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The role of attention in subitizing

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Abstract

The process of rapidly and accurately enumerating small numbers of items without counting, i.e. subitizing, is often believed to rest on parallel preattentive processes. However, the possibility that enumeration of small numbers of items would also require attentional processes has remained an open question. The present study is the first that directly contrasts the preattentive and attentive models of subitizing. We used an inattentional blindness paradigm to manipulate the availability of attentional resources during enumeration. In the inattention condition, the items to be enumerated were presented unexpectedly while participants focused on a line length comparison task. Divided- and full-attention conditions were also included. The results showed that only numbers one and two could be enumerated when the effects of attention were minimized. Freeing attentional resources increased the enumeration accuracies considerably, including for number two. The results suggest that even for enumerating small numbers, the attentional demands increase as the number of objects increases.
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Keywords: Subitizing; Enumeration; Attention; Inattentional blindness

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1. Introduction

1.1. Subitizing versus counting

The process of rapidly and accurately enumerating small numbers of items without counting, termed subitizing (Kaufman, Lord, Reese, & Volkmann, 1949), is often believed to rest on preattentive processes that distinguish it from attention demanding counting (Dehaene & Changeux, 1993; Sathian et al., 1999; Trick & Pylyshyn, 1994a). However, as the capacity of the preattentive processing stage is usually considered to be unlimited, there is reason to doubt the preattentive nature of subitizing, and argue that the limited resources of subitizing reflect an attentive bottleneck. In the present study, we directly contrast the preattentive and attentive models and examine if subitizing is possible when the effects of attention have been minimized.

The difference in enumerating small and large numbers is usually demonstrated in a design where people are asked to enumerate a spatial array of visually presented items as rapidly and accurately as possible. A typical result is that the reaction times for enumerating the first three or four items increase only slightly, after which the reaction times grow faster (Akin & Chase, 1978; Chi & Klahr, 1975; Jensen, Reese, & Reese, 1950; Mandler & Shebo, 1982; Piazza, Giacomini, Le Bihan, & Dehaene, 2003; Sathian et al., 1999; Trick & Pylyshyn, 1994a, 1994b). Error rates (Chi & Klahr, 1975; Kaufman et al., 1949; Mandler & Shebo, 1982; Piazza et al., 2003; Sathian et al., 1999) and confidence ratings (Kaufman et al., 1949) seem to follow a similar trend (but see Green & Bavelier, 2006). Many theories have tried to explain this distinction (e.g. Mandler & Shebo, 1982; Watson & Humphreys, 1999), but nowadays the speed and ease of subitizing is typically associated with parallelly processed information, whereas counting is thought to rely on serial attentional processes (Trick & Pylyshyn, 1994a).

At the core of the subitizing–counting controversy lie classical issues concerning the capacity limited processes of the cognitive system, and the relationship between preattentive and attentive processes (or parallel and serial processes). This is also connected to other areas in research on numerical abilities as many of the controversies are closely related to the presumed differences in the enumeration of small and large numbers of items. For example, some researchers believe there is a distinct representation for small numbers (Feigenson, Dehaene, & Spelke, 2004), and many researchers suggest that the subitizing ability underlies the development of counting skills (e.g. Hannula, Räsänen, & Lehtinen, 2007; Spelke, 2003; Wynn, 1992).

1.2. The spatial index theory of subitizing

A popular theory of enumeration, proposed by Trick and Pylyshyn (1994a), is based on Pylyshyn's (1989), Pylyshyn's (2001) hypothesis of a spatial indexing mechanism. According to this hypothesis the visual system is capable of indexing a limited number ($\sim$4) of objects (or feature clusters that roughly correspond to the actual objects) after parallel preattentive grouping processes. The purpose of this indexing is to individuate the objects so that they can be selected as targets of attentional focus and further processes. Pylyshyn argues that a bulk of operations carried out by the visual system, such as the multiple-object tracking, rests on the computations performed on these index tokens (Pylyshyn, 1989; Pylyshyn, 2001).

According to Trick and Pylyshyn (1994a) subitizing is a two-step process. First, each object is assigned an index token. This is usually thought to be an automatic bottom-up driven process. In the second stage, which takes place after a person decides to enumerate the objects, the tokens are mapped onto number names. Because the indexing mechanism can simultaneously assign only a limited number of tokens, the subitizing range is limited. The process is rapid because the tokens are assigned in parallel. Selection of the numerical response, however, is serial because according to Trick and Pylyshyn (1994a) the number representations must be activated in succession. This means that activating the representation of number three requires that numbers one and two are activated beforehand. This is how Trick and Pylyshyn (1994a) explain the fact that the enumeration times increase within the subitizing range. If the number of the objects to be enumerated exceeds the number of the index tokens, the objects must be counted. This is done by reassigning the tokens until all objects are enumerated.

Trick and Pylyshyn (1993), Trick and Pylyshyn (1994a) have tested their theory in experiments which required participants to enumerate objects that had to be distinguished from each other by attention (i.e. pop-out was prevented). For example, the participants had to enumerate concentric squares or target-objects that were distinguished from distractors by conjunctions of features. Their idea was that the "differential enumeration of small and large numbers of items should only occur if spatial attention is not needed to resolve items as wholes, or distinguish targets from distractors" (Trick & Pylyshyn, 1993, p. 336). The results revealed that the items became impossible to subitize if they had to be individuated by attention. However, as Dehaene and Cohen (1994) note, the manipulations that targeted the preattentive stage could have affected subitizing even if it was based on attention, because attentional processing always builds on preattentive processes. Furthermore, when Trick and Pylyshyn (1994b) investigated the relationship between attention and subitizing using a cueing paradigm, the cue improved enumeration even in the subitizing range although the effect was largest in the counting range, suggesting that attention does modulate enumeration within the subitizing range.

1.3. Why would subitizing require attention?

A problem for the theories that view subitizing as a parallel preattentive process is that reaction times for enumeration increase even within the subitizing range. And even though a handful of studies have reported constant quantification time (Atkinson, Campbell, & Francis, 1976; Mandler & Shebo, 1982; Sagi & Julesz, 1985), the results may be due to specific experimental designs (Folk, Egeth, & Kwak, 1988). In fact, it is now apparent that dividing the enumeration times into two separate linear components is an oversimplification; reaction times seem to increase by approximately 20 ms between one and two items, 50 ms between two and three items, and

100–200 ms between three and four items (Dehaene & Cohen, 1994). It has been suggested that the continuous non-linear growth of the enumeration times shows that there is no clear division between processes for enumerating small and large numbers (Balakrishnan & Ashby, 1991; Balakrishnan & Ashby, 1992). Even if this was the case, there still could be a qualitative difference in enumerating small and large numbers. The question is whether subitizing can be dissociated from counting by associating it with preattentive processes. It is also important to note that enumerating small numbers is by no means immediate. As Dehaene (1997) points out, enumerating three items, for example, takes about as long as recognizing a face.

