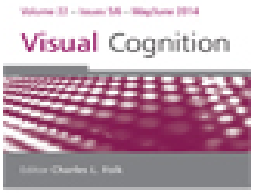

VISUAL COGNITION

ISSN: 1350-6285 (Print) 1464-0716 (Online) Journal homepage: https://www.tandfonline.com/loi/pvis20

Subitizing requires attention

Christian N. L. Olivers & Derrick G. Watson

To cite this article: Christian N. L. Olivers & Derrick G. Watson (2008) Subitizing requires attention, VISUAL COGNITION, 16:4, 439-462, DOI: 10.1080/13506280701825861

To link to this article: https://doi.org/10.1080/13506280701825861

Published online: 24 Apr 2008.

VISUAL COGNITION, 2008, 16 (4), 439–462

Psychology Press
Taylor & Francis Group

Subitizing requires attention

Christian N. L. Olivers
Vrije Universiteit Amsterdam, The Netherlands

Derrick G. Watson
University of Warwick, Warwick, UK

While counting objects is typically a slow, serial process, enumerating about four or fewer objects has been considered to be a relatively effortless, parallel, and even preattentive process often referred to as subitizing. However, by combining a subitizing task with an attentional blink task, we show that subitizing is systematically affected by a closely preceding letter identification task. Vice versa, letter identification is also affected by a closely preceding subitizing task. Importantly, performance not only depended on the time between the two tasks, but also on the number of to-be-enumerated dots, even though this number fell within the subitizing range. The results imply that the processes underlying subitizing require attentional resources, suggesting that they are either serial in nature, or parallel, with capacity limited by the overall resources available.

Research on visual attention has established that we are only aware of a few objects at a time. Several lines of evidence suggest that the limit lies at about four objects, units, or chunks of information. For example, Sperling (1960) found that the number of letters that can be reported from a briefly flashed display when no cues are provided is about four. Phillips (1974), Pashler (1988), and Luck and Vogel (1997) have calculated that observers can monitor a maximum of about four objects for changes across displays. Furthermore, studies on attentional capture in which varying numbers of new objects appear abruptly in a visual search display indicate that up to four such abrupt onsets are prioritized (Yantis & Johnson, 1990). Similarly,

Please address all correspondence to Chris Olivers, Cognitive Psychology, Faculty of Psychology and Education, Vrije Universiteit Amsterdam, Van der Boechorststraat 1, 1081 BT Amsterdam, The Netherlands. E-mail: cnl.olivers@psy.vu.nl

This work benefited from an NWO (Netherlands Organization for Scientific Research) Veni grant and an NWO-British Council travel grant awarded to the first author, as well as from a grant awarded to the second author from the Economic and Social Research Council of Great Britain (R000239180). We are also grateful to Lucy A. M. Bruce and Patrick van Olffen for assistance with some of the data collection, and to Howard Egeth for combining our efforts.

http://www.psypress.com/viscog DOI: 10.1080/13506280701825861

up to four items may receive priority in visual search when precued by placeholders (Burkell & Pylyshyn, 1997). In addition, up to about four objects can be successfully tracked in randomly moving dot arrays (Pylyshyn & Storm, 1988). Finally, and most relevant to the present study, is the finding that displays consisting of up to four items appear to be enumerated much more efficiently than displays of five and more items (e.g., Atkinson, Campbell, & Francis, 1976; Mandler & Shebo, 1982; Trick & Pylyshyn, 1994b). This rapid enumeration of small numbers of items has been referred to as "subitizing" (Kaufman, Lord, Reese, & Volkman, 1949).

Subitizing has been regarded by some to reflect a parallel, but capacity-limited process that should be distinguished from a more effortful and serial focusing of attention when counting larger numbers of items (e.g., Trick & Pylyshyn, 1994b). Indeed, looking at performance curves, there often appears to be a discontinuity in how steeply RTs and error rates rise with increasing numbers, with slopes being relatively flat in the 1–4 range, and steep in the 5+ range. The functional distinction between subitizing and counting has also been supported by neuropsychological evidence from patients who were severely impaired at counting larger numbers, but who were unimpaired at quantifying within the range of one to three items (Dehaene & Cohen, 1994). However, there are also arguments against two discrete processes. Instead, the apparent discontinuity in performance may reflect nonlinearities in factors such as how discriminable, canonical, or verbalizable different numbers of items are (Balakrishnan & Ashby, 1991; Gallistel & Gelman, 1992; Logan & Zbrodoff, 2003; Mandler & Shebo, 1982; van Oeffelen & Vos, 1982).

