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The perseverance of numerical distance effect in attentional blink

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Abstract. In a number comparison task, it is easier to respond faster when the two numbers are further apart than when they are close. This inverse relationship between the size difference and the time to judge such difference is called the numerical distance effect (NDE). In this study we investigated whether attention plays a critical role in the surfacing of NDE and the way we process Arabic numbers. In experiments 1 and 2, with an attentional blink paradigm that was designed to modulate attention, we tested whether a limited or unlimited pool of attentional resources would have an impact on the performance and trend of NDE. The results showed a dissociable effect of attention that changed the overall accuracy but not the trend of NDE. In experiment 3 we examined whether the number priming effect, another phenomenon associated with the distance-related effect, would be affected during the attentional blink period. We found the pattern of number priming effect was not affected by attentional blink. An explanation of the role of attention in number distance processing, as well as how it interacts with Arabic number representation, is discussed.

1 Introduction

1.1 *The numerical distance effect and representation*

The numerical distance effect (NDE) is a well-explored phenomenon that describes an inverse relationship between the difference between two numbers and the time it takes to judge such difference (Moyer and Landauer 1967; Moyer et al 1978). For example, people tend to judge the numbers as 'different' faster when the numerical distance between the targets is bigger (eg 9 and 5) rather than smaller (eg 9 and 8). This effect is also evident in an increased number of response errors in animals (for reviews see Brysbaert 2004; Dehaene et al 1998). Because this pattern looks strikingly similar to a physical ruler-like representation, NDE has sparked many interests in the connection between spatial and mathematical representation (Brysbaert 2004; Dehaene and Changeux 1993; Restle 1970; Walsh 2003). Indeed, Dehaene and Changeux attempted to link the spatial aspects of numerical information processing by proposing a representation that is analogous to a horizontal number line, with smaller digits on the left and larger digits at the right end of the spectrum. This idea was supported by their RT measures of 'odd or even' number judgments: smaller digits (eg 1 or 2) were responded to faster with a left button-press, and larger digits (eg 8 or 9) with a right button-press. The effect held true even when participants had to respond with their hands crossed: smaller digits still enjoyed faster RT on the left side, although they were responded to with the right hand, and vice versa. The phenomenon was termed 'spatial-numerical association of response codes' (SNARC), and is typically associated with a 'mental

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number line' representation that is organized spatially (Dehaene et al 1993; Fias et al 1996; Hung et al 2008; Nuerk et al 2005; Zebian 2005). Another phenomenon related to the mental number line is the 'number priming effect' (Brysbaert 1995, 2004; Reynvoet and Brysbaert 1999; Reynvoet et al 2002). The number priming effect is usually observed in a number naming task. When the numerical distance between the prime and the target is closer, the naming latency is also shorter. This effect can also be explained with a mental number line representation where the activation of a number produces a rippling effect towards its neighbors, allowing these adjacent numbers to be named quicker (Reynvoet and Brysbaert 1999; Reynvoet et al 2002; Roggeman et al 2007).

It is important to note that the NDE, SNARC, and the number priming effect all share the same concept of an 'analogue magnitude representation' (Dehaene et al 1993). In addition to a triple-code model, Reynvoet et al (2002) also proposed a three-route model which was modified from the Coltheart et al (2001) word recognition model. These authors suggested that there is a common code (number line) for all kinds of numerical format. However, since attention plays an important role in selecting information, a more complete model of number representation is required to investigate and account for the role of attention in number processing. Specifically, what kinds of effect would attentional resources have on number processing? Would the availability of attentional resources modulate number processing?

1.2 *NDE as an automatic process*

NDE is a robust effect and has been suggested to occur automatically (Ganor-Stern and Tzelgov 2010; Ganor-Stern et al 2007; LeFevre et al 1988; Lemaire et al 1994; Nuerk et al 2001, 2004; Tzelgov et al 2000). That is, NDE can take place even if it is irrelevant to the task at hand. Also, its occurrence does not require any conscious effort. LeFevre et al (1988) and Lemaire et al (1994) investigated this topic with a number-matching task. They displayed two digits as primes, and their participants were asked to decide whether the subsequent single-digit probe was identical to either priming digits. The results showed, for example, that when the primes were 1 and 5 subjects took more time to indicate the probe as different from the primes when the probe was a 6 than a 7. This is because 6 shares a unique semantic relationship with the primes (it is the sum of 1 and 5) and is somewhat activated upon seeing 1 and 5. More importantly, subjects showed a longer latency when probes were numerically close to the primes (eg a 7 took longer than an 8). Consistent with the mental number line representation and the physical ruler analogy, these results imply that people have a harder time differentiating between a smaller distance than between a larger distance. Further, since participants were not asked to add 1 and 5, yet they were slower to identify 6 as different from 1 and 5, these findings also suggest that people's semantic representation of NDE can be activated unintentionally and automatically regardless of task relevance (LeFevre et al 1988; Lemaire et al 1994; Tzelgov et al 2000). In light of these findings, it is reasonable to expect that NDE, as a byproduct of the mental number line, to also occur unintentionally and automatically. Indeed, this was what Dehaene and Akhavein (1995) had found. In their experiments, subjects were required to report whether the two digits were represented by the same or different numerosity when pairs of digits were presented in either the same notation (eg 4 and 7, or four and seven), or different one (eg 4 and seven). Although the task was specifically designed to be irrelevant to numerical comparison, participants' RT varied significantly and inversely with the magnitude distance between the pair of numbers. For example, the closer the distance between the two numbers, the longer it took people to judge the notation as same or different. Together, these studies explicitly demonstrate how NDE can occur unintentionally even in irrelevant tasks that are outside the domain of numerical comparison.

1.3 *Attentional resources and NDE*

On the basis of the aforementioned studies, if NDE can be activated automatically when people are directing their attention elsewhere, it should be safe to assume that the effect in symbols does not require attentional resources (LeFevre et al 1988; Lemaire et al 1994; Tzelgov et al 2000). How much attentional resource, then, does it take to perform such simple arithmetic? To investigate this issue, we used rapid serial visual presentation (RSVP) and the attentional blink (AB) paradigm to manipulate the availability of attentional resources and its effects on NDE. In a conventional AB task, subjects are required to report two temporally separated targets at a presentation rate of 10 displays per second. Detection rate of the second target (T2) usually suffers between ~200–500 ms after the onset of target one (T1). This decline in T2 performance led Chun and Potter (1995) to propose a two-stage model of information processing in AB. The first stage is parallel processing and attentional-resource-free; thus both targets can be processed completely at this stage. However, the second stage of processing is serial, time-consuming, and limited in attentional resources. Therefore, if the time interval between T1 and T2 is too short (~200–500 ms) to complete T1 processing, T2 is discarded and forgotten. It has been suggested that the so-called 'preattentive' features cannot survive the AB period (eg Joseph et al 1997). Several studies (Egeth et al 2008; Juan et al 2000; Olivers and Watson 2008; Railo et al 2008; Xu and Liu 2008) have also demonstrated that the subitizing process is severely impaired during this critical timeframe. However, some studies of event-related potentials have suggested that the semantic information of T2 can be partially preserved (eg Luck et al 1996; Shapiro et al 1994, 1997; Vogel et al 1998; for a review see Awh et al 2006). Therefore, whether NDE can occur in the AB period still remains unclear.

