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The effect of orientation on number word processing

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Abstract

Besner and Coltheart [Besner, D., & Coltheart, M. (1979). Ideographic and alphabetic processing in skilled reading of English. *Neuropsychologia, 17*, 467–472] found a size congruity effect for Arabic numbers but not for number words. They proposed that Arabic numbers and number words are processed in different ways. However, in their study orientation of the stimuli and notation were confounded. In the present study, it is found that orientation of number words affects numerical processing. Orientation modulates both the size congruity effect and the distance effect; horizontal presentation produces similar results to those produced by Arabic numbers whereas vertical orientation produces different results. Accordingly, it is proposed that our cognitive system is endowed with two different mechanisms for numerical processing; one relies on a visual-spatial code and the other on a verbal code.

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1. Introduction

Studies in the field of number processing documented two well-known effects. The first, referred to as the *numerical distance effect*, was first reported by Moyer and Landauer (1967). As the name implies, the distance between two numbers influences the comparison of the stimuli; the larger the distance, the shorter the reaction time (RT). The second effect is called the *size congruity effect* (Henik & Tzelgov, 1982) and is a Stroop-like phenomenon. When a stimulus has two dimensions but only one has to be attended while the other has to be ignored, participants process the irrelevant dimension unintentionally. Interference occurs when the two dimensions are incongruent and facilitation occurs when the two dimensions are congruent. For example, in number comparison, participants have to relate to the numerical value and ignore the physical size. In the congruent condition one of the two digits is larger in both dimensions (e.g., 2 4). In the incongruent condition one of the digits appears larger in the relevant dimension, whereas the other appears larger in the irrelevant dimension (e.g., 2 4). In the neutral condition there is no difference in the irrelevant dimension (e.g., 2 4). Facilitation is observed when the RT to the congruent trials is faster than that of the neutral trials. Interference is observed when the RT to the incongruent trials is slower than that of neutral trials.

The size congruity effect for the number comparison was first observed by Besner and Coltheart (1979). Since then, it has been shown that this effect is found not only when the numerical value is the relevant dimension and the physical dimension must be ignored (as shown by Besner and Coltheart), but also in the reverse task, when the physical dimension is relevant and the numerical dimension is irrelevant. This implies that not only physical size but also numerical value is processed automatically (e.g., Henik & Tzelgov, 1982).

In addition, an interaction between the size congruity effect and the distance effect was found in many studies (e.g., Cohen Kadosh & Henik, 2006a, 2006c; Cohen Kadosh, Henik, & Rubinsten, 2005a; Schwarz & Ischebeck, 2003), that is, as the numerical distance between stimuli in the numerical task increases, size congruity decreases. It has been suggested that numbers are processed serially (e.g., Dehaene, 1996; Schwarz & Ischebeck, 2000). Under serial processing, according to the additive factor method (Sternberg, 1969), an interaction between two factors occurs if processing of both factors is carried out at a common stage of processing. Hence, the interaction between numerical distance and size congruity suggests that processing of both factors is carried out at the comparison stage. Indeed, it was found that a shared area in the intraparietal sulcus (IPS) is activated for the numerical distance effect and for the size congruity effect (Kaufmann et al., 2005; Pinel, Piazza, Le Bihan, & Dehaene, 2004).

Neuroimaging studies reported shared processing of number words (e.g., EIGHT) and Arabic numbers (e.g., 8) at the comparison stage (e.g., Dehaene, 1996; Naccache & Dehaene, 2001; Pinel, Dehaene, Rivie‘re, & Le Bihan, 2001; Pinel et al., 1999). These results support the idea that numbers are *abstractly* represented on a mental number line. Additional support for the mental number line comes from a finding that participants respond faster to small numbers with their left hand and to large numbers with their right hand. This effect was first shown by Dehaene, Bossini, and Giraux (1993) and labeled the SNARC effect (spatial numerical association of response codes). Since then, it was reported by other groups (e.g., Bachtold, Baumuller, & Brugger, 1998; Berch, Foley, Hill,

& Ryan, 1999; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Fias & Fischer, 2004; Fias, Lauwereyns, & Lammertyn, 2001).