The present study looks at the role of attention in subitizing. The main question is whether attention is necessary for the enumeration of up to about four objects. A priori, the answer is probably going to be "yes, it is". It is hard to imagine that when observers are asked to count a number of items, they would not need some attention to implement and maintain the task set, to assign a number label to the encountered number, and to utter an appropriate word or press the right button. We will refer to these requirements as attentional overhead costs. The interesting question is whether, within the subitizing range, there will be additional attentional requirements apart from these overhead costs. In other words, will an increasing number of items result in the need for increasing amounts of attentional resources, even when the number falls within the subitizing range? If it is the case that, within the subitizing range, extra items can be added for free, then we would have strong evidence that subitizing should be dissociated from counting (of which we know already that it is an attention-demanding process). On the other hand, if it is the case that enumerating additional items requires additional attention, then subitizing and counting may still reflect different processes at some level, but at least we know that both processes require attentional effort. In other words, we could exclude attention as the distinctive factor between subitizing and counting.

SUBITIZING AND ATTENTION

Following Klahr (1973), Cowan (2000) has argued that the subitizing range reflects short-term memory capacity, which is limited to about four slots. When there are four or fewer items, slots are rapidly filled in parallel by directing attention to them, leading to an immediate apprehension of the number of items. When there are more than four items, STM has to be at least partly emptied and refilled by redirecting attention accordingly, and a running total has to be maintained. These additional processes lead to inefficient enumeration beyond the subitizing range. Thus, according to this account, attention is needed for subitization, but as long as the number of objects can be apprehended within a single focus of attention, the number of objects should have little effect. In other words, within the subitizing range, attentional costs should be fixed. In support of this, Tuholski, Engle, and Baylis (2001) found that observers with a low working memory span differed from high-span observers only on the counting part of an enumeration task, not on the subitizing part. Engle, Kane, and Tuholski (1999) have argued that individual differences in working memory capacity reflect differences in controlled attention rather than in storage capacity (which would lie around four). Counting involves such attentional control, whereas they argue that subitizing occurs automatically and is thus less subject to individual differences.

The FINST mechanism proposed by Pylyshyn and colleagues might be one way in which this automatic, parallel apprehension of low numbers is achieved. According to the FINST account, subitizing is mediated by the more general visual mechanism of assigning spatial indexes to objects (often referred to as FINgers of INSTantiation, hence FINSTs; Pylyshyn, 1989, 2001; Trick & Pylyshyn, 1993, 1994b). It is proposed that assigning FINSTs occurs preattentively, in a spatially parallel, and stimulus-driven fashion. For instance, according to Pylyshyn (2001), the appearance of a new object causes an index to be grabbed automatically. The number of available indexes is limited to about four.

Trick and Pylyshyn state that although the assigning of up to four FINSTs would occur preattentively and in parallel, this does not mean that the task as a whole is devoid of attention (Pylyshyn, 2001; Trick & Pylyshyn, 1994b). As argued before, one would expect attentional overhead costs reflecting the need to maintain the task rules and map the stimulus to an often arbitrary response. But again, since the underlying process is a preattentive parallel one, these costs would not be expected to vary with the number of items to be enumerated. In support of this, Trick and Pylyshyn (1994a) found that an array of dots could be subitized without great costs even when attention was cued to focus on a different spatial area. Furthermore, Trick and Pylyshyn (1994b) cite work by Logie and Baddeley (1987) showing that performing secondary tasks has little to no effect on subitizing.

On the other hand, there are signs that subitizing may break down when attentional resources are reduced. For example, recent ageing work has shown that enumeration of small numbers becomes serial when attentional resources are reduced due to a combination of normal ageing and increased competition from distractors (Watson, Maylor, Allen, & Bruce, 2007; Watson, Maylor, & Manson, 2002). Furthermore, Rock, Linnett, Grant, and Mack (1992) found that the correct enumeration of dots was affected even for the 1–4 range, when observers were asked to attend to a different task and were unaware that they would later be asked for numerosity. However, Rock et al.'s experimental design only allowed for relatively coarse analyses, and from their report we cannot assess whether performance further differentiated within the subitizing range. Finally, Olivers (2004) found that under dual task conditions comparable to the ones presented here, the number of spatial indexes that could be effectively used in a subsequent localization task was reduced at short lags between the tasks. If such spatial indexing is related to subitizing, as for instance argued under the FINST hypothesis, then we might expect the same manipulation to affect subitizing.

THE PRESENT STUDY

We sought to further explore the role of attention in subitizing. For this purpose we combined the rapid serial visual presentation (RSVP) paradigm with the enumeration paradigm. The same idea was recently independently arrived at by Egeth, Leonard, and Palomares (2008 this issue), and their work and ours should be regarded as a combined effort to answer the question as to what role attention plays in enumeration (see also Poiese, Spalek, & Di Lollo, 2008 this issue). Figure 1 illustrates the task used in Experiment 2. Participants identified a target letter of a particular colour from a stream of rapidly presented distractor letters of a different colour. All letters were presented at the same location. At varying intervals (lags) from the target letter, a set of dots was presented, followed by a mask. The participant's task was to report the target letter and the number of dots at the end of the trial.