Previous experiments have always reported NDE with RT measures in a comparison task. Owing to the RSVP paradigm that is being used in the present experiment, in experiment 1 we used accuracy to examine NDE. In this design, subjects were asked to identify the first double-digits (T1) and actively judge the second double-digits (T2) as larger or smaller than T1. Further, in experiment 2 we presented the targets in two streams in order to rule out the possible confound of visual masking in experiment 1. Since a comparison task might have encouraged our participants to strategically employ the idea of a magnitude and therefore unconsciously bias their responses that way, in experiment 3 we instructed our subjects to perform a simple naming task by pressing identical number keys on a keyboard instead of judging the distance between the targets. In these tasks, the occurrence of NDE would indicate that the effect could be processed automatically and unintentionally.

2 Experiment 1

The aim of this experiment was to investigate whether NDE can be observed in participants' accuracy of responses during the AB period. We systematically varied the distance between the two targets with a magnitude of 3, 6, 9, 18, and 36. According to previous studies, a close to linear relationship between the magnitudes and accuracy is expected (Moyer and Landauer 1967). That is, as the distance between the targets increases, participants' accuracy in judging T2 as larger or smaller than T1 should increase as well. Furthermore, we also varied SOA to create AB and non-AB periods. Under such manipulation, if the level of attention is critical to NDE, we would expect to observe a different trend of accuracy of responses between the AB and non-AB periods. Alternatively, if NDE is not affected by attention, the same trend should be preserved across the two periods.

2.1 *Method*

2.1.1 *Participants.* Twenty-one subjects were recruited from the National Central University (eleven males, ten females; mean age = 24 years). All were right-handed and had normal or corrected-to-normal vision.

2.1.2 *Stimuli and procedure.* Stimuli were presented on a 19 inch CRT color monitor with a 100 Hz vertical refresh rate. Subjects viewed the stimuli binocularly in a head-and-chin rest at a distance of 57 cm from the screen. The stimuli were presented in an RSVP paradigm. Each trial began with a fixation cross presented for 500 ms, followed by a blank gap and the RSVP stream. The duration of each stimulus was 40 ms and the interstimulus interval 20 ms. There were eight levels of stimulus onset asynchrony (SOA): 60, 120, 180, 240, 300, 360, 540, and 600 ms (see figure 1).

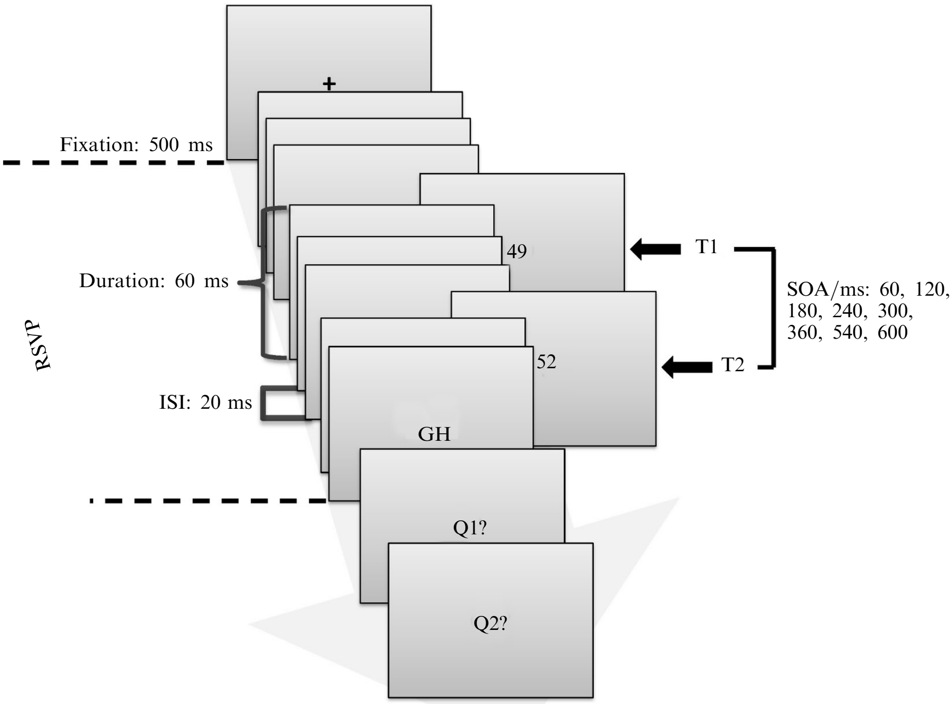

Figure 1. Rapid serial visual presentation (RSVP) task. At first, subjects were required to fixate on the center, then to look for T1 and T2 among distractors. After the RSVP, subjects manually answered two questions: (1) What is the value of T1?; (2) T2 is larger or smaller than T1?

The targets were pairs of Arabic double-digits, in which the first pair, T1, was white (CIE: $x = 0.282$, $y = 0.314$, $z = 85.5$ cd m^{-2}) and the second, T2, was gray (CIE: $x = 0.280$, $y = 0.339$, $z = 16.6$ cd m^{-2}), presented on a light-gray background (CIE: $x = 0.280$, $y = 0.295$, $z = 57.3$ cd m^{-2}). Throughout the experiment, T1 was randomly chosen from four numbers: 49, 50, 59, and 60. We systematically varied the numerical distance between the two targets with magnitudes of 3, 6, 9, 18, and 36 towards both positive and negative directions to cover different ranges of NDE [eg 53(T2) = 50(T1) + 3(numerical distance) or 47(T2) = 50(T1) − 3(numerical distance)]. The order of T1 and T2 was not fixed, as the order of two numbers can be reversed within the same pair (see table 1). The pairs were randomly assigned to every trial in the experiment. The distractors were paired gray letters (CIE: $x = 0.278$, $y = 0.301$, $z = 19.7$ cd m^{-2}), which were randomly chosen from 26 letters, except for letters I, O, Z, and W. We excluded letters I, O, and Z because of their featural similarities to

Table 1. Numerical distance between the two targets.