In contrast to the idea of notation independent representation of numbers, Besner and Coltheart (1979) found a size congruity effect with Arabic numbers (i.e., the irrelevant physical size affected numerical processing) but failed to find the same effect with word notation (i.e., the irrelevant physical size did not affect numerical processing of number words). They argued that these results indicated a distinction in the processing of Arabic and number words. However, it is important to note that in their experiment the two notations differed in orientation also. Namely, the Arabic notation appeared horizontally (one stimulus on the left and the other on the right) whereas the word notation appeared vertically (one stimulus above the other stimulus), leading to the possibility that the difference in orientation produced the discrepancy in the results. Accordingly, it is possible to argue that the vertical presentation of number words was incompatible with the mental representation of numbers, which in turn, slowed down processing of the number words so that by the time the numerical values were present in the system, activation of the physical dimension dissipated and did not affect numerical processing. In contrast with this idea, Foltz, Poltrok, and Potts (1984) argued that the absence of the size congruity effect for number words in Besner and Coltheart's report was an artifact of their experimental design. They suggested that the repetition of the same pairs of stimuli during the experiments eliminated the effect. When participants encountered a repeated pair they could retrieve the decision reached previously with the same pair (i.e., "the right number word was larger" or "the left number word was larger"). This would allow for ignoring the irrelevant dimension in most trials in Besner and Coltheart's study. Note that Foltz et al.'s criticism did not refer to the sequential effect, namely, the effect that a repeated stimulus in trial N had on the processing of the identical stimulus in trial $N + 1$ (Schwarz & Ischebeck, 2000). Rather, they referred to the effect of retrieval from the memory of a repeated stimulus, independent of the trials that preceded it.

Foltz et al. replicated Besner and Coltheart's experiment and found a size congruity effect for number words as well as for Arabic numbers. However, their experiment differed from Besner and Coltheart's experiment in two aspects. First, each pair appeared only once, and second, their stimuli were presented only horizontally and not vertically. Therefore, one cannot be sure whether the size congruity effect for number words in Foltz et al.'s study was due to the orientation of the stimuli presentation.

2. The current study

This experiment was carried out in order to investigate whether the size congruity effect can be modulated by the orientation of the number word stimuli. Participants were presented with two separate blocks of trials and asked to judge which stimulus was numerically larger. In one block stimuli were presented horizontally and in another block stimuli were presented vertically, which is similar to Besner and Coltheart (1979) experiment. In contrast to the work done by Foltz et al. (1984), each pair appeared more than once in our design.

3. Method

3.1. Participants

Seventeen university students (mean age 22.23, SD = 1.33) from Ben-Gurion University of the Negev participated in the experiment for partial fulfillment of a course requirement. All the participants had normal or corrected-to-normal vision, had no reading or mathematical deficits, and their mother tongue was Hebrew.

3.2. Stimuli

A computer display consisted of two number words in Hebrew which appeared at the center of the screen. In the horizontal block the center-to-center distance between the two number words was 10 cm. The participants sat 55 cm from the screen. The stimuli subtended a vertical visual angle of 0.7° or 0.9° and a horizontal visual angle of 1.7–5.4°. The same stimuli were used for the vertical and the horizontal blocks.

There were three types of pairs: congruent, neutral and incongruent. The number words, one through nine excluding five, were used to produce three numerical distances: 1 (the number word pairs 1–2, 3–4, 6–7, or 8–9), 2 (the number word pairs 1–3, 2–4, 6–8, or 7–9) or 5 (the number word pairs 1–6, 2–7, 3–8, or 4–9). Each number word was presented for an equal number of times for each distance. Stimuli were arranged in blocks of trials (i.e., horizontal or vertical block) with each block composing 72 different stimuli that were presented twice (a total of 144 trials in each block). Each number word and each physical size appeared for an equal number of times on the left and the right. Each block had nine different conditions; three numerical distances × 3 congruency conditions. Each condition was represented by 16 trials (i.e., 4 number word pairs × 2 physical sizes × 2 sides of the computer screen) in a given block.

Every experimental block was preceded by a block of 36 practice trials. This block was similar to the experimental block with the exception that we used number words that were different from those employed in the experimental blocks. For a numerical distance of 1 unit, the practice number words were made out of the pairs 4–5 and 5–6, and for numerical distance of 2 units the number words were 3–5 and 5–7. In the case of the 5 unit numerical distance we used the number word pairs 1–6 and 4–9, which were also used in the experiment. This was due to an error in the design of the experiment and we examine its effect in the result section.