On the basis of previous studies, we expected the letter identification task to induce an episode during which the availability of attention would be

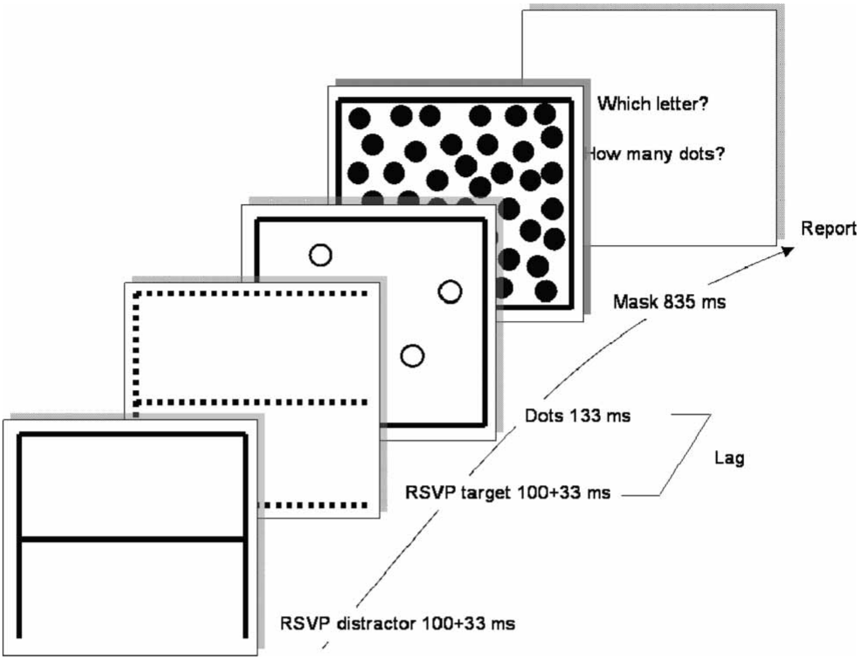

Figure 1. Illustration of the procedure of Experiment 2. Participants saw a series of box-shaped letters, one of which was a target (as defined by a different colour, here indicated by dotted lines). At various lags, the letter target was followed by a second target consisting of a number of dots, in turn followed by a mask. In Experiment 3, the roles of dots and letters were reversed: A series of dot patterns, one of which was the first target, was followed by a letter as second target. In Experiment 1, the procedure was as in Experiment 2, but the preceding letters were replaced with a single figure-of-eight premask. There was no letter target.

reduced—an episode referred to as the *attentional blink* (Raymond, Shapiro, & Arnell, 1992; see, for supporting evidence using the same stimuli as here, Olivers, 2004, and Olivers & Watson, 2006). We were interested in how subitization would behave under such conditions of attentional strain—in other words, how it would be affected by the lag between the target letter and the dot display.[1] From the FINST account as well as the parallel, fixed-capacity STM account, we expected overall performance to be affected by lag. The attentional blink would result in a reduction of resources available for the overhead processes such as remaining task control and assigning an

[1] Recently, alternative accounts of the attentional blink have been proposed which do not rely so much on a temporary strain or depletion of attentional resources (Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Nieuwenstein & Potter, 2006; Olivers, 2007; Olivers, van der Stigchel, & Hulleman, 2007). However, resource depletion may be more likely when a task switch is involved, as was the case here.

appropriate number tag. Importantly, we would expect these effects to be the same regardless of the number of dots, as long as this number stays within the subitizing range. This is because within this range, processing occurs in parallel, and, according to the FINST account, even before attention is involved at all. If, however, each additional object requires some additional attentional resources (or attentional control), then we would expect a clear effect of the number of dots at the shorter lags, when attentional resources are under strain.

In Experiment 3 the roles were reversed: We assessed the effects of a subitization task on subsequent letter identification. If enumerating additional dots requires additional resources, then increasing the number of dots should adversely affect letter recognition, as a function of lag. Before we present Experiment 2 and Experiment 3, however, we describe Experiment 1, which served to establish the basic subitizing effect under current stimulus conditions.

EXPERIMENT 1: ESTABLISHING SUBITIZING UNDER THE PRESENT STIMULUS CONDITIONS

The attentional blink tasks used in Experiments 2 and 3 included dot patterns that were either preceded or followed by a box-shaped letter, and were followed by a white pattern mask (see Figure 1). To be able to claim that subitizing is subject to attentional resources, we first need to make sure that the usual subitizing/counting pattern is obtained under these stimulus conditions. In Experiment 1 we therefore presented the same dot patterns, for the same duration, preceded and followed by the same box making up the letters, and followed by the same pattern mask. We measured verbal enumeration RTs and accuracy. To control for differences in pronunciation times for different verbal number labels, we also included a condition in which observers verbally named single digits presented at the centre of the screen. Measurements were then subtracted from the enumeration condition.