Targets	Numerical distance				Numerical distance			
	3				6			
(T1, T2)	(39, 42)	(49, 52)	(50, 53)	(60, 57)	(34, 40)	(46, 52)	(52, 46)	(59, 65)
(T1, T2)	(42, 39)	(52, 49)	(53, 50)	(57, 60)	(40, 34)	(52, 46)	(46, 52)	(65, 59)
	9				18			
(T1, T2)	(35, 44)	(43, 52)	(58, 67)	(67, 58)	(42, 60)	(45, 63)	(51, 69)	(68, 50)
(T1, T2)	(44, 35)	(52, 43)	(67, 58)	(58, 67)	(60, 42)	(63, 45)	(69, 51)	(50, 68)
	36							
(T1, T2)	(37, 73)	(41, 77)	(59, 23)	(68, 32)				
(T1, T2)	(73, 37)	(77, 41)	(23, 59)	(32, 68)				

numbers 1, 0, and 2. Letter W was also excluded from the list owing to its relatively larger size. All the stimuli subtended 1 deg $\times$ 1 deg. The presentation was programmed with E-prime Version 1.0 (Psychological Software Tool Inc.) on a Pentium IV desktop computer. All responses were recorded via a keyboard. All participants used their right hand to respond throughout the entire experiment.

Participants were instructed to initiate each trial by pressing the space bar. They were told to identify the first target number (T1) and to indicate whether the second target number (T2) was smaller or larger by pressing the identical double-digits on the keyboard for T1, and the 'L' (larger) or 'S' (smaller) keys for T2. There were 20 practice trials to start with and three blocks in the formal experiment. Each block consisted of 120 trials (360 trials in experiment 1).

2.1.3 *Analysis.* Normally AB becomes evident as the accuracy of T2 decreases when T2 onset is 200 to 500 ms after T1 presentation (Broadbent and Broadbent 1987; Chun and Potter 1995; Lawrence 1971; Raymond et al 1992; Weichselgartner and Sperling 1987). During this period, T2 accuracy is significantly lower than that of other SOAs because most of the attentional resources are devoted to the processing of T1. When applying AB to NDE, however, T1 also plays the role of a reference point in addition to its original role as a resource grabber. Since our subjects were asked to judge whether T2 was larger or smaller than T1, this task was virtually impossible if T1 was not correctly identified in the first place. Only when T1 identification is correct can we confidently use T2 accuracy as a reliable measure of NDE. Therefore, to investigate the influence of attention on NDE, judgment of T2 under the condition when T1 was correctly identified (referred to as T2/T1 performance hereafter) was used throughout this study to further compare NDE between the AB and non-AB periods. Note that most studies to date on NDE have relied on RT as their only measure. Since RT information is less accessible and reliable in an RSVP paradigm, we used accuracy (in this case T2/T1) to measure NDE.

A three-way ANOVA was applied in this experiment: targets (2 levels), SOAs (8 levels), and distances (5 levels). The 2 levels of target accuracy used the mean accuracy of T1 identification and T2/T1 (T2 accuracy given correct T1 identification). This variable was broken down into three 2 levels and was submitted to a 2-way ANOVA along with various lags because the effect of lags (AB) should only be present in T2 but not in T1. A main effect of distance would tell us that NDE can indeed occur in an RSVP paradigm. However, if attention is critical for the occurrence of NDE, then a two-way interaction (SOA $\times$ distance) should be observed instead. That is, NDE should only occur in the non-AB SOAs if attentional resource is not necessary.

2.2 *Results and discussion*

2.2.1 *Attentional blink (AB).* In a three-way ANOVA, the main effects of targets ($F_{1,10} = 2.789$, MSE = 0.283, $p = 0.126$) were not significant. The main effects of SOAs ($F_{7,70} = 23.527$, MSE = 0.038, $p < 0.01$) and distance ($F_{4,40} = 9.774$, MSE = 0.020, $p < 0.01$) were all significant. Analyses also showed a significant interaction between SOAs and targets ($F_{7,70} = 34.760$, MSE = 0.022, $p < 0.01$). T2 performance, given correct T1 identification (T2/T1), was significantly better ($F_{7,140} = 7.686$, MSE = 0.013, $p < 0.01$) at SOAs of 540 and 600 ms than at other SOAs. Fisher's LSD on T2/T1 showed that hit rates at SOAs of 60, 300, and 360 ms were not significantly different from those at 540 and 600 ms. On the other hand, hit rates at 120, 180, and 240 ms were significantly lower than at 540 and 600 ms. Since SOAs of 120, 180, and 240 ms mark the window of the AB period, the conventional effect of AB was successfully replicated here. Our participants had an overall T1 accuracy of 0.80; therefore we had sufficient trials for T2/T1 analysis (see figure 2).

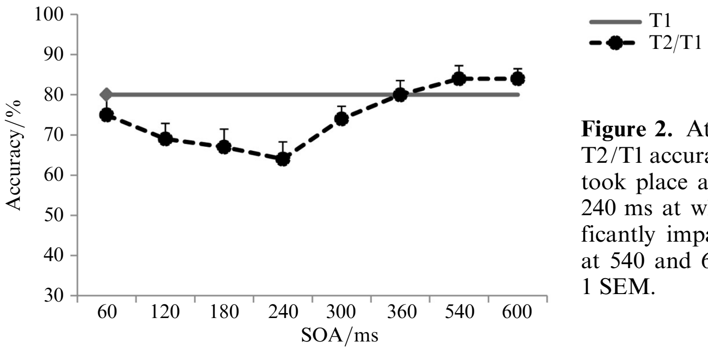

Figure 2. Attentional blink (AB) effect. T2/T1 accuracy shows that the AB period took place at the SOAs of 120, 180, and 240 ms at which performance was significantly impaired in comparison to that at 540 and 600 ms. Error bars represent 1 SEM.