An important and vital characteristic of subitizing theories is that they usually admit that subitizing requires a conscious decision. For example, Trick and Pylyshyn (1994a), Trick and Pylyshyn (1994b) do not view subitizing as a simple and fully preattentive perceptive operation, but as a cognitive process that involves a conscious decision to enumerate the objects. In concert with this view, a series of longitudinal and experimental studies on young children's enumeration development has shown that their use of exact number recognition in natural settings involves a separate attentional process of focusing on the aspect of numerosity both in the subitizing and counting ranges of numbers (Hannula, 2005; Hannula & Lehtinen, 2005). It should also be noted that reporting the contents of conscious perception is believed to be based on attentional selection (Lamme, 2003; Mack & Rock, 1998; Wolfe, 1999). Consequently, if subitizing is considered to rely on conceptualizing the contents of conscious perception, it would always be an attention dependent process. It could also be argued that even though naming the numerosity requires attentional processing, the process of subitizing can still operate on preattentively processed information. The most radical option would be to view subitizing as a totally automatic preattentive process, and argue that exact number can be represented implicitly. However, then one would have to demonstrate – by using a priming procedure, for example – that exact number can be represented without the observer being explicitly aware of this.

So, as an alternative to the preattentive models one could assume that enumerating small numbers also requires attentional processing, and the more items there are to enumerate, the longer it takes to process them. The attentional demands might come from selecting and binding the preattentively processed features (Treisman & Gelade, 1980; Wolfe & Bennett, 1996), and activating the number concept. This might effectively explain the growth of enumeration times in the subitizing range. Also, this way one would not have to assume a bottleneck in the preattentive architecture.

1.4. Purpose of the present study

The enumeration studies conducted so far have not explicitly manipulated attention, but have inferred the presence or absence of attentional influence from reaction times and error rates. Another problem has been the fact that in the previous studies, participants' attention has already been deployed to the location where the items are shown and they have been focusing on the task of enumeration. In addition, even though some brain imaging studies have reported that brain activations during subitizing are consistent with its supposed preattentive nature (Piazza et al., 2003; Sathian et al., 1999), others have not found significant differences in brain activations associated with subitizing and counting (Piazza, Mechelli, Butterworth, & Price, 2002).

By using an inattentional blindness[1] procedure, Rock, Linnett, Grant, and Mack (1992) have examined how different numbers of objects are perceived when the effects of attention are minimized, but the study concentrated generally on visual perception and not enumeration. The results indicated that when two, three, or four objects were each presented at different quadrants of the visual field for 200 ms, and the participants' attention was engaged with another task, the participants could detect the right number of objects when two or four items were presented. When three items were presented, only one of five participants reported the correct number. As the other four participants reported seeing four items, the authors argue that the results "should not be taken to mean that inattention affects the perception of blob number", but that the results suggest a kind of "symmetry or completion effect" (Rock et al., 1992, p. 511). In another experiment the authors presented one or more items in one quadrant. Although specific enumeration accuracies were not presented, the mean accuracies were low. However, because the participants' answers were approximately correct, the authors come to the conclusion that numerosity can be at least roughly recognized under inattention.

The present study is the first one to directly contrast the preattentive and the attentive models of subitizing by straightforwardly manipulating the amount of attention deployed to an enumeration task. As in the study conducted by Rock et al. (1992), this was achieved by applying the inattentional blindness (Mack & Rock, 1998) paradigm to study enumeration. In our study the participants' primary task was to estimate which arm of a cross presented briefly on a screen is longer. Therefore, their attention was not focused on numerosity, and the resources of spatial attention were deployed to the cross task. After a few trials, dots unexpectedly appeared in the same display, simultaneously with the primary task. If the participant reported seeing the dots, she was asked to report the number of the dots just presented. Because the participant attended to the cross task, concentrating on line length estimation, and because the dots were presented unexpectedly for only 200 ms, enumeration had to be performed with very limited attentional resources. We refer to this critical trial as the "inattention condition". The high difficulty level of the cross task ensured that it engaged the participants' attention almost completely, minimizing the possibility that unused attentional resources would be devoted to the task-irrelevant dot stimuli (Lavie, 1995). The effects of attentional processing probably cannot be eliminated completely because the unexpectedly appearing stimuli are likely to draw some attentional resources to themselves. Moreover, as already noted, it is widely assumed that reporting a perception of a stimulus already requires attentional processing (Lamme, 2003; Mack & Rock, 1998; Wolfe, 1999).

[1] The term "inattentional blindness" refers to a failure to report an unexpected stimulus (or stimuli) presented outside the focus of attention (Mack & Rock, 1998).

Because the inattention trial is based on surprise, it only permits one trial per subject. In the following trials the experiment continued normally with the presentation of the primary task, although now the dots were presented every now and then (divided-attention condition). In the last part of the experiment the participants concentrated solely on enumerating the dots (full-attention condition).[2] The preattentive model predicts that enumeration within the subitizing range should already be accurate in the inattention condition and performance within the subitizing range should not be affected by the manipulation of attention, whereas the attentive model predicts that the accuracies should decrease as the number of the objects increases and attention would have an effect even within the subitizing range. The previous subitizing studies have typically corresponded to the full-attention condition.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Seventy-two adults (37 females) took part in the experiment. Sixty-two (86%) of the participants were 16–25 years old. Six of the remaining participants were between ages 26 and 40, and four between ages 41 and 50. All participants reported having normal or corrected-to-normal visual acuity. Oral informed consent was obtained, and the participants were not paid for their participation.

2.1.2. Stimuli and apparatus

The stimuli were presented by a laptop computer (HP Pavilion ze4900; 1.40 GHz; resolution 1024×768 pixels; 32 bits; screen refresh rate 60 Hz) at a viewing distance of approximately 70 cm using Presentation® program (Neurobehavioral Systems, www.neurobs.com). The experiment was conducted in a quiet and dimly illuminated room. The target stimuli were black and presented on a white circle-shaped background (diameter 10.7 cm; ~8.9°). The luminance for the black color was 1.6 cd/m^2, and 124.8 cd/m^2 for the white.