3.3. Procedure

The participant's task was to decide which of two number words in a given display is larger, with the term "larger" applying to the numerical value. Each participant took part in one session composed of two different blocks. Participants were asked to respond as quickly as possible but were asked to avoid errors, and attend only to the numerical values. The stimuli in each block were presented in a random order. Participants used the index finger of both hands to indicate their choices by pressing one of two keys corresponding to the side of the display with the larger digit (i.e., vertically aligned keys for vertical orientation, and horizontally aligned keys for the horizontal orientation). Each trial began with an asterisk as a fixation point, which was presented for 300 ms at the center of a computer screen. Five hundred ms after the fixation point disappeared a pair of number words appeared and remained in view until the participant pressed a key (but not for longer than 5000 ms). A new stimulus appeared 1500 ms after the participant's response. The order of the two blocks was counterbalanced across individual participants.

3.4. Design

The variables manipulated were: orientation (vertical vs. horizontal), numerical distances (1, 2, or 5) and congruity (incongruent, neutral and congruent). Thus, we had a $2 \times 3 \times 3$ factorial design.

4. Results

Error rates were generally low (3% and 3.5% for horizontal and vertical blocks, respectively). One participant was dropped from the analyses due to a high error percentage (more than 10%). For the remaining 16 participants, for each condition mean RT was calculated for correct trials only. These mean values were subjected to a three-way analysis of variance (ANOVA) with orientation, numerical distance and congruity as within-subject factors.

There was a main effect of numerical distance [$F(2,30) = 42.56$, MSE = 2000, $p < 0.001$]. Participants responded faster to large numerical distances than to small ones, with mean RTs of 844 ms, 807 ms, and 785 ms, for 1, 2, and 5 units distance, respectively. There was also a significant effect of congruity [$F(2,30) = 31.27$, $MSE = 2384$, $p < 0.001$], with mean RTs of 838 ms, 816 ms and 783 ms for incongruent, neutral and congruent pairs, respectively. The main effect for orientation was not significant [$F < 1$]. In addition, two interactions were significant: orientation and numerical distance [$F(2,30) = 4.54$, MSE = 2009, $p < 0.05$], and orientation, numerical distance and congruity [$F(4,60) = 3.29$, MSE = 1592, $p < 0.05$]. The latter three-way interaction is presented in Fig. 1.

It seems that there was a congruity effect regardless of orientation. The congruity effect in the horizontal orientation seems to have both interference and facilitatory components whereas the congruity effect in the vertical orientation was mostly based on facilitatory. Moreover, the congruity effect seems to be modulated by numeric distance for horizontal orientation but not for vertical orientation. Additional analyses of the three-way interaction which were conducted separately for horizontal and vertical orientation (Keppel, 1991), supported these conclusions.

4.1. Horizontal orientation

A distance effect [$F(2,30) = 39.20$, MSE = 1775, $p < 0.001$], and a size congruity effect indicated by the congruity simple main effect [$F(2,30) = 12.75$, MSE = 3333, $p < 0.001$] were obtained. For numerical distance we found a decrease of RT with distance (845 ms, 808 ms, and 769 ms for the 1 unit, 2 units and 5 units distances, respectively). The differences between 1 unit and 2 units, and between 2 units and 5 units were signifi-