2.2.2 *NDE during the AB period.* The question here was whether NDE can be found during the AB period. To examine NDE in the AB and non-AB periods separately, we grouped different SOAs into the AB (120, 180, and 240 ms) and non-AB (540 and 600 ms) periods. A repeated-measures ANOVA analysis was then conducted on T2/T1 accuracy for both AB and non-AB periods to measure the effect of number distance. The analysis revealed a significant main effect of number distance both during the AB ($F_{4,80} = 4.322$, MSE = 0.013, $p < 0.005$), and non-AB ($F_{4,80} = 3.014$, MSE = 0.013, $p < 0.05$) periods. In other words, participants' performance declined as T2 became closer to T1, which indicated that the numerical distance effect was indeed present in both periods. Fisher's LSD analyses of T2/T1 from the AB period showed that T2/T1 performance at distance 3 was significantly lower than at all other distances (6, 18, and 36) except for distance 9 (figure 3). We also conducted a trend analysis that examined the shape of the overall line pattern, and a significant linear trend was

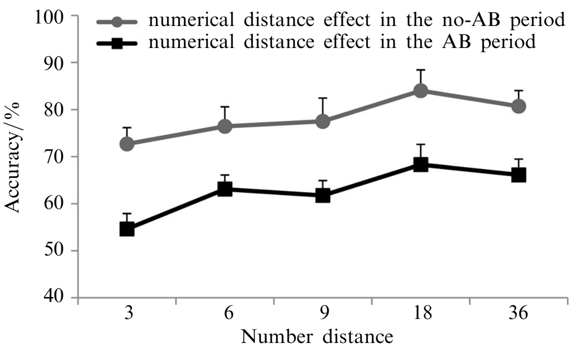

Figure 3. Numerical distance effect. The numerical distance effect is significant both in the AB and non-AB periods. The positive slope indicates that T2/T1 accuracy increases with the distance between T1 and T2. Therefore, the same NDE is observed regardless of the amount of attentional resources. Error bars represent 1 SEM.

observed ($F_{1,20} = 28.581$, MSE = 0.010, $p < 0.001$). No significant interactions were found between AB and NDE ($F_{4,80} = 0.242$, MSE = 0.013, $p = 0.914$). This further supports the notion that the NDE is not dependent on the amount of attentional resources. To ensure that the results were not driven by any specific strategy, such as RT – accuracy trade-off, the correlation between RT and accuracy was analyzed. There was no correlation between these two measures, neither during the AB period ($r = 0.122$, $n = 21$, $p = 0.298$) nor during the non-AB period ($r = -0.307$, $n = 21$, $p = 0.088$). These results suggest that there was no RT – accuracy trade-off.

One important objective of this experiment was to use the AB paradigm and examine how it modulates attention in NDE. Indeed, hit rates during the non-AB period were better than those during the AB period. This drop in hit rates indicates that AB does effectively limit the availability of one's attentional resources. In addition, our results showed a significant NDE in T2/T1 accuracy both during the AB and non-AB periods. This indicates that NDE can indeed occur regardless of the availability of attentional resources. It is worth noting that the decreased overall accuracy during the AB period suggests that the AB paradigm does work well in modulating the amount of attentional resources. Even so, the trend of NDE was still observed within the AB period despite the decreased accuracy due to limited resources. We refer this dissociation between the overall accuracy and NDE with that the AB paradigm does work, and might be a useful tool for investigating the role of attention in numerical processes.

Although NDE was found in this experiment, there had been reports suggesting that visual masking could be a potential confound in traditional RSVP tasks (Potter et al 2002). At such speeds of presentation, it is possible that targets could have been masked by the screens that followed, and therefore the targets were not perceived at all. It is therefore possible that the observed poor performance was driven solely by the absence of unambiguous perceptual information (visual masking), and not by the absence of attention (AB). To rule out this possible confound, we adopted Potter et al's (2005) experimental design in the next experiment.

3 Experiment 2

In the previous experiment, a significant relationship was observed between NDE and T2/T1 accuracy. However, although a large NDE was successfully elicited in the RSVP task, the conventional one-stream RSVP paradigm has a potential confound of visual masking (Potter et al 2002). Simply put, there is a high possibility that T2 was not perceived at all. To control for the masking effect, Potter et al displayed T1 and T2 in two spatially separate visual streams. Following the same logic, in the present experiment we also applied two streams of presentation as they did. If the observed NDE from experiment 1 was driven by a masked visual input of T2 rather than a depletion of attentional resources, then no significant NDE should be observed when the spatial locations of both targets are properly controlled. Alternatively, the same NDE should be present if visual masking did not play a role in our AB paradigm. We also changed the parameters of this experiment to specifically zoom-in on the AB period in order to look closer at NDE when attention is absent. If the effects in experiment 1 were not due to visual masking, our findings here should remain the same: that NDE can be found with limited attentional resources.

3.1 *Method*

3.1.1 *Participants.* Fourteen participants were recruited from the National Central University (five males, nine females; mean age = 23 years). All were right-handed and had normal or corrected-to-normal vision.

3.1.2 *Stimuli and procedure.* The stimuli and apparatus were the same as in experiment 1 except for:

(1) Two streams of stimuli, one positioned at the top and one at the bottom, were presented in RSVP paradigm in the center of the screen. Since the purpose of this design was to rule out visual masking between the targets, T1 and T2 were programmed to always appear in different streams. Each trial began with a fixation cross presented for 500 ms, followed by a blank display for 107 ms, and then the RSVP stream.

(2) Each trial lasted 700 ms, composed of fourteen 50 ms displays and 0 ms ISIs. In the two-stream condition, both targets could only appear anywhere within the 4th and 9th displays of the fourteen SOAs; thus the difference between T1 and T2 onsets can be as small as 0 ms or as large as 250 ms.

(3) T1 and T2 were randomly selected from a pool of 19 and 18 numbers, respectively. These numbers were randomly generated and ranged from 23 to 77. Throughout the experiment, subjects saw twenty unique pairs of these numbers. We noticed that alphabetical distractors severely impaired our subjects' performance in our pilot study. To avoid floor effect in our subjects' accuracies, we changed the distractors to five Chinese characters: 圓 圈 園 圖 國. All targets and distractors were randomly paired. All stimuli subtended 1.5 deg × 1.5 deg and were presented in black on a light-gray background.

Participants were instructed to initiate each trial by pressing the space bar. All participants used their right hand throughout the experiment. They were told to identify the first target by pressing identical digits on the keyboard and judge whether the second target is larger or smaller than the first target. If the two targets happened to be displayed at the same time on different streams, they were asked to identify the upper target as first (T1) and lower as second (T2), and perform the comparison task. T1 and T2 were always presented in different RSVP streams in a single trial. There were 24 practice trials and 240 trials in the formal experiment.

3.2 *Results and discussion*

Data were analyzed with a three-way ANOVA. The variables were the same as in the previous experiment: targets (2 levels), SOAs (6 levels), and numerical distances (5 levels). Note that we intentionally included all SOAs (0 to 250 ms with an increment of 50 ms) in the subsequent analyses because they were specifically chosen to fall within the AB period.