The stimulus for the primary task was a cross composed of a horizontal and a vertical line, with 2, 3, or 4 mm difference between the lengths of the arms. Altogether six different crosses were used: A, 4×3.6 cm; B, 3.6×4 cm; C, 3.6×3.3 cm; D, 3.3×3.6 cm; E, 4×3.8 cm; and F, 3.8×4 cm. Black dots with a diameter of 2 mm (~0.16°) were used as the critical stimuli. The number of the dots ranged from 1 to 6, and the dots were presented in random order together with cross C or D. The presentation order of the critical stimuli and the crosses that appeared together with the critical stimuli was counterbalanced and thus varied between participants.

[2] In the divided- and full-attention conditions the participants also had an intention to enumerate the objects. That is, they were also focusing on the task of enumeration. Although the preattentive views of subitizing make no specific claims about the participants' intentions, it remains possible that this also improves the participants' enumeration performance on the divided- and full-attention conditions.

For example, each number of dots appeared 12 times as the critical stimuli in the inattention condition, and for half of the participants the dots appeared together with cross C and for the other half together with cross D. The presentation order for the crosses presented alone (without the dots) was constant.

The overall pattern formed by the dots did not resemble any familiar shapes. The arrangement of the dots was based on the patterns used by Wender and Rothkegel (2000), and one pattern of dots corresponded to each number (1–6). To make sure that the critical stimuli always appeared outside the ‘‘spotlight’’ of attention, the dots were presented outside the area squared by the cross. The dots could appear in one of the four quadrants of the white circular background area, approximately 4 cm (3.3°) from the fixation cross. The dots were presented within one quadrant to minimize the possibility that attention would be deployed only to a subset of the dots. The configurations of the dots covered at most a 2×2 cm ($1.6° \times 1.6°$) area.

2.1.3. Procedure

The use of an inattentional blindness paradigm allowed us to observe the enumeration of identical stimuli in inattention, divided-attention and full-attention conditions. In the beginning of the experiment the participants were given a written instruction stating that their task was to estimate which arm of the cross presented briefly on the screen was longer (i.e. the primary task).

Fig. 1 illustrates one of the trials in which the critical stimulus also appeared. Each trial began with a fixation cross that was presented in the middle of the screen for 1300 ms. This was followed by the primary task's cross, and on some trials also the critical stimuli, that appeared for 200 ms. Right after this a mask was presented. The participants were told to fixate on the center of the screen until they saw the mask, and the mask remained on the screen until the participants had responded and the experimenter, sitting on the left side of the participant, had initiated the next trial. The participants responded to the cross task by pressing either the up- or right-arrow (up-arrow indicated that the participants thought the vertical arm was longer).

The third trial (seventh including the practice trials) was the critical *inattention trial*, that is, the trial in which the dots appeared for the first time. As the inattention

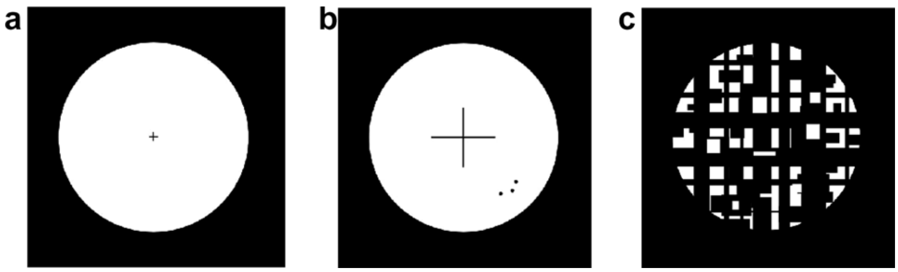

Fig. 1. An example of a trial with critical stimuli. In the beginning of each trial, a fixation cross was presented (a). After this, the cross of the primary task and on some trials also the critical stimulus (i.e. 1–6 dots) was presented for 200 ms (b). A mask was presented at the end of each trial (c).

trial is based on surprise, it permits only one trial per subject. Therefore, the measurement of enumeration in inattention trial uses a between-subjects design.

After the critical stimuli had appeared for the first time and the participants had responded to the cross task, they were subsequently asked if they detected anything new that had not been present on the prior trials. If the answer was positive they were asked what they saw, and how many objects there were. The participants were not told how many objects were actually present, and even the experimenter was unaware of the number. After reporting the number, the participants were asked how confident they were about their response. The confidence was reported on a scale from 1 to 5; five indicating full confidence. If the participant did not report having perceived the critical stimulus, he or she was told that one or more dots appeared near the edge of the white background. Therefore they would also expect something besides the cross to appear in future trials.

After the inattention trial the experiment used a within-subjects design. That is, the participants completed the divided- and full-attention conditions with their order counterbalanced across observers: half of the participants performed the full-attention condition prior the divided-attention condition. In the *divided-attention condition* the participants continued to perform the cross task, but now they would also expect the dots to appear on the screen. Even though the dots appeared every now and then, the participants were asked whether they saw anything in addition to the cross after each trial. Confidence ratings were also collected after every trial. The divided-attention condition lasted until every number was presented once. In the *full-attention condition* the participants were asked to concentrate on enumerating the dots that would appear on every trial. Even though the participants did not have to perform the cross task, the cross appeared on the screen as before, and as before the participants had to fixate on the center of the screen while performing the task. After every trial the participants were asked to report the number of the dots and their response confidence. The full-attention condition lasted until every number had been presented. Testing one participant took about 10 min, and after the experiment the participants were informed about the objectives and rationale of the experiment.

2.1.4. Analyses

The comparison of the enumeration accuracies for different numbers was based on correct and incorrect responses. Only the participants who detected the critical stimulus were taken into account in the comparisons within the inattention condition. The data of the inattention condition were analyzed with χ^2 test, but when any cell had an expected value smaller than five, Fisher's Exact test was used. In the divided- and full-attention conditions the general variation in enumeration accuracies and confidence ratings for different numbers within a single condition were first analyzed using Friedman's test. If the variation was significant the enumeration accuracies and confidence ratings of adjacent numbers within single condition were compared using Wilcoxon's test. The possible differences in the accuracies and confidence ratings between the conditions were also examined using the Wilcoxon's test.

2.2. Results

Sixty-one percent of the participants reported detecting something additional when the dots appeared for the first time (inattention condition). The detection percentages for each number are shown in Table 1. The number of the dots did not affect the detection percentage ($\chi^2 = 2.57$, $df = 5$, $p > .05$).