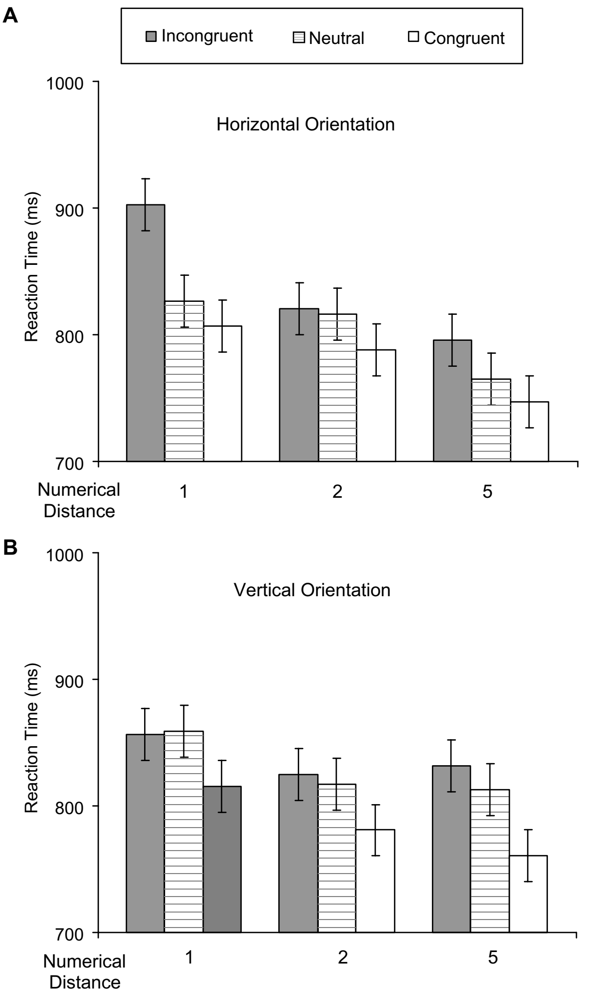

Fig. 1. Reaction time as a function of numerical distance and congruity under horizontal (A) and vertical orientation (B). 95% confidence intervals are given for the triple interaction (Masson & Loftus, 2003).

cant, [$F(1,15) = 22.56$, MSE $= 1468$, $p < 0.001$] and [$F(1,15) = 13.97$, MSE $= 2610$, $p < 0.005$], respectively. Examination of the components of the congruity effect revealed a facilitatory component (congruent relative to neutral) of 22 ms [$F(1,15) = 6.13$, MSE $= 1895$, $p < 0.05$], and an interference of 37 ms [$F(1,15) = 10.64$, MSE $= 3065$, $p < 0.005$]. The simple interaction between congruity and numerical distance was significant [$F(4,60) = 3.08$, MSE $= 2134$, $p < 0.05$], showing a decrease in the congruity effect with the increase in numerical distance.

Examination of the facilitatory and interference components for each distance revealed an interference component [$F(1,15) = 10.40$, MSE $= 4489$, $p < 0.01$] but no facilitatory [$F(1,15) = 1.26$, MSE $= 2381$, ns] component for distance 1. In contrast, the reverse result was obtained for distance 2, namely, a non-significant interference component [$F < 1$], and a marginally significant facilitatory component [$F(1,15) = 4.44$, MSE $= 1481$, $p = 0.052$].

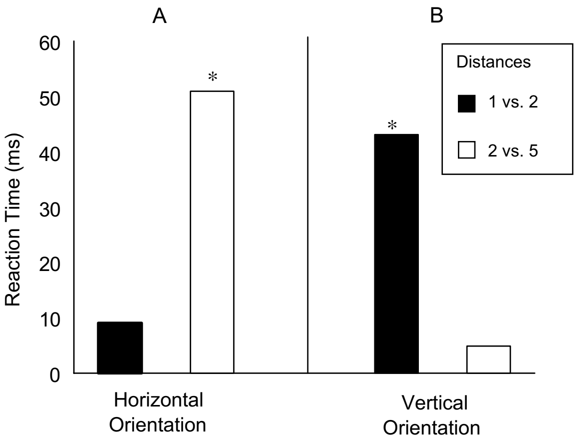

Fig. 2. Reaction time differences for distance as a function of horizontal (A) and vertical (B) orientations in the neutral condition (*$p < 0.05$).

For distance 5, both interference [$F(1,15) = 6.14$, MSE = 1200, $p < 0.05$] and facilitatory [$F(1,15) = 6.18$, MSE = 416, $p < 0.05$] components were significant.

In order to examine the "pure" numerical distance (without the affect of physical size) we analyzed the distance effect under the neutral condition separately (Fig. 2A). The distance effect was significant [$F(2,30) = 12.67$, MSE = 1368, $p < 0.001$]. Additional analyses revealed that the difference between 1 unit and 2 units was not significant [$F < 1$]. In contrast, the distance between 2 units and 5 units was significant [$F(1,15) = 15.91$, MSE = 1328, $p < 0.001$].

4.2. Vertical orientation

A distance effect [$F(2,30) = 11.03$, MSE = 2233, $p < 0.001$] and a size congruity effect indicated by the congruity simple main effect [$F(2,\ 30) = 16.45$, MSE = 2276, $p < 0.001$] were obtained. For numerical distance we found a decrease of RT with distance (843 ms, 807 ms, and 801 ms for the 1 unit, 2 units and 5 units distances, respectively). The difference between 1 unit and 2 units was significant [$F(1,15) = 22.56$, MSE = 1468, $p < 0.001$], but the difference between 2 units and 5 units was not significant [$F < 1$]. Examination of the components of the congruity effect revealed that it was composed of only a facilitatory component (congruent relative to neutral) of 44 ms [$F(1,15) = 12.34$, MSE = 3728, $p < 0.005$] whereas the interference component was insignificant [$F < 1$]. The simple interaction between numerical distance and congruity was also not significant [$F < 1$]. Since the interaction between distance and congruity was not significant, we did not analyze the interference and facilitatory components for each distance separately.