The classic pattern of results would consist of efficient and accurate enumeration for the smaller numbers of dots (up to four), and slow and error-prone enumeration for the higher numbers (more than four).

Method

Participants. Six students from the Vrije Universiteit Amsterdam (five male, two left-handed) with normal or corrected vision participated voluntarily. Ages ranged from 24 to 30 years (average 27.0). Participants who reported to be colour-blind or to have a history of epilepsy or migraine were not admitted to the study. The same criteria applied to all subsequent experiments.

Apparatus, stimuli, procedure, and design. Stimulus presentation and response recording were performed by a purpose-written Turbo Pascal program running on a Pentium PC linked to a 17-inch SVGA monitor running in $800 \times 600 \times 256$ mode, which was viewed from 75 cm. A trial started with a 750 ms blank, followed by a "box-shaped figure-of-eight" premask ($5.3 \times 5.3^\circ$ visual angle) presented for 600 ms. In the *dot enumeration* condition, this premask was followed by between 1 and 8 dots (0.45° in diameter), plotted randomly in the cells of a 6×6 virtual matrix, comprising the same $5.3 \times 5.3^\circ$ area as the premask. Within the cells, the dots were randomly displaced by between 0 and 0.2° in any direction. In the *digit naming* condition, the premask was followed by a digit between 1 and 8 (about 0.45° tall). The premask, the dots, and the digits could be red (0.61, 0.35, 7.9 cd/m^2), green (0.26, 0.60, 10.1 cd/m^2), blue (0.16, 0.10, 7.4 cd/m^2), or brownish yellow (0.41, 0.50, 12.6 cd/m^2; CIE x, y coordinates, and luminance within brackets), and were presented on a black background (approx. 0 cd/m^2). These colours were chosen to be isoluminant for the first author according to a flicker test (Ives, 1912), except for yellow, which was chosen somewhat brighter to make it more distinct from the other colours (i.e., less brown). The colours had no purpose in the present experiment other than equating conditions in relation to experiments published elsewhere in which colour served a function (Olivers & Watson, 2006). Colour combinations were fully counterbalanced across participants (see subsequent experiments for details). Experiment 2 used an RSVP of letters preceding the dot display, but here we opted for only a single figure-of-eight premask, assuming that additional masking strength of preceding items would be minimal. Furthermore, the figure-of-eight covers more line segments than the average letter in later experiments, making it, if anything a slightly stronger mask. The dots (in the dot enumeration condition) and the digits (in the digit naming condition) were presented for 133 ms, immediately followed by a postmask consisting of the same 6×6 virtual matrix, but now fully filled with bright white dots (53 cd/m^2), which were again randomly displaced within their cells. The postmask remained visible until response, with a maximum of 835 ms. The participant's task was to verbally report the number of dots (in the dot enumeration condition) or to name the digit (in the digit naming condition) as quickly as possible. The verbal response triggered a voice key, providing a response time (RT) measurement. The experimenter then entered the participant's response on a standard keyboard (providing an accuracy measurement). The digit naming condition was included to control for differences in number pronunciation times. The experimenter did not watch the screen, and the participant could see what the experimenter had entered. The experiment started with a practice part of 20 digit naming trials and 20 dot enumeration trials, in which the presentation time was gradually shortened. The experimental part consisted of five digit naming and five dot enumeration blocks in alternating, counterbalanced order. Each block consisted of 40 trials, 5 for each dot number or digit (1 to 8), resulting in 25 trials per data cell.

Results and discussion

RTs below 200 ms, above 5000 ms (in the dot enumeration condition), or above 2000 ms (in the digit naming condition) were excluded (six trials in total). Trials on which the response was correct were entered in an ANOVA with condition (dot enumeration or digit naming) and number (1 to 8) as factors. Trivially, participants were overall slower in the dot enumeration task (average 949 ms) than in the digit naming task (average 486 ms), $F(1, 5) = 69.69$, $MSE = 15.60$, $p < .001$, especially at the higher numbers, leading to a condition $\times$ number interaction, $F(7, 35) = 15.76$, $MSE =$ 21,403.62, $p < .001$. The digit naming task only served to control for differences in pronunciation times for the numbers 1 to 8, and so we subtracted the naming RTs from those in the dot enumeration task. Figure 2a shows the resulting pattern of dRTs after this subtraction. From the graph, it is clear that participants had little trouble enumerating one to three dots: RTs remained fast across the range, and variance was low. In contrast, for five to eight dots, both RTs and variance increased considerably. For four dots, performance fell in between.[2] This pattern was confirmed by separate t-tests revealing no significant differences between one and two dots, $t(5) = -1.67$, $p = .16$, or between one and three dots, $t(5) = 1.24$, $p = .27$. In contrast, there were significant differences between one and four dots, $t(5) = 8.82$, $p < .001$, and all higher number of dots, all ts $\geq$ 4.5, all ps $< .01$. From this pattern we conclude that one to three dots could be subitized whereas more dots required slower counting or guessing strategies.[3]

[2] The drop in RTs for eight dots probably reflects the fact that eight was the end of the range and therefore the default response whenever observers saw too many dots to count.