2.2.1. Enumeration accuracy

2.2.1.1. Enumeration accuracies within different conditions. The enumeration accuracies for different numerosities differed in the *inattention condition* ($\chi^2 = 32.44$, $df = 5$, $p < .001$). Comparisons of adjacent numbers showed that the only significant difference was between numbers two and three (Fisher's Exact test: $p = .015$). The mean enumeration accuracies are shown in Fig. 2; the enumeration accuracy for numbers one and two is near ceiling, but then drops radically. The participants who were not able to correctly enumerate the objects underestimated the numerosity on 86% of the trials.

The enumeration accuracies differed in the *divided-attention condition* ($\chi^2 = 145.80$, $df = 5$, $p < .001$). All adjacent numbers, except three and four, had different accuracies (p's $\leqslant .025$). As Fig. 2 shows, the accuracies drop slightly already between numbers one and two, and the accuracy in enumerating number three is under 60%. The enumeration accuracies differed in *full-attention condition* as well ($\chi^2 = 158.11$, $df = 5$, $p < .001$). Accuracies for adjacent numbers other than one and two, and four and five differed from each other (p's $\leqslant .011$). In the divided-attention condition 76%, and in the full-attention condition 68%, of the answers were underestimates. Also, deviation in the responses increased as numerosity increased.

2.2.1.2. Enumeration accuracies between conditions. Because of the between-subjects nature of the inattention condition and small group sizes (see Table 1) due to inattentional blindness, statistical comparison of inattention condition to divided- and full-attention conditions was not carried out. The main interest would have been in number two, since it is clearly inside the subitizing range, and the accuracy for it is highest in the full-attention condition (see Fig. 2). This suggests that the enumeration of number two does not reach its full accuracy when the effects of attention are

Table 1
Number of participants (percentage in parentheses) reporting the perception of the dots in the inattention condition (each number served as the critical stimulus twelve times)

Number of dots	Reported seeing the dots
1	8 (66.7%)
2	6 (50.0%)
3	6 (50.0%)
4	8 (66.7%)
5	9 (75.0%)
6	7 (58.3%)
Total	44 (61.1%)

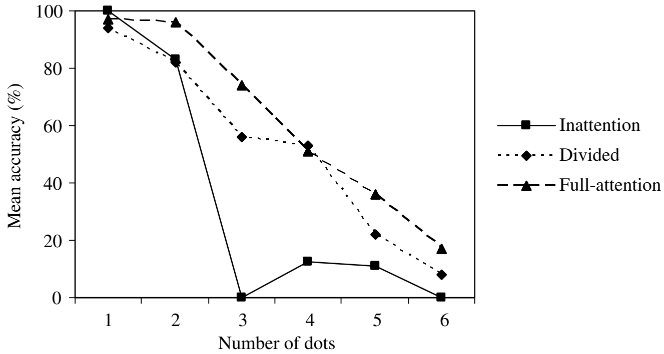

Fig. 2. Mean enumeration accuracies in different conditions.

minimized. However, because the enumeration accuracies for number two are similar in inattention and divided-attention conditions, the divided-attention condition can be compared to the full-attention condition.

The overall pattern of differences between the inattention, divided-attention, and full-attention conditions can be seen in Fig. 2: while in the inattention condition the accuracies collapse at number three, the accuracies descend more steadily in the divided- and full-attention conditions as the number of the dots increases. The enumeration accuracies were higher in the full-attention condition than in the divided-attention condition, with significant differences in numbers two ($Z = -3.16$, $p = .002$), and three ($Z = -2.26$, $p = .024$). The difference in accuracies for number five was nearly significant ($Z = -1.96$, $p = .05$). The order of performing the divided- and full-attention conditions had no effect on enumeration accuracies ($p > .05$), except for number one ($Z = -2.04$, $p = .041$), where the enumeration accuracy was 11% higher in the divided-attention condition when it followed rather than preceded the full-attention condition.

2.2.2. *Confidence ratings*

Confidence ratings (scale 1–5) were collected to enable us to examine whether the participants' subjective sense of the enumeration accuracy corresponded to the actual accuracies, and whether minimizing the effects of attention affected the subjective sense of the enumeration accuracy. The mean confidence ratings for different numbers are shown in Fig. 3.

In the *inattention condition* the confidence ratings for enumerating different numbers did not differ statistically significantly ($\chi^2 = 28.79$, $df = 5$, $p > .05$). Only the participants who detected the critical stimulus ($N = 44$) were taken into account. In the inattention condition the confidence ratings drop steadily except for number three, for which the mean confidence is the highest when compared to other numerosities in the same condition, or number three in other conditions.

The confidence ratings differed in the *divided-attention condition* ($\chi^2 = 103.72$, $df = 5$, $p < .001$). The biggest drop in the confidences was between numbers one and two ($Z = -4.81$, $p < .001$), and numbers two and three ($Z = -4.21$, $p < .001$).

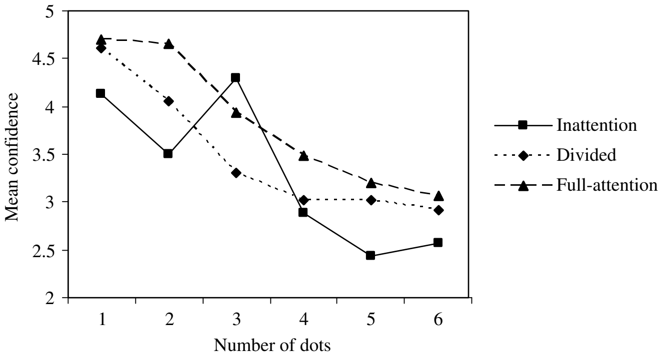

Fig. 3. Participants' mean confidence ratings in different conditions (scale 1–5).

Also, in the *full-attention condition* the confidence ratings differed for different numbers ($\chi^2 = 124.49$, $df = 5$, $p < .001$), with significant decreases in confidences between adjacent numbers in the range from two to five (p's $\leqslant .029$).

The divided- and full-attention conditions differed from each other in confidence ratings for numbers two ($Z = -4.08$, $p < .001$), three ($Z = -4.01$, $p < .001$), and four ($Z = 2.59$, $p = .009$). The enumeration confidence was higher in the full-attention condition (see Fig. 3). The order of performing the divided- and full-attention conditions had no effect on confidence ratings ($p > .05$).