3.2.1 *NDE.* There were enough T2/T1 trials as our subjects achieved an overall T1 accuracy of 0.64. In the two-way ANOVA, there was a significant interaction between targets and numerical distance ($F_{8,104} = 3.061$, MSE $= 0.027$, $p < 0.05$). Fisher's LSD analysis showed that numerical distance 3 had a significantly lower T2/T1 accuracy than numerical distances 9 and 36 but not 12 and 18 ($F_{4,52} = 3.261$, MSE $= 0.006$, $p < 0.05$). This indicates that NDE was also present in this experiment, albeit in a weaker form after controlling for visual masking. Further trend analysis also revealed significant linearity ($F_{1,13} = 6.449$, MSE $= 0.008$, $p = 0.025$), which provides support for the presence of NDE. In conclusion, the different-stream design confirmed the finding from experiment 1: that NDE persists even when attentional resources are scarce (figure 4).

To control for the visual masking effect, a two-stream RSVP paradigm was applied in this experiment. NDE was still observed in the different-stream design. This result, along with that of experiment 1, both point to the conclusion that attention is not a critical factor in number distance processing. In the past, some studies have also used a *naming* task to test the idea of number distance (Reynvoet et al 2002; Roggeman et al 2007). Their reasoning was that number naming required one less cognitive stage than comparison. Therefore, our next experiment followed their procedures with our AB paradigm to test whether NDE can be replicated even when attentional resource is limited.

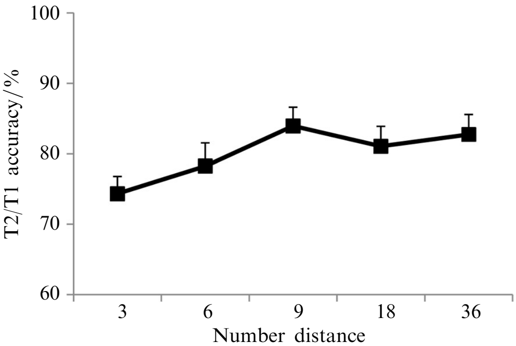

Figure 4. NDE without visual masking. NDE was significant with a similar positive slope to that found in experiment 1. This result is consistent with our findings in experiment 1, thus suggesting that our AB paradigm and the observed NDE from experiment 1 were not driven by visual masking. Error bars represent 1 SEM.

4 Experiment 3

The previous two experiments both showed a significant NDE during the AB period when subjects were asked to actively nominate the second target as larger or smaller than the first one. The results indicated that NDE was significant regardless of the availability of attentional resources. In the literature on number distance, however, other researchers have also used a naming task to look at number processing, assuming that a comparison task often involves an extra stage of processing (Roggeman et al 2007). Thus, some suggested that a naming task is purer in investigating NDE (Brysbaert 2004; Koechlin et al 1999; Reynvoet et al 2002; Roggeman et al 2007). With this paradigm, previous studies have shown a reversed number distance, or priming, effect where T2 accuracies increased as its distance from T1 decreased (Reynvoet and Brysbaert 1999; Reynvoet et al 2002; Roggeman et al 2007). Reynvoet and Brysbaert (1999) described it as a 'distance-related priming effect', where the activation of a number has a rippling effect towards its neighbors, making the adjacent numbers easier and quicker to respond to. Based on our findings from experiments 1 and 2, we should be able to replicate the same effects in our AB paradigm. Therefore, to further investigate the role of attention in number processing, in the third experiment we employed a naming task within the same AB paradigm. Instead of judging the magnitude of T2 based on T1, subjects were asked to identify the two targets. If attention is critically involved in such numerical processing, then we should not be able to replicate such priming effect within our AB paradigm, but, if attentional resource is not critical, then we should acquire similar findings with our paradigm.

4.1 *Method*

4.1.1 *Participants.* Twelve subjects were recruited from the National Central University (six male, six female; mean age = 22 years). All were right-handed and had normal or corrected-to-normal vision.

4.1.2 *Stimuli and procedure.* The stimuli and procedure were identical to those in experiment 2, with the exception that participants were asked to identify both targets by pressing identical digits on the keyboard at the end of the RSVP stream.

4.2 *Results and discussion*

4.2.1 *Numerical distance effect of T2/T1.* Overall, T1 accuracy was 0.63. There was a significant interaction between targets and numerical distances ($F_{8,80} = 5.522$, MSE = 0.019, $p < 0.01$) (figure 5). LSD a posteriori analyses for T2/T1 performance indicated that the accuracy of numerical distance 3 was significantly higher than that of other numerical distances ($F_{4,44} = 7.274$, MSE = 0.010, $p < 0.01$). A significant linear trend was also observed ($F_{1,11} = 12.727$, MSE = 0.015, $p < 0.005$) (see figure 5).

The result here is consistent with previous studies: T2/T1 accuracy is higher when T1 and T2 are numerically close than when they are far (Reynvoet and Brysbaert 1999).

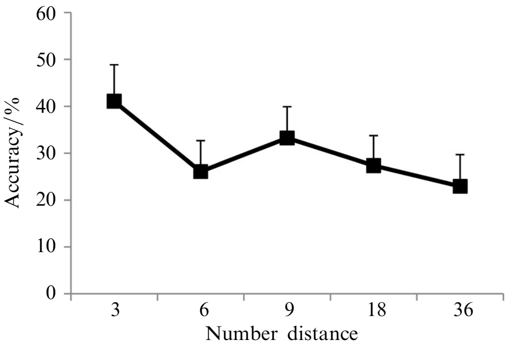

Figure 5. Reversed NDE. The figure shows a significant reversed NDE (ie distance-related priming effect): T2/T1 accuracy increases as the distance between T1 and T2 decreases. On the basis of the idea of a mental number line and spreading activations of the adjacent nodes, one can interpret this as NDE from another angle: as T2 becomes closer to T1, it becomes more activated by the spreading T1 activation, thus easier to identify. In the case of numerical comparison, however, the spreading activation from T1 also makes neighboring T2 more activated, and therefore harder to compare. Error bars represent 1 SEM.

Although the direction of the accuracy trend is opposite to that in our previous two experiments, this priming effect in essence is indeed a reversed NDE. That is, without the cognitive effort to compare the two targets, the nearby numbers are now being facilitated rather than interfered with by the adjacent activations from the first number. Again, this result is obtained within the AB time frame. Therefore, our present result is consistent with the idea that limited attention does not affect NDE.

5 General discussion

The aim of this study was to investigate whether the involvement of attention is critical to the processing of NDE in Arabic numbers. The RSVP paradigm was used, and the non-AB and AB periods represented an unlimited and limited pool of attentional resources, respectively (Dux and Marois 2009; Marois and Ivanoff 2005). In addition, a priming effect was also observed when numerical comparison was replaced by a numerical naming task.