[3] Perhaps the more typical way of assessing the subitizing range is a trend analysis to see if the slopes of the enumeration functions differ for lower versus higher numbers of dots. The present analysis actually provides a somewhat stronger (i.e., more conservative) test of subitizing as the pairwise t-tests may pick up small differences that would normally fall within the same trend. For the same reason we report these analyses without corrections for multiple comparisons (e.g., Bonferroni, but note that the same pattern holds under $p = .05/8$ here). This is because we are trying to establish a subitizing range here, and the more conservative the correction, the more likely that higher numbers will be spuriously included in this range. Thus, the more conservative test of subitizing is actually the one without corrections. Another reason for not performing a trend analysis is that in the subsequent experiments these analyses were not possible, because there the maximum number of dots was five (since we were only interested in the subitizing range anyway). We preferred to keep the analyses the same across experiments.

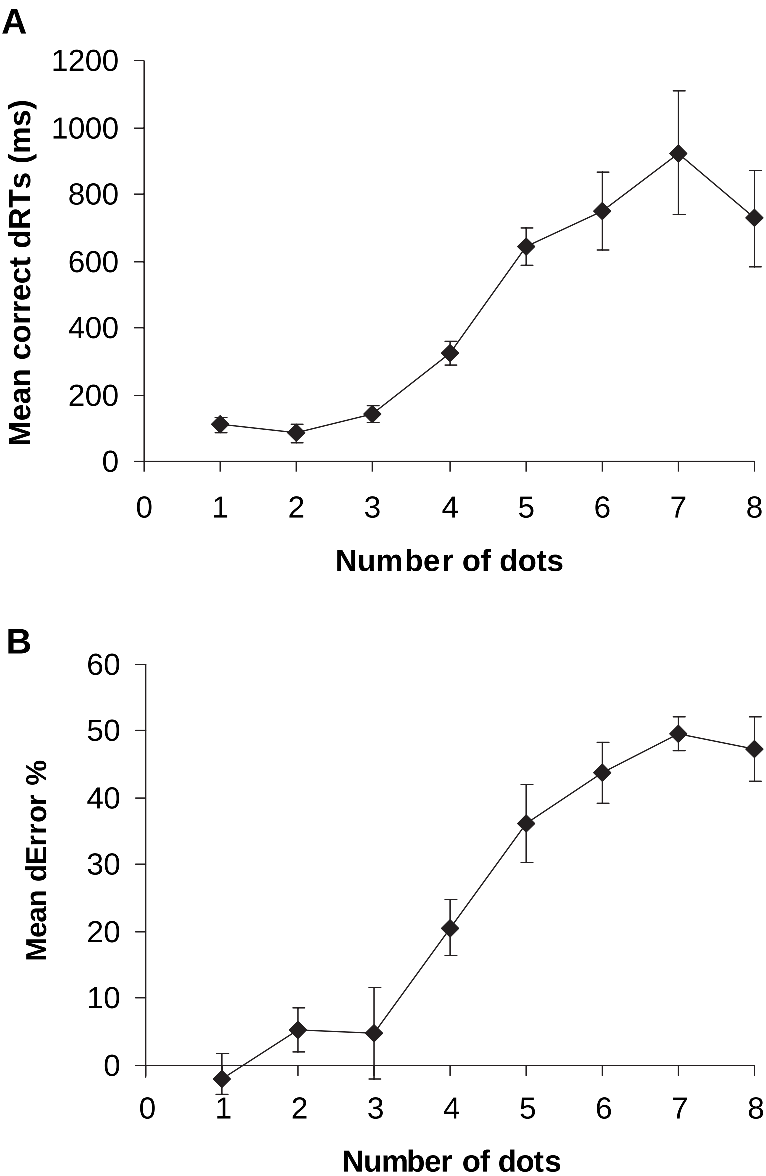

Figure 2. Performance in Experiment 1 as a function of the number of dots, with (A) the RT differences between the dot enumeration task and the digit naming task, and (B) the error differences between the two tasks.

The same conclusion can be derived from the error data. Error percentages were first arcsine transformed to compensate for end of scale compression effects. The few errors that were made in the digit naming task (0.8% on average) were subtracted from the dot enumeration task. Figure 2b shows the resulting error pattern as a function of the number of dots. Again, the graph indicates an efficient process operating for the lower range of dots (1–3), and an inefficient, error-prone process for the higher range (4–8). Separate *t*-tests revealed a small but significant difference between one and two dots, $t(5) = 2.78$, $p < .05$, no significant difference between one and three dots, $t(5) = 0.847$, $p > .4$, a significant difference between one and four dots, $t(5) = 3.89$, $p < .02$, and between one and all the higher numbers of dots, all $t\text{s} > 5.8$, all $p\text{s} \leq .002$.