2.2.3. Primary task of length comparison

In the primary task (cross task), the performance in the two trials that preceded the inattention condition was high (mean 88% correct). Participants' performance on these two trials did not affect the detection of the critical stimulus in the inattention condition ($p > .05$). In the *inattention condition* 61% of the participants who detected the dots responded correctly to the cross task. Statistically, this is lower than performance on the first trial ($\chi^2 = 5.45$, $df = 1$, $p = .040$), but not lower than performance on the second trial ($p > .05$). Seventy-one percent of the participants who did not detect the dots responded correctly to the cross task. When compared to the two first trials, the performance is not significantly different ($p > .05$). In the *divided-attention condition* 81% of the responses were correct when no dots were presented, and accuracy decreased (58% correct) when the critical stimulus was also presented ($Z = -5.98$, $p < .001$). Performance in the cross task did not correlate with the enumeration accuracy (Spearman's rho, $r = -.13$, $p > .05$).

2.3. Discussion

The numerosity of the dots had no effect on the number of participants who detected the critical stimuli in the inattention trial. This finding is surprising because in the present study the physical difference between the sizes of one dot and six dots is sixfold, for example. Moreover, previous studies have shown that when using a single object as a critical stimulus, larger size leads to better detection (Mack & Rock, 1998). Thus, it seems that when examining the combined physical size of multiple, relatively small, unexpected stimuli, a larger size does not necessarily lead to better detection. In fact, the results of Rock et al. (1992) are in line with ours: in the inattention condition the probability of detecting one (Rock et al., 1992; exp 1), two, three, or four (Rock et al., 1992; exp 2) critical stimuli presented in different quadrants was the same. It is possible that in the present experiment the dots were grouped so close to each other that it was hard to individuate and perceive the individual dots when their numerosity increased. This possibility is discussed and addressed in Experiment 2.

2.3.1. Enumeration accuracy

The fact that only numbers one and two could be successfully enumerated in the *inattention condition* suggests that enumeration requires the deployment of attention, at least when there are three or more objects to enumerate. This contradicts theories that explain the subitizing ability with preattentive selection of targets, as it is widely believed that in adults, the subitizing range reaches at least to number three.

The results of the *divided-attention condition* show that freeing attentional resources considerably improved the accuracy for enumerating numbers three and four. Freeing attentional resources had no effect on the accuracies for numbers one and two, which were already near ceiling. However, the accuracy for enumerating number two was lower than for number one. Thus, even in the divided-attention condition the enumeration of number two was not perfect.

The enumeration accuracies were even better in the *full-attention condition*, so the effect of attention was cumulative; the more attention was deployed, the more accurate was the enumeration. What is more, even the accuracy for enumerating two dots – a number that is clearly within the subitizing range – was higher in the full-attention than in the divided-attention condition. Still, the accuracy of enumerating three dots remains significantly lower than the accuracy of enumerating two dots. This is surprising, as previous studies have shown that three objects can be accurately enumerated, even if they were presented briefly (e.g. Kaufman et al., 1949; Mandler & Shebo, 1982; Piazza et al., 2003; Sathian et al., 1999). It is thus possible that the parafoveal presentation and close proximity of the dots made it hard for the participants to perceive the dots saliently. This would mean that decreases in the enumeration accuracy could be partly explained by perceptual demands. Furthermore, the observation that enumeration accuracy decreases significantly between numbers two and three in all three conditions hints that this might be the point where the perceptual demands became particularly disruptive. These questions are addressed in Experiment 2.

The order of performing the divided- and full-attention conditions had no effect on enumeration accuracies (except for number one in divided-attention condition), so learning cannot explain the increases in accuracies between conditions. The finding that most of the incorrect answers were underestimates is consistent with previous studies: the numerosity of a random set of dots is systematically underestimated when the dots are presented briefly (Dehaene, 1992).

2.3.2. Participants' subjective sense of enumeration accuracy

On the whole, participants' subjective sense of the enumeration accuracy corresponded to the actual accuracies. Participants' confidence about enumeration was higher for low numbers. Also, their confidence grew as attentional resources were released, which indicates that the participants were more comfortable in enumerating small numbers when more attentional resources were available. The higher confidences did not result from the fact that the participants became more confident during the experiment, since the order of the divided- and full-attention conditions had no effect on confidence ratings.

The confidence rating did include one surprising result: the participants' confidence about enumerating three dots was highest in the inattention condition (see Fig. 3). The conflict between actual accuracies and the participants' confidence is clear since none of the participants who detected the critical stimulus responded correctly when three dots were presented. Instead, 66.5% reported seeing two dots and the rest only one. One probable explanation for the discrepancy between accuracies and confidence ratings is pure coincidence, as the result is also based on a small group size ($N = 6$). Nevertheless, one could argue that the high confidence resulted from a kind of perceptual illusion: when three dots were presented, the participants had a tendency to see them as only one or two dots, and reported this illusory perception with high confidence. Before speculating further, the presence of such a perceptual illusion should be replicated in a larger sample.

2.3.3. Primary task of length comparison

The participants' performance in the two first trials of the primary task did not correlate with critical stimulus detection in the inattention condition. Thus, the detection of the critical stimulus in the inattention condition cannot be explained the participants not concentrating on the cross task. Furthermore, the participants' performance in the cross task in the divided-attention condition did not correlate with the enumeration accuracy. This, and the fact that the performance on the cross task was high when no critical stimulus was presented, implies that the participants followed the instructions and concentrated on the cross task in the divided-attention condition. It is also logical that the participants' performance in the cross task decreased in trials that contained the critical stimulus as the appearance of the additional stimulus is likely to draw some attention and impede the performance in the cross task.

3. Experiment 2

The results of the first experiment suggest that attention is needed to enumerate numerosities larger than two, and that deploying more attention to the items makes the enumeration more accurate. However, because performance was surprisingly low even in the full-attention condition, it is reasonable to argue that the enumeration accuracies did not fall because of the brief presentation time of the dots, or because of the fact that the cross task drew attention to itself, but because at certain point the critical stimuli fell under attentional resolution. This would mean that it was impossible to individuate a single item, although the participant could still perceive multiple objects in the periphery (Intriligator & Cavanagh, 2001). This way, the decreases in enumeration accuracy could reflect perceptual, rather than attentional, limitations. The critique is plausible because as the number of dots increased, they also became closer together, and so approached the limits of attentional resolution.

To see if the stimuli used in Experiment 1 actually were perceptually demanding, we examined how accurately the same stimuli could be enumerated when the presentation time of the dots was extended from 200 ms to 3 s. This way the participants would have time to count the items, and so, if it was possible to individuate the dots, the enumeration accuracies should be high. The results are shown in Fig. 4. The general form of the enumeration accuracies and confidence ratings were similar to the results obtained in the full-attention condition of Experiment 1: the accuracies started to decline at number three, and the decreases in confidence ratings were clearest between numbers two and four. The fact that the accuracies and the confidence ratings dropped as the number of the dots increased indicates that perceptual limitations may explain at least a part of the poor enumeration accuracies in Experiment 1, especially for numbers higher than three.