As in the horizontal orientation analysis, we analyzed the distance effect under the neutral condition (Fig. 2B). The distance effect was significant [$F(2,30) = 4.61$, MSE = 2297, $p < 0.05$]. The difference between 1 unit and 2 units was significant [$F(1,15) = 6.05$, MSE = 2355, $p < 0.05$]. In contrast, the distance between 2 units and 5 units was not significant [$F < 1$].

In order to examine the possibility as to whether the congruity effect was due to confounding of word length, a variable that Besner and Coltheart (1979) controlled, we ran an additional analysis of the vertical orientation only. This analysis included only pairs of words that had the same number of letters for the smaller numbers and the larger numbers. We excluded pairs with asymmetric length from the analyses (e.g., the pair six-eight, in Hebrew: שש-שמונה, was excluded since there was a difference of three letters between the two words). Similar to the results reported above, this analysis produced a significant size congruity effect [$F(2, 30) = 11.58$, MSE = 4617, $p < 0.001$].

Since some of the 5 units pairs (i.e., the number word pairs 1–6 and 4–9) were used both in the experimental and practice blocks, we analyzed only those pairs that were used during the experiment (i.e., the number word pairs of 2–7 and 3–8) in order to eliminate any possibility of difference due to the practice effect. No significant difference, due to practice was observed.

4.3. Error rates

Due to lack of variance in several conditions, a correlation analysis was conducted between RTs and error rates. The results did not show any RT-accuracy trade-off ($r(144) = 0.31, p < 0.01$ for horizontal block, and $r(144) = 0.23, p < 0.05$ for vertical block).

5. Discussion

Finding a size congruity effect in word notation seems to contradict Besner and Coltheart (1979) report. They reported a size congruity effect for Arabic numbers but not for word notation. Accordingly, Besner and Coltheart concluded that Arabic numbers and number words are processed differently. However, in their experiment the notation was confounded with orientation of the stimuli (i.e., words were presented vertically whereas Arabic numerals were presented horizontally). Hence, it is difficult to decide whether the source of the discrepancy was difference in the notation or in the orientation. In contrast to Besner and Coltheart's results, a size congruity effect was obtained in our study for vertical orientation as well as for horizontal orientation. The discrepancy between our results and the null result reported by Besner and Coltheart might be due to a stronger effect of orientation in their experiment (as can be indicated by the higher error rate (above 10%) in their study in contrast to the current study). Indeed, in our experiment the manipulation of orientation played a significant role. When we compare the two orientations of the stimuli, it seems that the two effects that are of interest here are modulated by orientation of the display: (1) The size congruity effect was composed of a facilitatory component in the vertical orientation whereas it was composed of both facilitatory and interference components in the horizontal orientation. (2) The same pattern of interaction between numerical distance and congruity as reported in other studies (e.g., Cohen Kadosh & Henik, 2006a, 2006c; Cohen Kadosh et al., 2005a; Schwarz & Ischebeck, 2003; Tzelgov, Meyer, & Henik, 1992), was observed in the horizontal orientation but was absent in the vertical orientation. (3) The "pure" distance effect (as reflected by the neutral condition) showed modulation by orientations; in the horizontal orientation only the difference between 2 units and 5 units was significant, whereas in the vertical orientation we found a mirror image (Fig. 2A and B), namely, only the difference between 1 and 2 units was significant.