In experiment 1, the requirement was to compare T2 with T1 and answer whether T2 was larger or smaller than T1. NDE was observed both during the AB and the non-AB periods. This indicated that the amount of attentional resources affected subjects' general performance of the numerical tasks but did not hinder their access to number representations, thus allowing the comparison process to elicit NDE.

In experiment 2, we employed a two-stream presentation to account for the possible confound of visual masking effect that might have been present in experiment 1 (Potter et al 2002). When visual masking was no longer present, our results from experiment 2 remained consistent with those of experiment 1: NDE was found during the AB period.

Together, experiments 1 and 2 demonstrated that NDE can be elicited even when the attentional resource is scarce. While it is true that T2/T1 accuracy decreases as a whole in the AB period in comparison with the non-AB period, the basic trends of NDE are the same across both conditions. This suggests that perhaps attention can modulate our overall accuracy (presumably by impairing the capability to correctly identify T2 for comparison), but our representation of numbers remains the same as a mental number line (Dehaene and Changeux 1993), and therefore will always reveal itself in the form of NDE in a comparison task. When this is applied to our data, the amount of attentional resources seems to influence overall T2/T1 accuracy, shifting everything along the *Y*-axis (accuracy) without changing the basic trend. The trend only changes when tasks are changed (experiment 3), which reflects a difference in measurement of the same numerical representation. This explanation accounts for the discrepancy between our results and recent findings that suggest a critical role of spatial and temporal attention in processing a masked (unconscious) prime (Fabre et al 2007; Lachter et al 2004; Naccache et al 2002). In this light, our accuracy rates are modulated by the amount of attentional resources, which reflects a causal role of attention in processing numeric information. Since the manifestation of NDE requires numerical processing (or else it cannot be measured), and the present results suggest that numerical processing relies heavily on attention, it is plausible to assume that the manifestation of NDE is dependent on attention. What is new in the present study, then, is the automatic activation of NDE which was present regardless of the amount of attentional resources. If the NDE is dependent on attention, it should be affected during the AB period owing to an insufficient amount of attentional resources to access the mental number line. However, the present results implicate that attention and NDE are independent of each other. What is meant by automatic activation of NDE?

(1) The representation of mental number line can be quickly maintained and accessed even when the duration of target display is very short (60 and 40 ms).

(2) The mental number line is easily activated even when the attentional resources are limited.

Hence, the similar linear trends throughout all levels of accuracies can be interpreted as evidence for the automatic nature of NDE as well as the underlying organization of the number line representation, which are not dependent on attention.

In experiment 3, we attempted to replicate NDE in the naming task from Reynvoet and Brysbaert (1999). Reynvoet and Brysbaert have systematically manipulated the distance between the prime and the target and asked their subjects to name the target as soon as they can. The target RTs were faster when they followed a priming digit of smaller distance. Reynvoet and Brysbaert described it as a 'distance-related priming effect'. This priming effect is basically an NDE revealed in a reversed format because the adjacent activations are now facilitative rather than interfering. Therefore, the requirement of comparison was replaced by a naming task (for both T1 and T2) in experiment 3. The results also showed a significant priming effect. By simply switching our task from comparison to identification, we have obtained two different forms of NDE. According to the triple-code model (Dehaene 1992), there are three subcomponents: analogue magnitude representation, visual Arabic number form, and auditory verbal word form. The analogue magnitude representation shows a direct path to comparison. This indicates that the Arabic numbers can be transformed into analogue magnitude codes before any comparison, hence our observation of NDE in a number comparison task. Furthermore, the priming distance effect can also access the analogue magnitude codes via spreading activations: the closer neighbors of the target are activated more and responded quicker than more remote digits. Both trends are consistent with the mental number line, and perhaps are interesting reciprocals of each other. Thus, NDE and the priming distance effect represent the same concept of a semantic magnitude representation. Our experiment 3 was essentially a replication of experiment 2 from another perspective.

The present experiments used the AB to temporarily induce attentional lapse while participants performed the numerical comparison task. The results showed a robust NDE, but the overall accuracy was modulated by the amount of attentional resources. These results are quite compatible with findings from the developmental dyscalculia literature, where people who experience arithmetic problems also show different aspects of attentional difficulties (Ashkenazi and Henik 2010; Ashkenazi et al 2009a, 2009b; Cohen Kadosh and Walsh 2007). This non-specific impairment in brain function also has been demonstrated in normal subjects in many neural correlate studies (Cohen Kadosh et al 2005, 2007, 2010; Cohen Kadosh and Walsh 2009a, 2009b. Even normal participants can also exhibit dyscalculia-like patterns when attentional load becomes high (Ashkenazi et al 2009b). Therefore, it is likely that people with developmental dyscalculia still maintain intact representations of numbers on the mental number line, but cannot easily distinguish the numbers due to limited attentional resources (Ashkenazi and Henik 2010). Our findings here are consistent with the attentional account of developmental dyscalculia and may shed new light on this topic.

6 Conclusions

In the past, a large number of studies have used a number stroop task (Ganor-Stern et al 2007; Tzelgov and Ganor-Stern 2004), number matching task (Dehaene and Akhavein 1995), priming task (Koechlin et al 1999; Reynvoet et al 2002), subliminal priming task (Kouider and Dehaene 2009; Naccache and Dehaene 2001), and continuous flash suppression (Bahrami et al 2010) to demonstrate the automatic nature of number processing. Instead of manipulating the amount of attentional resources directly, most studies use other indirect measures to make such claim. The AB paradigm employed here, then, is novel in the way that it directly manipulates the amount of attentional resources available.

Our results demonstrated that Arabic double digits on the mental number line can be rapidly and successfully accessed regardless of priming or comparison requirement in the AB tasks. This implies that the representation of a mental number line is not easily modified by other forces such as limited attentional resources. The availability of attentional resources did not make the remote digits easier to detect than the close ones. Furthermore, attention seems to open a gate and equally spread out the information along the mental number line. It was quickly and automatically activated even when target duration was very short, regardless of whether the task explicitly or inexplicitly required the use of a mental number line. In a similar line of research, AB paradigm was used in non-symbolic number stimuli (dots) to examine whether the subitizing process could survive the AB period. Results suggested that subjects could not count/subitize more than four dots in the AB period (Burr et al 2010; Juan et al 2000). These results are consistent with a recent demonstration of subjects' failure to subitize in the inattentional blindness state (Railo et al 2008). Although the attentional demand in the inattentional blindness paradigm involves less *active* attention processes in the task (the subitizing task) and is very different from that in AB (Awh et al 2006; Mack and Rock 1998; for a review see Kim and Blake 2005), both Ralio et al and Juan et al's findings suggest that non-symbolic numerical information requires a certain amount of attention to be processed correctly (Burr et al 2010; Egeth et al 2008; Juan et al 2000; Olivers and Watson 2008; Railo et al 2008; Vetter et al 2008; Xu and Liu 2008). In contrast, findings from the current study suggest that the pattern of symbolic numerical stimulus processing (ie NDE) may be preserved during the AB period, presumably accomplished by accessing the preserved semantic information. The underlying mechanism of this pattern of results may originate from an intact initial encoding of T2 (NDE) coupled with an impaired retrieval for the precise identification of T2 (overall deterioration in the AB period) (Luck et al 1996; Shapiro et al 1997; for a review see Awh et al 2006).