In order to disentangle the effects of perceptual demands from attentional requirements, we conducted Experiment 2. We modified the dot stimuli, making them larger and increasing the distance between them, thus rendering the dots clearly discernible. Pilot testing confirmed that, given enough time, numbers up to four could be perfectly enumerated while fixating on the centre of the screen (see Fig. 5). The accuracy in enumerating five dots was also high, but six dots proved more difficult to enumerate – a result also reflected in the confidence ratings. As the stimuli are now easily separable at least for small numerosities, differences in the results between different conditions in Experiment 2 should be due to manipulations of attention.

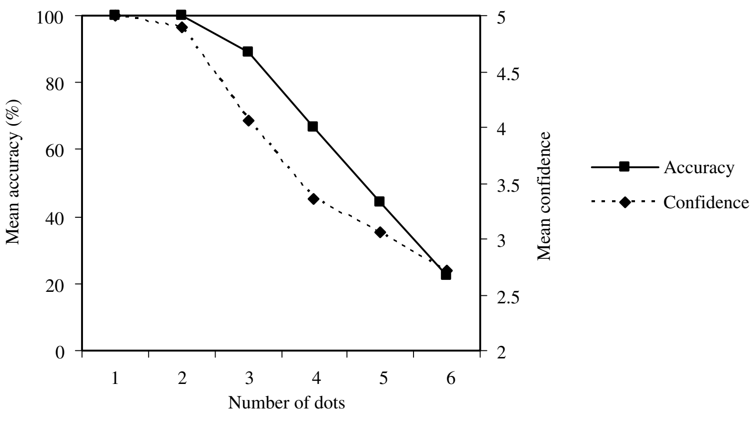

Fig. 4. The results of the control experiment that examined the perceptual demands of the stimuli used in Experiment 1. Six university students (4 males) who had not taken part in Experiment 1 participated in the experiment. Apart from the presentation time of the critical stimuli, the procedure corresponded to the full-attention condition of Experiment 1. Each numerosity (1–6) was presented three times.

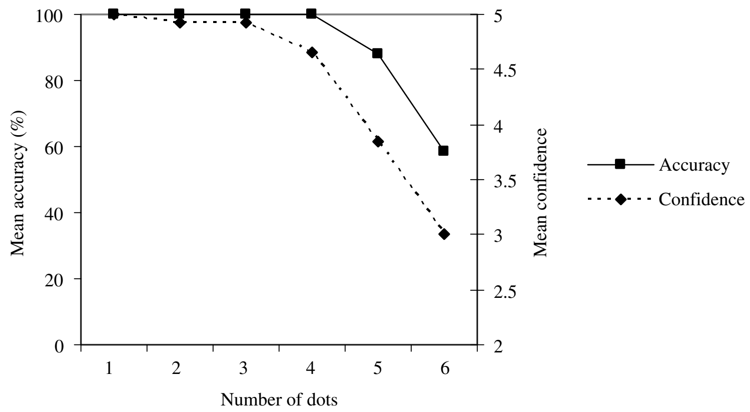

Fig. 5. The results of the pilot experiment. Six university students (4 males) who had not participated the earlier experiments took part of the pilot experiment. Except for the stimuli (see Section 3.1.2 of Experiment 2 for details), the procedure was similar to the one used in the control experiment reported above. Each numerosity (1–6) was presented twice.

3.1. Methods

3.1.1. Participants

Forty novel participants (22 females), recruited from upper secondary school, took part in Experiment 2. The participants were between 16 and 21 years of age, and had normal or corrected-to-normal visual acuity. Oral informed consent was obtained, and the participants were not paid for their participation.

3.1.2. Stimuli and procedure

The procedure and the apparatus corresponded to Experiment 1. However, for Experiment 2 the size of the dots was increased to 4 mm (~0.32°). To enable larger distances between the dots, the size of the white circular background area, on which the dots would appear, was also increased to 22.4 cm in diameter (18.6°). A single random arrangement of dots corresponded to each numerosity (1–6). To assure that each dot was easily separable from each other, the dot patterns were designed to be different from the ones used in Experiment 1.

In divided- and full-attention conditions, numerosities from one to six were used. Because inattention condition utilizes a between-subjects design, numerosities from one to four were used to maximise statistical power. As in Experiment 1, the dots were presented randomly in one of the four quadrants outside the area squared by the cross of the primary task. The crosses for the primary task were the same as in Experiment 1.

3.2. Results

Thirty-six of the 40 participants (90%) reported detecting something additional on the inattention trial. Of the four participants who did not detect the dots, two were presented with two, and two with four dots. The detection of the dots did not vary in respect of the number presented ($\chi^2 = 4.44$, $df = 3$, $p > .05$).

3.2.1. Enumeration accuracy

As in Experiment 1 the comparison of the enumeration accuracies was based on correct and incorrect answers (the same analyses as in Experiment 1), and in the inattention condition, only the participants who detected the critical stimulus were taken into account. The mean enumeration accuracies in different condition are shown in Fig. 6. In the *inattention condition*, the enumeration accuracies for different numbers differed in general ($\chi^2 = 13.61$, $df = 3$, $p = .003$), and of all adjacent numbers, only the accuracies of numbers two and three had a significant difference between them ($\chi^2 = 5.45$, $df = 1$, $p = .02$). Incorrect answers were underestimates on 79% of the trials.

The accuracies differed within the *divided-attention condition* as well ($\chi^2 = 89.44$, $df = 5$, $p < .001$), with significant decreases in accuracies between numbers two and three ($Z = -2.45$, $p = .014$), four and five ($Z = -2.50$, $p = .013$), and five and six ($Z = -2.32$, $p = .020$). Fig. 6 shows that the enumeration accuracies decline as numerosity increases, although the accuracies in enumerating numbers one and two are at ceiling. There were also significant differences in the enumeration accuracies in the *full-attention condition* ($\chi^2 = 71.16$, $df = 5$, $p < .001$). Accuracies were different between numbers three and four ($Z = -3.16$, $p = .002$), and five and six ($Z = -3.55$, $p < .001$). As Fig. 6 shows, the first notable decrease in accuracy occurs between numbers three and four, and the accuracy in enumerating five dots was higher than the accuracies in enumerating numbers four and six. In both the divided- and full-attention conditions, most of the incorrect answers were underestimates (except for number two in the divided-attention condition, and for number three in the full-attention condition).