Taking the RT and error pattern together, we suggest a subitizing range of up to three dots for the present set of stimuli. We take this finding as a basis for the subsequent experiments, which use the same stimuli and masks.

EXPERIMENT 2: THE ATTENTIONAL BLINK AFFECTS SUBITIZING

In Experiment 2, participants identified a target letter (defined by colour) from a series of distractor letters, and determined the number of dots in a subsequent frame (between 0 and 5), presented at various lags from the target letter. The dots were of a different colour than all the other items in the stream, and were followed by a white mask (see Figure 1). The letters were relatively large and box-shaped, encompassing the area within which the subsequent dots could fall. This was to ensure that attention was in a reasonably wide, distributed state in all conditions—at least sufficiently wide to cover the dots. Had we used smaller characters, attention may have been highly focused on the centre of the display, and any deficits would have been attributable to attention having to change its spatial focus, rather than to attention being temporarily unavailable. It is worth emphasizing though that subitizing does not appear to be much affected by where the exact spatial focus of attention is (Trick & Pylyshyn, 1994a).

If the letter identification task uses up resources necessary for subitzing, then we would expect an interaction between lag and number of dots, even within the subitizing range established in Experiment 1 (i.e., 1–3). This is because the shorter the lag, the more likely the attentional resources are reduced. When lag is long, attention should be available again by the time the dots arrive, and subitizing should be intact.

Method

Participants. Twenty-four students from the Vrije Universiteit Amsterdam and the University of Warwick (10 male, 4 left-handed) with normal or corrected vision participated either voluntarily or for monetary payment. Ages ranged from 19 to 52 years (average 25.3).

Stimuli, design, and procedure. Many aspects were identical to Experiment 1. Instead of single character, the dot patterns were preceded by an RSVP stream of $5.3 \times 5.3°$ visual angle box-shaped capitals. A trial started with a 750 ms blank, followed by a "fixation" square the size of the subsequent characters. After 600 ms, the stream of between 15 to 20 letters started, randomly drawn (with replacement) from the set {A, C, E, F, H, J, L, P, O, S, U, Y}, with the limitation that no two consecutive letters were identical. Each letter was presented for 100 ms, followed by a 33 ms blank. All letters were of one colour (e.g., green) except the target letter, which was of a different colour (e.g., red). The target letter was randomly drawn from the same set as the distractors and was presented 1, 2, 3, 5, or 8 temporal positions from the end of the series, corresponding to lags of 133, 267, 400, 667, and 1067 ms respectively. The letter series was immediately followed by the presentation of a set of dots for 133 ms, varying in number between 0, 1, 2, 3, 4, and 5. The dots differed in colour from both the target letter and the distractor letters (e.g., blue when the latter were red and green). The background was again black. The target dots were followed by the mask for 835 ms. The participants were then asked to type in the target letter and the number of dots they had seen (between 0 and 5). Accuracy was stressed in the instructions, as was the unimportance of speed. To keep letter detection accuracy high, errors on the letter task were followed by a feedback tone. Counting errors were not followed by feedback, because we thought that the large number of errors on this task might discourage participants. The number of dots (six levels) and the different lags (five levels) were randomly mixed within a block of 60 trials (2 trials per combination). Each participant completed 10 blocks (with breaks in between), resulting in 20 trials per cell. The experiment was preceded by one practice block of 60 trials, in which presentation times gradually decreased. The colours used (red, green, blue, and yellow) were counterbalanced partly within and partly across participants. For instance, one participant would extract red targets from an otherwise green stream in one block, and green targets from an otherwise red stream in the following block. For this participant, the dots on a particular trial would then be either all blue or all yellow, with dot colour mixed within blocks. With 24 participants, each combination of colours was represented four times. The different colours were a remnant of other experiments that we have published elsewhere (Olivers & Watson, 2006).

Results and discussion

Letter identification errors. Figure 3a shows the error rates for the first target as a function of the number of dots (in the second target) and lag. On average, 9.3% of the letter targets were misidentified. The error proportions were first arcsine transformed and then submitted to an ANOVA with number of dots and lag as factors. Error rates increased with lag, $F(4, 92) =$