In summary, we have found significant NDE in the AB period, which suggests that NDE does not require much attentional resource. The only difference our attentional resource makes between the AB and non-AB periods, then, seems to be the *Y*-intercept of the overall accuracy. Accuracy during the AB period is overall lower than during the non-AB period, but the trends in both periods appear the same. The similar pattern of results was also observed in the number priming effects. This indicates that even when the available attentional resource is limited, significant numerical distance/priming effect can still be observed. Using the AB paradigm, our results here support an automatic account of NDE. Most importantly, the present experiment provides a more direct and quantitative approach to investigating the role of attention in numerical processing.

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References

Ashkenazi S, Henik A, 2010 "Attentional networks in developmental dyscalculia" *Behavioral and Brain Functions* **6**:2, doi:10.1186/1744-9081-6-2

Ashkenazi S, Mark-Zigdon N, Henik A, 2009a "Numerical distance effect in developmental dyscalculia" *Cognitive Development* **4** 387 – 400

Ashkenazi S, Rubinsten O, Henik A, 2009b "Attention, automaticity and developmental dyscalculia" *Neuropsychology* **23** 535 – 540

Awh E, Vogel E K, Oh S H, 2006 "Interactions between attention and working memory" *Neuroscience* **139** 201 – 208

Bahrami B, Vetter P, Spolaore E, Pagano S, Butterworth B, Rees G, 2010 "Unconscious numerical priming despite interocular suppression" *Psychological Science* **21** 224 – 233

Broadbent D E, Broadbent M H P, 1987 "From detection to identification: Response to multiple targets in rapid serial visual presentation" *Perception & Psychophysics* **42** 105 – 113

Brysbaert M, 1995 "Arabic number reading: On the nature of the numerical scale and the origin of phonological recoding" *Journal of Experimental Psychology: General* **124** 434 – 452

Brysbaert M, 2004 "Number recognition in different formats", in *Handbook of Mathematical Cognition* Ed. J I D Campbell (Hove, UK and New York: Psychology Press) pp 23 – 43

Burr D, Turi M, Anobile G, 2010 "Subitizing but not estimation of numerosity requires attentional resources" *Journal of Vision* **10**(6):20, 1 – 10, doi:10.1167/10.6.20

Chun M M, Potter M C, 1995 "A two-stage model for multiple target detection in rapid serial visual presentation" *Journal of Experimental Psychology: Human Perception and Performance* **21** 109 – 127

Cohen Kadosh R, Cohen Kadosh K, Kaas A, Avishai H, Goebel R, 2007 "Notation-dependent and -independent representations of numbers in the parietal lobes" *Neuron* **53** 307 – 314

Cohen Kadosh R, Henik A, Rubinsten O, Mohr H, Dori H, Van de Ven V, Zorzi M, Goebel R, Linden D, 2005 "Are numbers special? The comparison systems of the human brain investigated by fMRI" *Neuropsychologia* **43** 1238 – 1248

Cohen Kadosh R, Muggleton N, Silvanto J, Walsh V, 2010 "Double dissociation of format-dependent and number-specific neurons in human parietal cortex" *Cerebral Cortex* **9** 2166 – 2171

Cohen Kadosh R, Walsh V, 2007 "Dyscalculia" *Current Biology* **17** R946 – R947

Cohen Kadosh R, Walsh V, 2009a "Numerical cognition: reading numbers from the brain" *Current Biology* **19** R898 – R899

Cohen Kadosh R, Walsh V, 2009b "Numerical representation in the parietal lobes: Abstract or not abstract?" *Behavioral and Brain Sciences* **32** 313 – 328

Coltheart M, Rastle K, Perry C, Langdon R, Ziegler J C, 2001 "DRC: A dual route cascaded model of visual word recognition and reading aloud" *Psychological Review* **108** 204 – 256

Dehaene S, 1992 "Varieties of numerical abilities" *Cognition* **44** 1 – 42

Dehaene S, Akhavein R, 1995 "Attention, automaticity, and levels of representation in number processing" *Journal of Experimental Psychology: Learning Memory and Cognition* **21** 314 – 326

Dehaene S, Bossini S, Giraux P, 1993 "The mental representation of parity and number magnitude" *Journal of Experimental Psychology: General* **122** 371 – 396

Dehaene S, Changeux J-P, 1993 "Development of elementary numerical abilities: A neuronal model" *Journal of Cognitive Neuroscience* **5** 390 – 407

Dehaene S, Naccache L, Le Clec'H G, Koechlin E, Mueller M, Dehaene-Lambertz G, Moortele P F van de, Le Bihan D, 1998 "Imaging unconscious semantic priming" *Nature* **395** 597 – 600

Dux P E, Marois R, 2009 "The attentional blink: a review of data theory" *Attention, Perception, & Psychophysics* **71** 1683 – 1700

Egeth H E, Leonard C J, Palomares M, 2008 "The role of attention in subitizing: Is the magical number 1?" *Visual Cognition* **16** 463 – 473

Fias W, Brysbaert M, Geypens F, d'Ydewalle G, 1996 "The importance of magnitude information in numerical processing: Evidence from the SNARC effect" *Mathematical Cognition* **2** 95 – 110

Fabre L, Lemaire P, Grainger J, 2007 "Attentional modulation of masked repetition and categorical priming in young and older adults" *Cognition* **105** 513 – 532

Ganor-Stern D, Tzelgov J, 2010 "Across-notation automatic processing of two-digit numbers" *Experimental Psychology* (Epub ahead of print)

Ganor-Stern D, Tzelgov J, Ellenbogen R, 2007 "Automaticity of two-digit numbers" *Journal of Experimental Psychology: Human Perception and Performance* **33** 483 – 496

Hung Y-H, Hung D L, Tzeng O J-L, Wu D H, 2008 "Flexible spatial mapping of different notations of numbers in Chinese readers" *Cognition* **106** 1441 – 1450

