodeerd worden in dezelfde code. In de tweede hypothese, de late interactie hypothese, wordt gesteld dat de processen van verschillende grootheden gescheiden van elkaar verlopen en pas met elkaar in aanraking komen op het nivo van de reactie. In de eerste hypothese vind de interactie dus voor en in de tweede hypothese tijdens de voorbereiding of de uitvoering van de reactie plaats.

In hoofdstuk 3 heb ik met behulp van de stippen en de cijfer Stroop taak gekeken naar het moment in de tijd waarop grootheden bij volwassenen interacteren. De interactie tussen numerieke en fysieke grootte vond plaats voordat de reactieprocessen werden geïnitieerd. Hierdoor kan uitgesloten worden dat het congruentie-effect het resultaat is van een conflict op het nivo van de reactie; wellicht is het een effect op semantisch nivo. Dit resultaat ondersteunt de vroege interactie hypothese en dus het idee dat er een systeem in ons brein zit dat informatie van verschillende grootheden verwerkt. Echter, op basis van deze gegevens kan men alternatieve verklaringen niet uitsluiten. Een voor de hand liggende alternatieve verklaring is dat er in eerste instantie een categorisatie-proces optreedt: Beide stimulus dimensies worden gecategoriseerd in bijvoorbeeld groot en klein, en pas op dat nivo vindt de interactie plaats. In dit geval hoeft er geen sprake te zijn van een enkel, algemeen, numeriek systeem.

In hoofdstuk 6 ben ik verder gaan kijken naar interacties tussen verschillende grootheden. In plaats van de fysiek–numerieke-grootte interactie taken hebben we de helderheid-numerieke interactie bekeken. Met behulp van een helderheid-Stroop-taak heeft men eerder laten zien dat verschillende niveaus van helderheid geassocieerd zijn met numerieke grootte. De resultaten uit eerdere studies lieten echter conflicterende resultaten zien, waardoor de vraag wat nu precies de onderliggende mechanismen van deze interacties zijn des te interessanter werd. Om dit verder uit te zoeken voegden we extra condities aan de al bestaande Stroop taak toe. De resultaten lieten zien dat eenzelfde stimulus op basis van de taakinstructie een andere associatie met een cijfer kan hebben. Met behulp van deze gegevens losten we het probleem van conflicterende resultaten in eerdere studies op en concludeerden we dat er een categorisatie proces aan de interactie vooraf zou moeten zijn gegaan.

Interacties tussen arbitraire associaties.

Grafeem-kleur synestheten nemen een kleur waar zodra ze een cijfer, een letter of een woord zien. Dit is de meest bekende variant van synesthesie. Sommige synestheten nemen de kleur waar alsof het geprojecteerd is op de grafeem, anderen zeggen het meer “in hun hoofd” te zien. De eerste groep synestheten wordt projecteerders genoemd en de laatste groep associeerders. Deze synesthetische effecten werken maar 1 kant op. Een synestheet ziet alleen een kleur wanneer een cijfer gepresenteerd wordt maar niet andersom.

In hoofdstuk 7 hebben we gekeken of kleuren op een impliciete wijze cijferprocessen kunnen activeren ondanks de afwezigheid van een synesthetische waarneming. Om uit elkaar te kunnen houden of de waargenomen kleur cijferprocessen activeerde of het waargenomen cijfer kleurenprocessen, maakten we gebruik van de priming taak waarbij de kleur en de cijfer stimulus na elkaar gepresenteerd worden. In een priming taak reageert men sneller als de zogenaamde prime en de target met elkaar in overeenstemming zijn en langzamer naarmate de prime en target minder met elkaar in overeenstemming zijn. In het geval van synesthesie wordt verwacht dat een synestheet sneller de target kleur rood benoemt als deze voorafgegaan is door het cijfer dat de synestheet in het rood ziet dan een cijfer die de synestheet in een andere kleur ziet. Om te kijken of een kleur cijferprocessen kan activeren hebben we ook gekeken naar het priming afstand effect. Het priming afstand effect houdt in dat de reactietijd korter wordt wanneer de afstand tussen twee cijfers afneemt. Dus men is sneller als de kleur-prime het getal 3 activeert en de target nummer 4 is dan wanneer de target nummer 5 is. Dus zo zou je kunnen zeggen hoe verder het cijfer die bij de kleur-prime hoort van het andere cijfer af ligt hoe kleiner het priming effect. Als zo’n afstand effect zichtbaar is in de taak dan weten we dat 2 numerieke processen met elkaar geïnteracteerd hebben. Als er een priming effect is maar geen afstand priming effect dan weten we dat 2 kleuren met elkaar geinteracteerd hebben. De resultaten lieten een priming effect zien voor zowel de cijfer-kleur als de kleur-cijfer priming taak. Een numeriek afstand effect was alleen aanwezig in de kleur-cijfer taak. Kortom kleuren kunnen cijferprocessen activeren in synestheten.