The accuracies were significantly higher in the full-attention condition than in the divided-attention condition for numbers three ($Z = -2.12$, $p = .034$), and five ($Z = -3.87$, $p < .001$). The order of performing the divided- and full-attention conditions had no effect on the enumeration accuracies ($p > .05$).

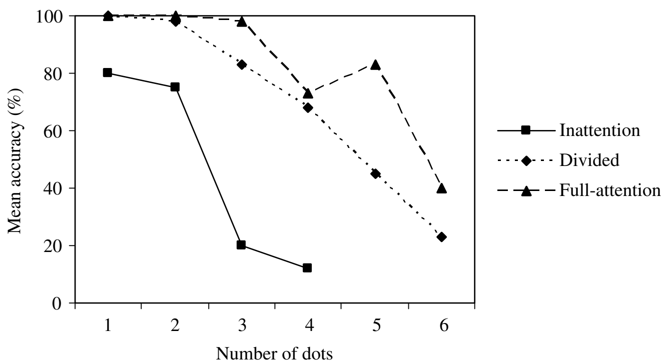

Fig. 6. Mean enumeration accuracies in different conditions in Experiment 2.

3.2.2. Confidence ratings

The overall variation in confidence ratings was significant for divided- ($\chi^2 = 117.71$, $df = 5$, $p < .001$) and full-attention conditions ($\chi^2 = 134.59$, $df = 5$, $p < .001$), but not for the inattention condition ($p > .05$). As Fig. 7 shows, in the inattentional condition, the mean confidence rating for enumerating one dot was highest, after which the ratings drop until they rise again in number four. For the divided- and full-attention conditions the mean rating drops as the number increases. In the divided-attention condition the decrease in confidence ratings was significant between the adjacent numbers in the range from two to five (p's $\leqslant .04$). In the full-attention condition, ratings in numbers ranging from three to six were significantly different (p's $\leqslant .004$). Participants' confidence was higher in the full-attention condition than in the divided-attention condition for numbers three ($Z = -3.72$, $p < .001$), four ($Z = -2.66$, $p = .008$) and five ($Z = -4.06$, $p < .001$). The order of the divided- and full-attention conditions had no effect on confidence ratings ($p > .05$).

3.2.3. Primary task of length comparison

Participants' performance in the cross task in the two trials preceding the inattention trial was high (mean 86% correct). The performance on the first two trials had no effect on the detection of the critical stimuli ($p > .05$). On the inattention trial 69% of the participants who detected the critical stimuli responded correctly to the cross task. In the divided-attention condition the difference in cross task performance between trials on which no dots were presented (78% correct), and when the dots were also presented (74% correct), was not significant ($p > .05$). Performance on the cross task did not correlate with enumeration accuracy (Spearman's rho, $r = .06$, $p > .05$).

3.3. Discussion

The percentage of participants who detected the dots when they were first presented (90%) was higher than in Experiment 1. We assume this resulted from the

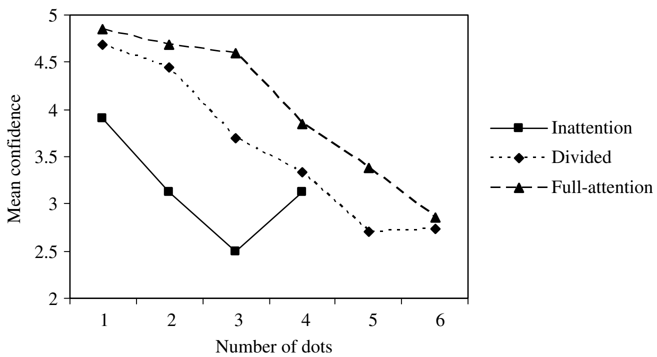

Fig. 7. Mean confidence ratings in different conditions in Experiment 2.

increased size of the dots, and the larger circular background area that might have made the dots stand out better. Because the detection rate was at or near ceiling for every number, it is impossible to say whether the number of the dots had any effect on the detection of the critical stimuli.

The enumeration accuracies in Experiment 2 were similar to those obtained in Experiment 1. When the effects of attention were minimized, most participants correctly enumerated numbers one and two, but the accuracy in enumerating higher numbers was low. In the divided-attention condition, when more attention could be deployed to enumeration, accuracies grew higher, and declined more steadily as the numerosity increased. Deploying attention solely to enumeration raised the accuracies for numbers three and five, yielding a slope where the accuracies remain almost perfect for numbers up to three. This differs from Experiment 1, where the accuracies begin to decline at number two. This improvement in performance probably resulted from lower perceptual demands. Another conspicuous feature of the slope in the full-attention condition is the peak at number five. One possible explanation for this result is guessing: even though the participants were not able to enumerate the dots perfectly, they were convinced that the numerosity was higher than four, and so guessed that the number was five. Another alternative is that for some reason, there is a coincidental decrease in accuracies at number four.

The participants' subjective sense of enumeration accuracy goes together with the actual accuracies. For example, in the full-attention condition, both the confidences and actual accuracies remain high for number up to three. In general, the participants' confidence decreased as the number of dots increased, and the more attention the participants could deploy on enumeration, the more certain they became. The increase in mean confidence in the inattention condition at number four resembles the result obtained in Experiment 1, where the mean confidence in enumerating three dots was highest in inattention condition. However, both increases are statistically insignificant, so coincidence is a credible explanation.

The results of the cross task are similar to those obtained in Experiment 1. The high performance in the inattention condition confirms that the participants deployed their attention to the cross task and did not expect the appearance of the critical stimulus. In the divided-attention condition the performance remained high, indicating that the participants continued to concentrate on the cross task.

4. General discussion

The purpose of this study was to examine the role of attention in enumerating small numbers of items. By using the inattentional blindness paradigm (Mack & Rock, 1998) we examined whether enumeration accuracies are affected by the amount of available attentional resources. In the inattentional condition, the effects of attention on enumeration were minimized by presenting the targets of enumeration unexpectedly, while the participants were performing another task. In the divided-attention condition, the participants could expect the targets of the enumeration task to appear, but they also continued to perform the primary task. In the full-attention condition, the participants focused exclusively on enumerating the dots. Experiments 1 and 2 are identical in procedure, but in Experiment 2 the stimuli were made perceptually less demanding. Experiment 2 examined whether the decreases in enumeration accuracy in Experiment 1 resulted from perceptual, rather than attentional demands.