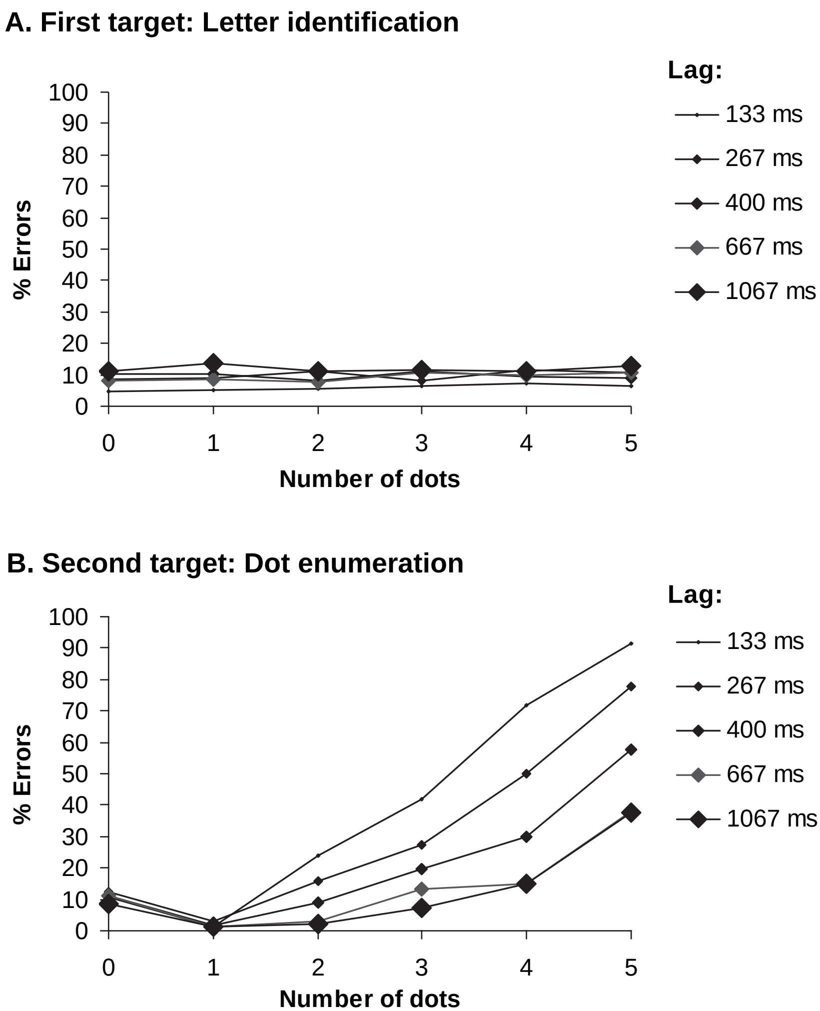

Figure 3. Performance in Experiment 2, as a function of the number of dots and the lag between the first (letter) and second (dot pattern) target. (A) Error percentages for the first target (letter identification task). (B) Error percentages for the second target (dot enumeration task).

16.74, $MSE = 0.007$, $p < .001$; they were overall lowest at the shortest lag, 6%, and highest at the longest lag, 12%. There were no effects involving the number of dots, $F\text{s} < 1.8$, *ns.*

Dot counting errors. Figure 3b shows the proportion of errors on the dot enumeration task, as a function of the number of dots present and the lag between the dots and the target letter.[4] Trials on which the letter target was missed were excluded. Errors increased with increasing number of dots, $F(5, 115) = 69.41$, $MSE = 0.071$, $p < .001$, and increased with shorter lags, $F(4, 92) = 108.76$, $MSE = 0.015$, $p < .001$. There was a significant Number of dots × Lag interaction, $F(20, 460) = 23.1$, $MSE = 0.008$, $p < .001$, as the number of dots had a stronger effect at shorter lags than at longer lags. In order to assess whether participants were able to subitize, we took the error rates for the longest lag (1067 ms) as a baseline, and compared performance for each number of dots against performance when only one dot was present. From zero to one dot there was a small, nonsignificant decrease in errors, $t(23) = 1.26$, *ns.* Between one and two dots there was virtually no difference, $t(23) = 0.89$, *ns.* Between one and three items there was a small, but significant increase in errors, $t(23) = 2.49$, $p < .05$. This difference was somewhat inflated by three participants who showed 25% to 45% increases. Without these participants, average error rates were more than halved for the three dots condition (and did not differ from the one dot condition). Finally, error rates were significantly increased for four and five dots relative to one dot, $t(23) = 6.88$, $p < .001$, and $t(23) = 9.79$, $p < .001$. Together, these data indicate that most participants could subitize at least two, and probably three items without much cost. Costs increased more substantially with four and five items. To assess the subitizing range under attentional blink conditions, we performed the same tests in the shortest lag condition (133 ms). Between zero and one dot, there was a small significant drop in errors, $t(23) = 2.10$, $p < .05$. For all the other numbers of dots there was a highly significant increase in errors relative to the one dot condition, all $t\text{s} > 8.36$, all $p\text{s} < .001$.

The results show a clear limitation in the ability to enumerate dots under attentional blink conditions, as induced by processing a letter target. Error rates rose steeply when the lag between the target letter and the dots was short, even when the number of dots fell within the subitizing range of one to three items (or, if one wants to be very conservative, one to two items).