Joseph J S, Chun M M, Nakayama K, 1997 "Attention requirements in a 'preattentive' feature search task" *Nature* **387** 805 – 808

Juan C H, Walsh V, McLeod P, 2000 "Preattentive vision and enumeration" *Investigative Ophthalmology and Visual Science* **41** S39

Kim C Y, Blake R, 2005 "Psychophysical magic: rendering the visible 'invisible'" *Trends in Cognitive Sciences* **9** 381 – 388

Koechlin E, Naccache L, Block E, Dehaene S, 1999 "Primed numbers: Exploring the modularity of numerical representations with masked and unmasked priming" *Journal of Experimental Psychology: Human Perception and Performance* **25** 1882 – 1905

Kouider S, Dehaene S, 2009 "Subliminal number priming within and across the visual and auditory modalities" *Experimental Psychology* **56** 418 – 433

Lachter J, Foster K I, Ruthruff E, 2004 "Forty-five years after Broadbent (1958): still no identification without attention" *Psychological Review* **111** 880 – 913

Lawrence D H, 1971 "Two studies of visual search depends on physical rather than conceptual differences" *Perception & Psychophysics* **10** 85 – 89

LeFevre J A, Bisanz J, Mrkonjic L, 1988 "Cognitive arithmetic: Evidence for obligatory activation of arithmetic facts" *Memory & Cognition* **16** 45 – 53

Lemaire P, Barrett S, Fayol M, Abdi H, 1994 "Automatic activation of addition and multiplication facts in elementary school children" *Journal of Experimental Child Psychology* **57** 224 – 258

Luck S J, Vogel E K, Shapiro K L, 1996 "Word meanings can be accessed but not reported during the attentional blink" *Nature* **383** 616 – 618

Mack A, Rock I, 1998 *Inattentional Blindness* (Cambridge, MA: MIT Press)

Marois R, Ivanoff J, 2005 "Capacity limits of information processing in the brain" *Trends in Cognitive Sciences* **9** 296 – 305

Moyer R S, Bradley D R, Sorensen M H, Whiting C, Mansfield D P, 1978 "Psychophysical functions for perceived and remembered size" *Science* **200** 330 – 332

Moyer R S, Landauer T K, 1967 "Time required for judgements of numerical inequality" *Nature* **215** 1519 – 1520

Naccache L, Blandin E, Dehaene S, 2002 "Unconscious masked priming depends on temporal attention" *Psychological Science* **13** 416 – 424

Naccache L, Dehaene S, 2001 "Unconscious semantic priming extends to novel unseen stimuli" *Cognition* **80** 215 – 229

Nuerk C, Kaufmann L, Zoppoth S, Willmes K, 2004 "On the development of the mental number line: More, less, or never holistic with increasing age?" *Developmental Psychology* **40** 1199 – 1211

Nuerk C, Weger U, Willmes K, 2001 "Decade breaks in the mental number line? Putting tens and units back into different bins" *Cognition* **82** B25 – B33

Nuerk C, Wood G, Willmes K, 2005 "The universal SNARC effect: The association between number magnitude and space is amodal" *Experimental Psychology* **52** 187 – 194

Olivers C N L, Watson D G, 2008 "Subitizing requires attention" *Visual Cognition* **16** 439 – 463

Potter M C, Dell'Acqua R, Pesciarelli F, Job R, Peressotti F, O'Connor D H, 2005 "Bidirectional semantic priming in the attentional blink" *Psychonomic Bulletin & Review* **12** 460 – 465

Potter M C, Staub A, O'Connor D H, 2002 "The time course of competition for attention: attention is initially labile" *Journal of Experimental Psychology: Human Perception and Performance* **28** 1149 – 1162

Railo H, Koivisto M, Revonsuo A, Hannula M M, 2008 "The role of attention in subitizing" *Cognition* **107** 82 – 104

Raymond J E, Shapiro K L, Arnell K M, 1992 "Temporary suppression of visual processing in an RSVP task: an attentional blink?" *Journal of Experimental Psychology: Human Perception and Performance* **18** 849 – 860

Restle F, 1970 "Speed of adding and comparing numbers" *Journal of Experimental Psychology* **83** 274 – 278

Reynvoet B, Brysbaert M, 1999 "Single-digit and two-digit Arabic numerals address the same semantic number line" *Cognition* **72** 191 – 201

Reynvoet B, Brysbaert M, 2004 "Cross-notation number priming investigated at different stimulus onset asynchronies in parity and naming tasks" *Experimental Psychology* **51** 81 – 90

Reynvoet B, Brysbaert M, Fias W, 2002 "Semantic priming in number naming" *Quarterly Journal of Experimental Psychology A* **55** 1127 – 1139

Roggeman C, Vergutsa T, Fias W, 2007 "Priming reveals differential coding of symbolic and non-symbolic quantities" *Cognition* **105** 380 – 394

Shapiro K L, Raymond J E, Arnell K M, 1994 "Attention to visual pattern information produces the attentional blink in rapid serial visual presentation" *Journal of Experimental Psychology: Human Perception and Performance* **20** 357 – 371

Shapiro K L, Raymond J E, Arnell K M, 1997 "The attentional blink" *Trends in Cognitive Sciences* **1** 291 – 296

Tzelgov J, Ganor-Stern D, 2004 "Automaticity in processing ordinal information", in *Handbook of Mathematical Cognition* Ed. J I D Campbell (Hove, UK and New York: Psychology Press) pp 239 – 261

Tzelgov J, Yehene V, Kotler L, Alon A, 2000 "Automatic comparisons of artificial digits never compared" *Journal of Experimental Psychology: Learning, Memory and Cognition* **26** 103 – 120

Vetter P, Butterworth B, Bahrami B, 2008 "Modulating attentional load affects numerosity estimation: evidence against a pre-attentive subitizing mechanism" *PLoS ONE* **3** e3269

Vogel E K, Luck S J, Shapiro K L, 1998 "Electrophysiological evidence for a post-perceptual locus of suppression during the attentional blink" *Journal of Experimental Psychology: Human Perception and Performance* **24** 1656 – 1674

Walsh V, 2003 "A theory of magnitude: common cortical metrics of time, space and quantity" *Trends in Cognitive Sciences* **7** 483 – 488

Weichselgartner E, Sperling G, 1987 "Dynamics of automatic and controlled visual attention" *Science* **238** 778 – 780

Xu X, Liu C, 2008 "Can subitizing survive the attentional blink? An ERP study" *Neuroscience Letters* **440** 140 – 144

Zebian S, 2005 "Linkages between number concepts, spatial thinking, and directionality of writing: The SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers" *Journal of Cognition and Culture* **5** 165 – 190

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