Experiments 1 and 2 both produced very similar results, although in Experiment 2 the smaller perceptual demands resulted in increased accuracies for the divided- and full-attention conditions. In both experiments, only numbers one and two could be enumerated accurately when enumeration was performed under very limited attentional resources. Enumerating larger numbers became possible in the divided-attention condition. In the full-attention condition, the enumeration accuracies increased further: in Experiment 1 for number two, and in Experiment 2 for number three, resulting in a slope where the enumeration accuracies remain high for numbers up to three. This breakpoint in enumeration accuracies between three and four items, observed in Experiment 2, might reflect the same bottleneck as the breakpoint in enumeration latencies, observed in previous studies (Jensen et al., 1950; Kaufman et al., 1949; Mandler & Shebo, 1982; Piazza et al., 2003).

In Experiments 1 and 2, the fall in enumeration performance in inattention condition between numbers two and three is strikingly clear. This seems to imply that subitizing cannot be explained by purely preattentive mechanisms as the subitizing range is usually considered to reach up to number three or four (e.g. Akin & Chase, 1978; Mandler & Shebo, 1982; Trick & Pylyshyn, 1994a, 1994b). As already noted, in the previous studies the conclusions have been based on reaction times and error rates, whereas in this study the availability of attentional resources was directly manipulated. Furthermore, the fact that in Experiment 1 the accuracy for enumerating two dots increased in the full-attention condition suggests that even the enumeration of two items was not working perfectly when the resources of spatial attention were not fully available. Thus, the results seem to imply that even for very small numbers of items, the attentional demands increase as the set size increases. The reason why enumeration latencies in previous studies tend to increase in the subitizing range as the numerosity increases (Chi & Klahr, 1975; Mandler & Shebo, 1982; Trick & Pylyshyn, 1994a, 1994b) can therefore be explained by increased attentional demands. This entails that the breakpoint in enumeration latencies and accuracies cannot be explained by the preattentive–attentive dichotomy.

According to Mack and Rock (1998) attention is necessary for conscious perception, and so stimuli that do not catch attention are not consciously perceived. A competing explanation says that the unattended stimuli do temporarily rise to the level of conscious perception, but the participants fail to report them because attention is necessary for memory consolidation (e.g. Chun & Potter, 1995; Wolfe, 1999). Following the latter view it could be argued that in the inattention condition the participants did perceive the dots, but due to inattention failed to report their number. This could hold for the participants who detected the dots, but failed to enumerate them correctly, and even for those who did not detect the dots at all. However, in order to support this view, one would have to show that correct numerosity was, in fact, implicitly represented. Based on results that demonstrate the relevance of attention in identification (Lachter, Forster, & Ruthruff, 2004), shape perception (Rock et al., 1992), and simple feature detection (Joseph, Chun, & Nakayama, 1997), for example, and the differences in enumeration accuracies between the divided- and full-attention conditions in the present study, we argue that the difficulty was not in memory consolidation, but in enumeration. In other words, the enumeration accuracies were severely limited in the inattention condition because the brief and unexpected presentation of the targets limited the time of attentional processing. Furthermore, increasing the number of dots increased attentional load, thereby decreasing enumeration accuracies. Supporting this view, Olivers and Watson (2006) have shown that enumerating small numbers of objects is not immune to attentional blink, and that enumeration performance is modulated by excitatory or inhibitory attentional control even at small numerosities.

Because in the present experiments the dots were always presented on either left or right hemifield, the enumeration accuracies in the inattention condition might reflect an independent capacity limit of a single a hemifield. Alvarez and Cavanagh (2006) have indeed demonstrated that in multiple object tracking (MOT), the capacity limit of four is actually split between right and left hemifields. The authors suggested the bottleneck might lie in deploying attention to objects or spatial information. The possibility that in subitizing the capacity might be divided between hemifields could be straightforwardly investigated using an inattentional blindness paradigm, and presenting the dot stimuli in both hemifields at the same time. However, it is also worth noting that in the study by Rock et al. (1992), number three was not accurately enumerated even though the presentation of the dots was not limited to one hemifield.

It could be argued that in the present study the enumeration accuracies in the inattention condition were not limited because the time of attentional processing was limited, but because the power of preattentive processes was only sufficient to enable the enumeration of numbers one and two. Furthermore, one could argue that the capacity of the indexing mechanism proposed by Pylyshyn is divided between hemifields, as he argues that MOT and subitizing rest on the same mechanism (Pylyshyn, 1989; Pylyshyn, 2001). This is possible, but there are also reasons to believe that the selection of objects in MOT is based on clearly attentional processing (Oksama & Hyönä, 2004). The preattentive view also seems to be unable to explain why in Experiment 1 the accuracies drop already between numbers one and two.

Although it is plausible to assume that MOT taxes the same processes and capacity limits as subitizing (e.g. Cowan, 2001; Pylyshyn, 1989; Pylyshyn, 2001), Green and Bavelier (2006) argue that this is not the case. Their results show that even though training can enhance the ability to track multiple moving objects and enumerate small numbers more accurately, the training does not shift the breakpoint in enumeration *latencies*. They conclude that whereas the breakpoint in reaction times at number three appears to be a sign of parallel processing, the shift in the breakpoint in enumeration accuracies demonstrates the facilitating effects of working memory (see also, Tuholski, Engle, & Baylis, 2001). However, we have argued that the breakpoint cannot be explained by the preattentive–attentive dichotomy, and enumerating would always require attention. This result calls for an alternative explanation to clarify the differences between enumerating small and large sets of items.

One possible candidate is visual short-term memory (or working memory; Cowan, 2001; Watson & Humphreys, 1999). This would make subitizing an attention-demanding process because the selection of contents of short-term memory is thought to be done by attention (Awh & Jonides, 2001; Marois & Ivanoff, 2005). It might be that in subitizing the requirements of attention come largely from resolving the items and loading them to visual short-term memory to enable number recognition, whereas enumerating higher numbers (and tracking multiple objects, for example) requires continuous reallocation of attention and *updating* the contents of short-term memory. Subitizing might also be efficiently explained without referring to short-term memory capacity, as visual search, for example, seems to remain efficient even when visual short-term memory capacity is crowded with similar stimuli that are used in the search task (Woodman, Vogel, & Luck, 2001). All in all, it seems that in order to fully understand subitizing, the somewhat overlapping functions of attention and short-term memory need to be clarified. Still, when it comes to the attentional demands of subitizing, the present results imply that as the number of items to be enumerated increases, the attentional demands also increase – even for very small numerosities.

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