In hoofdstuk 8 deden we dezelfde priming studie maar nu bekeken we ook de onderliggende neurale processen. De EEG resultaten lieten zien dat dezelfde neurale correlaten betrokken zijn bij beide processen. Naast deze bevinding hebben we ook gekeken naar de verschillende groepen synestheten. Onze groep bestond uit projecteer- en associeer-synestheten. Beide groepen lieten dezelfde resultaten zien. Vervolgens hebben we de groep opgesplitst op basis van de gedragsdata. Nu bleek dat de groep met grote gedragseffecten andere neurale patronen liet zien dan de groep met kleine gedragseffecten. Op basis van deze resultaten kunnen we het idee bevestigen dat synestheten geen homogene groep vormen.

Tot slot.

De resultaten gepresenteerd in dit proefschrift laten zien dat de mechanismen die de basis vormen voor de ontwikkeling van numerieke processen slechts grofweg bekend zijn. Dit proefschrift geeft een basaal inzicht in deze processen. Echter er blijven vragen omtrent de ontwikkeling in de processen die gebruikt worden om Arabische cijfers (hoofdstukken 2 en 4) te verwerken, alsook de geobserveerde afname in gebruik van aantallenkennis in volwassenen vergeleken met baby’s of kinderen (hoofdstukken 4 en 5). Verder heb ik laten zien dat de interacties tussen verschillende grootheden op een nivo vóór responsverwerking plaats vindt, hetgeen de vroege interactie hypothese ondersteunt. Dit bewijst niet direct het bestaan van een algemeen grootheden systeem (hoofdstukken 3 en 6). Ik heb een alternatieve hypothese geopperd welke het debat over de neurale representatie van grootheden zou kunnen bevorderen. De resultaten van gerelateerd onderzoek over arbitraire interacties lieten zien dat kleuren en cijfers met elkaar kunnen interacteren en dat synestheten geen homogene groep vormen (hoofdstukken 7 en 8). Men zou kunnen beargumenteren dat deze interacties ontstaan zijn door lange termijn leren.

De experimentele paradigma's die we gebruikten in onze studies over de ontwikkeling van numerieke processen en de interacties tussen grootheden waren allemaal varianten van het Stroop paradigma. Ook al is dit een paradigma dat frequent gebruikt wordt om geautomatiseerde kennis van grootheden representaties te bestuderen, er bestaan ook andere taken die inzicht kunnen geven in deze processen. Het priming paradigma is bijvoorbeeld een goed alternatief. Dit paradigma bevat geen conflict component en maakt dus geen gebruik van inhibitie processen die nog in ontwikkeling zijn in kinderen. Daarom zou het gebruik van zo'n paradigma erg van pas kunnen komen om de verschillen in het ontstaan van geautomatiseerde nummerprocessen, de verandering in het gebruik van processen in de symbolische stroop taak als wel de interacties tussen verschillende grootheden te bestuderen.