All the differences between orientations that were mentioned above strengthen the idea that the orientation of the stimuli affected the processing of the number words. We suggest that when the stimuli appeared horizontally, they resembled the representation of the mental number line and hence were less demanding on cognitive resources than in the vertical orientation condition. In contrast, the vertical orientation of the stimuli, which is incompatible with the representation of the mental number line, impacted on the congruity and distance effects. Consequently, in the horizontal orientation the distance and congruity effects are implemented almost completely. It is important to note the opposite pattern of the distance effect under different orientations (i.e., the difference between the neutral conditions in the two orientations). A possible explanation for such a mirror image might be the existence of two mechanisms for number comparison: (1) The more dominant mechanism processes numbers using a *visuospatial code*. In this, code numbers are compared by representing them on a horizontal mental number line. Imaging and patient studies have pinpointed the IPS as the brain area that is dedicated to numerical comparisons (for review see, Dehaene, Piazza, Pinel, & Cohen, 2003) by representing numbers on a mental number line (Zorzi, Priftis, & Umilta, 2002). (2) An additional mechanism processes numbers via a *verbal code*. This suggestion is supported by fMRI studies that found that numerical distance modulated brain activations in semantic language areas (superior temporal sulcus (STS) and the middle temporal gyrus (MTG)) (Cohen Kadosh et al., 2005a, 2005b; Pinel et al., 2001). Given the abstract nature of numerical information, and the dependence between language and numbers (Wiese, 2003), it is plausible that such temporal brain structures are also active during number processing. Bloch-David, Henik, and Rafal (submitted for publication), and Cohen Kadosh et al. have proposed that numbers are connected to one another in similar way as representations of words are (e.g., DOG-CAT, TABLE-CHAIR). Thus, close numbers with a numerical distance of one unit (e.g., ONE-TWO) are more difficult to compare because they are linked by stronger connections than numbers that are further apart (e.g., ONE-FOUR). The further apart the numbers are, the less they are affected by the verbal code, due to the simple fact that connections between such numbers are negligible or even absent. When participants compare numbers presented horizontally, the dominant visuospatial code is more active. Hence, numbers that are further apart (e.g., numerical distance of 5 units) are processed faster than a closer numbers (i.e., numerical distance of one and two units). However, in the case of incompatible presentation of numbers (e.g., vertical presentation), the close numbers can still be compared in an efficient way due to the verbal code, and the numerical distance effect will still be observed. The existence of two mechanisms for numerical comparison also supplies an explanation for the observable numerical distance effect after damage to visuospatial abilities (e.g., Zorzi et al., 2002) or to the left and right IPS (Bloch-David et al., submitted for publication).

The lack of interaction between congruity and the distance effect in the vertical orientation, which stands in contrast with horizontal orientation, also supports the possible existence of two mechanisms for number comparison: The interaction between numerical distance and size congruity suggests that processing of both factors is carried out at the comparison stage. As was mentioned in Section 1, numbers are processed serially (Dehaene, 1996; Schwarz & Ischebeck, 2000). Based on the additive factor method (Sternberg, 1969) the interaction in the horizontal presentation between distance and congruity suggests that the processing is probably carried out at the comparison stage. This hypothesis is supported by Kaufmann et al. (2005) and Pinel et al. (2004) who found that the IPS is activated by the numerical distance effect and by the size congruity effect. The IPS is known to play a role not only in numerical processing but also in visuospatial representation (Corbetta & Shulman, 2002; Hubbard, Piazza, Pinel, & Dehaene, 2005). Hence, it is possible that with horizontal orientation the IPS is involved in processing the physical size of the displayed numbers as well as their numerical value via a *visuospatial code*. Under vertical presentation numerical distance and size congruity were additive. In this case it is possible that numerical value is processed via a *verbal code*, probably by the temporal structure (Cohen Kadosh et al., 2005b; Pinel et al., 2001), and physical size is processed by the IPS (Cohen Kadosh et al., 2005b; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Pinel et al., 2004).

The current idea that the overlap between brain structures can modulate chronometric data is not new. It has been suggested that the degree of interference between relevant and irrelevant information stems from the overlap in neural activity/brain structures (Cohen Kadosh & Henik, 2006a, 2006b, 2006c; Fias et al., 2001; Kinsbourne & Hicks, 1978; Lammertyn, Fias, & Lauwereyns, 2002; Posner, Sandson, Dhawan, & Shulman, 1990). For example, Fias et al. (2001) and Lammertyn et al. (2002) showed that irrelevant and relevant information which are processed by a shared brain area, as in the case of orientation and representation of numbers, tend to interfere with one another.

6. Conclusions

The current study showed that the orientation of the presented stimuli can modulate the distance and the size congruity effects. However, in the current study we used number word notation. It is an open question whether such an effect will also be found with other notations such as Arabic numbers, or roman numerals. On the one hand, it is a common belief that numbers are abstractly represented (Dehaene, Dehaene-Lambertz, & Cohen, 1998) and hence other notations should yield effects similar to the current study. On the other hand, it might be that the spatial representation is weaker in number words (at least the automatic aspect of the spatial representation (Fias, 2001)), and the verbal code is stronger due to the use of words, thus, giving rise to the effects that were observed here.

Future studies are needed to uncover the relationship between numbers and language in general, and shared brain areas in particular.

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