Het priming paradigma bleek in mijn proefschrift al een goede methode om arbitraire interacties te bestuderen. Ook al ging dit gedeelte van het proefschrift niet over de ontwikkeling van deze arbitraire interacties, het gebruik van dit paradigma en het bestuderen van synesthesie kan van grote invloed zijn op onze kennis over de ontwikkeling van numerieke processen in de niet synesthetische populatie. Het bestuderen van de synesthetische ervaringen zou kunnen laten zien of the de impliciete associatie tussen kleuren en de synesthetische cijferprocessen het gevolg zijn van lange termijn leren. Deze associatie van kleur en aantal zou de automatisering van cijfers kunnen reflecteren. Omdat synestheten een expliciet beeld hebben van de kleurassociatie zodra de link geautomatiseerd is kan de link tussen verschillende grootheden meer expliciet bestudeerd worden. Om kinderen te betrekken in de studie die op het punt staan deze associaties te ontwikkelen is natuurlijk een groot probleem. Een mogelijke strategie is om kinderen te zoeken die al synesthesie hebben met niet-symbolische aantallen of, omdat synesthesie een erfelijke component zou hebben, zouden kinderen betrokken kunnen worden met één of meer familieleden die synesthesie hebben.

Samenvattend: in het veld van de numerieke cognitie is de studie naar de neurale correlaten van numerieke processen van fundamenteel belang. Kennis van deze processen in de normaal ontwikkelende populatie is een vereiste voordat er conclusies getrokken kunnen worden over kinderen of volwassenen met problemen in (het leren) rekenen. Uiteindelijk zou dit kunnen leiden tot een betere begeleiding van leraren en dus beter onderwijs.

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Gebuis, T., Kenemans, J.L., de Haan E.H.F. & van der Smagt M.J. (submitted). Conflict processing of symbolic and non-symbolic numerosity.

Gebuis, T., Kenemans, J.L., de Haan E.H.F. & van der Smagt M.J. (submitted). Numerosity detection and its neural correlates

Gebuis, T., & van der Smagt M.J. (submitted). Number-luminance congruency effects and their origins.

Anema, H., de Haan, A., **Gebuis, T.** & Dijkerman, C.H. (submitted). Thinking Touch.

Nijboer, T.C.W., **Gebuis, T.**, Plukaard, S., de Haan E.H.F. & van der Smagt M.J. (submitted). Differences in neural correlates between synesthetic colour and normal colour processing.

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Gebuis, T., Nijboer, T.C.W. & van der Smagt M.J. (2008). Of colored numbers and numbered colors; Interactive processes in grapheme-color synesthesia, 26th European Workshop on Cognitive Psychology.

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DANKWOORD

Voor de studies in mijn boekje heb ik vooral taken gebruikt die varianten zijn op de zogenaamde Stroop taak. In zo'n Stroop taak reageert een proefpersoon sneller wanneer de eigenschappen van de gepresenteerde stimuli met elkaar in overeenstemming zijn en langzamer wanneer de eigenschappen van de stimuli niet met elkaar in overeenstemming zijn. Tijdens mijn AiO-schap had ik het idee zelf een proefpersoon te zijn in een Stroop experiment met de nodige interfererende en faciliterende stimuli:

Faciliterende stimuli

"Als naast interferentie ook facilitatie aanwezig is dan verloopt het proces volledig geautomatiseerd".

De promotoren en co-promotoren: Edward en Jan, mijn promotoren, bedankt voor de kans die jullie mij hebben gegeven om dit project te doen. Edward, de vrijheid die je me hebt gegeven en je positieve kijk op alles omtrent het uitvoeren van onderzoek werkte motiverend en heeft ervoor gezorgd dat ik uiteindelijk mijn weg wist te vinden in de wetenschap. Maarten; in het tweede jaar werd jij als co-promotor betrokken bij het onderzoek. "Zonder een bioloog is een psycholoog nergens" had een uitspraak van jou kunnen zijn. Terugkijkend op mijn AiO-schap kan ik niet anders zeggen dan dat dit zeker voor mij gold. Heel erg bedankt voor je interesse, hulp, kennis en natuurlijk de vele gezellige momenten! Leon, jij kwam als promotor ook pas later bij het project. Jouw kennis over EEG en Stroop was voor mij een grote steun.

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Interfererende stimuli

"Interfererende effecten zijn niet alleen eerder maar ook sterker aanwezig dan de faciliterende effecten."

De koffiekamer: Al vanaf de eerste dag als AiO kwam ik erachter dat, in tegenstelling tot wat je zou verwachten, koffie halen bij experimentele psychologie in het Van Unnik niet faciliterend werkt. De ambiance rondom onze koffiezetter is dusdanig van aard dat je, eenmaal daar gezien, er niet meer weg komt. Daarom Frans en Dennis S. bedankt voor de (sterke) toevoer al in de vroege uurtjes en alle (ex)collega's voor de vele gezellige momenten in de koffiekamer.

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Both interfering and facilitory

"Whether conflict happens at the semantic or motor level was questioned in this thesis. In contrast to what was found in my research, in real life, conflict appeared to happen at both the semantic as well as motor level."

The "Bressanone langlauf team": Two times during my PhD period I went to Bressanone to attend "the ski conference". The conference is a Stroop task in itself. The possibility to do (cross-country) skiing or attend the lectures was each day again a though choice. Martin, Silke, Julia, Guilherme, Samuel, Roi, Kathrin and all the others, it was great fun with you all on the piste and during the conference.

Arbitrary interactions

"Associations do not only arise between magnitudes but also between arbitrary sensory or cognitive processes"

A remarkable variant is gustatory-stroop(wafel) synesthesia.I encountered in the last years that subjects RCK and KCK have extraordinary gustatory sensations when a stroop wafel is perceived. These intruiging subjects were an inspiration during my PhD thesis not only in the scientific aspect but also as friends. Roi and Kathrin, thanks!

Neutrale stimuli

"Neutrale stimuli zorgen voor een baseline. Ten opzichte van deze gegevens zet je al het andere af en weet je pas echt wat er echt toe doet"

De meiden: Loes, Lot, Maart en Eve, het was altijd weer fijn jullie te zien. Jullie leven is zo anders dan de wereld waarin ik me de afgelopen jaren bevonden heb, dat het altijd weer een verademing was om bij jullie te zijn. Bedankt dat jullie mijn vriendinnetjes zijn.

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CURRICULUM VITAE

Titia Gebuis werd geboren op 19 februari 1981 te Leidschendam. In 1999 behaalde zij haar VWO diploma aan de scholengemeenschap ‘t Rijks in Bergen op Zoom, waarna zij Psychologie ging studeren aan de Universiteit van Maastricht. In mei 2004 studeerde zij af met neuropsychologie als specialisatie.

Tijdens deze studie vervulde zij in haar derde jaar een bestuursfunctie binnen de studenten toneelvereniging Alles is Drama. In haar vierde jaar deed ze haar onderzoeksstage bij Prof. dr. David Linden aan de afdeling Psychiatry en Psychotherapy van de Johan Wolfgang Goethe Universiteit in Frankfurt, Duitsland. Van september tot mei 2005 ging zij bachelor en master vakken Kennistechnologie volgen aan de Universiteit van Maastricht en heeft ze onderzoek verricht als student assistent bij de afdeling cognitieve neurowetenschappen van Psychologie aan de Universiteit van Maastricht onder leiding van Prof. dr. Niels Schiller.

Direct daarna begon zij aan haar promotieonderzoek aan de afdeling psychologische functieleer aan de Universiteit van Utrecht. Tijdens haar promotieonderzoek heeft zij ook onderzoek gedaan in Israel aan de Ben Gurion Universteit in Beer Sheva onder begeleiding van Prof. dr. Avishai Henik en in Belgie aan de Universiteit van Gent onder begeleiding van Prof. Dr. Wim Fias.

Titia Gebuis was born on February 19th, 1981 in Leidschendam. In 1999 she completed her secondary education at the scholengemeenschap ‘t Rijks in Bergen op Zoom, after which she studied Psychology at the University of Maastricht. In May 2004, she obtained her master’s degree, specializing in neuropsychology.

During the third year of her studies she filled an executive role in the student drama school: Alles is Drama. In her fourth year she did her internship in the department of Psychiatry and Psychotherapy of the Johan Wolfgang Goethe University in Frankfurt, Germany under the supervision of Prof. dr. David Linden. From September till May 2005 she attended bachelor and master courses in knowledge engeneering at the University of Maastricht and performed research as a student assistent at the department of cognitive neuroscience at the University of Maastricht under the supervision of Prof dr. Niels Schiller.

After her studies, she started her PhD at the department of experimental psychology at the University of Utrecht. During her PhD she conducted research at the Ben Gurion University of the Negev in Beer Sheva, Israel under supervision of Prof. dr. Avishai Henik and in Belgium at the University of Gent under the supervision of Prof. dr. Wim Fias.