[4] Note that in Figure 3 and Figure 4, we have put the number of dots on the x-axis, and the percentage errors on the y-axis. This is the convention in enumeration studies. It is not the convention in attentional blink studies, in which lag is usually on the x-axis, and percentage correct (rather than error) on the y-axis. Since we were interested in subitizing, we follow the first convention.

Exactly the same pattern of results is reported by Egeth et al. (2008 this issue). It appears then that including an object for enumeration purposes is subject to some attentional control or resources, such that when attention is taken away, enumeration is limited to about one object. Note that one dot was virtually always counted correctly (less than 2% errors were made, and this did not vary with lag). This is important, because it means that, in the current setting, the attentional blink did not simply prevent *any* processing of the dot display. The basic perceptual processes appear intact (since at least something is perceived), as do the number retrieval and response generation processes. In other words, overhead processes appear relatively unaffected. Instead, it is the process that has been assumed to run automatically and in parallel that appears to be most affected. The same conclusion was reached by Poiese et al. (2008 this issue).

The letter identification task (i.e., the first target) was only affected by lag. In contrast to the dot enumeration task, error rates dropped with shorter lags. This can be explained by the fact that at longer lags the target letter may have suffered more from interference from the trailing distractor letters. Furthermore, when lag was long, the trial itself was also longer, allowing for more forgetting by the time the letter was to be reported.

EXPERIMENT 3: ENUMERATION INDUCES AN ATTENTIONAL BLINK

In Experiment 3, the roles of the dots and the letters in the RSVP stream were reversed. Now the bulk of the RSVP stream consisted of displays filled with random numbers of distractor dots. In one of the displays the dots were of a different colour, and the participant's task was to enumerate these target dots. The dots were then followed by a second target, now a square-shaped letter, which was masked. As before, we systematically varied the number of dots (now in the first target display) and the lag between the target displays. If the dot enumeration task induces an attentional blink, we should see an effect of lag on letter identification accuracy. Moreover, if each additional dot demands additional attentional resources, then, at the shorter lags, letter identification is expected to suffer with increasing dot numbers, even within the subitizing range.

We ran two versions of this experiment. In Experiment 3a we used target letters that were of the same size as in Experiment 2, which meant that they were slightly wider than the area within which the dots were positioned. This means that any deficit may be due to the letter falling outside the focus of attention, rather than due to it being unavailable. In Experiment 3b the size of the letter was therefore reduced so that it fell inside the area covered by the dots (without ever actually being covered by a dot). This way, attention would have to be in a reasonably distributed state to perceive the dots (if attention is needed), and the letter would fall within the centre of this distributed area.

Method

Thirty students from the Vrije Universiteit Amsterdam and the University of Warwick (16 male, 5 left-handed) took part. Ages ranged from 17 to 31 years (average 22.0). Eighteen participated in Experiment 3a, twelve in Experiment 3b.

The experimental method was the same as in Experiment 1, except that the roles of the letters and the dots were reversed. The first target now consisted of a number of dots ranging from 0 to 5 embedded in a stream of sets of distractor dots ranging from 1 to 15. The target and distractor dots differed in colour (e.g., red amongst green; the same colours as in the previous experiments were used). At lags of 133, 267, 400, 667, and 1067 ms from the target dots, a second target was presented—this time a letter. The letter was square-shaped (as in the previous experiments) and differed in colour from both the target and the distractor dots. The target letter was followed by a white mask consisting of a square-shaped figure-of-eight filled with white dots. The figure-of-eight covered the letters. At the end of the trial, the participants were asked to first type in the number of dots they had seen, and then the target letter. To keep dot detection accuracy high, errors on the enumeration task were followed by a feedback tone. Letter identification errors were not followed by feedback. The number of dots (six levels) and the different lags (five levels) were randomly mixed within 10 blocks of 60 trials, resulting in 20 trials per cell. The experiment was preceded by one practice block of 60 trials, in which presentation times gradually decreased. Experiment 3a and Experiment 3b were identical, except that in the latter, the letter target and its figure-of-eight mask measured $0.75 \times 0.75^{\circ}$ visual angle, rather than the $5.3 \times 5.3^{\circ}$ used in Experiment 3a and the previous experiments. Also, no dots could fall in the four central cells of the 6×6 virtual grid. This meant that all dots fell outside the letter area.

Results

The results from Experiments 3a and 3b were virtually identical. We will therefore present the results combined across experiments, and mention any exceptions.

Dot counting errors. Figure 4a shows the proportion of errors on the dot enumeration task, as a function of the number of dots present and the lag between the target dots and the target letter. Note that the dot enumeration task was now the *first* task. Analyses on arcsine transformed rates revealed that errors increased with increasing number of dots, $F(5,\ 140) = 40.00$, $MSE = 0.04$, $p < .001$, and increased with longer lags, $F(4,\ 112) = 17.85$, $MSE = 0.006$, $p < .001$. The overall effect of lag was a little stronger in

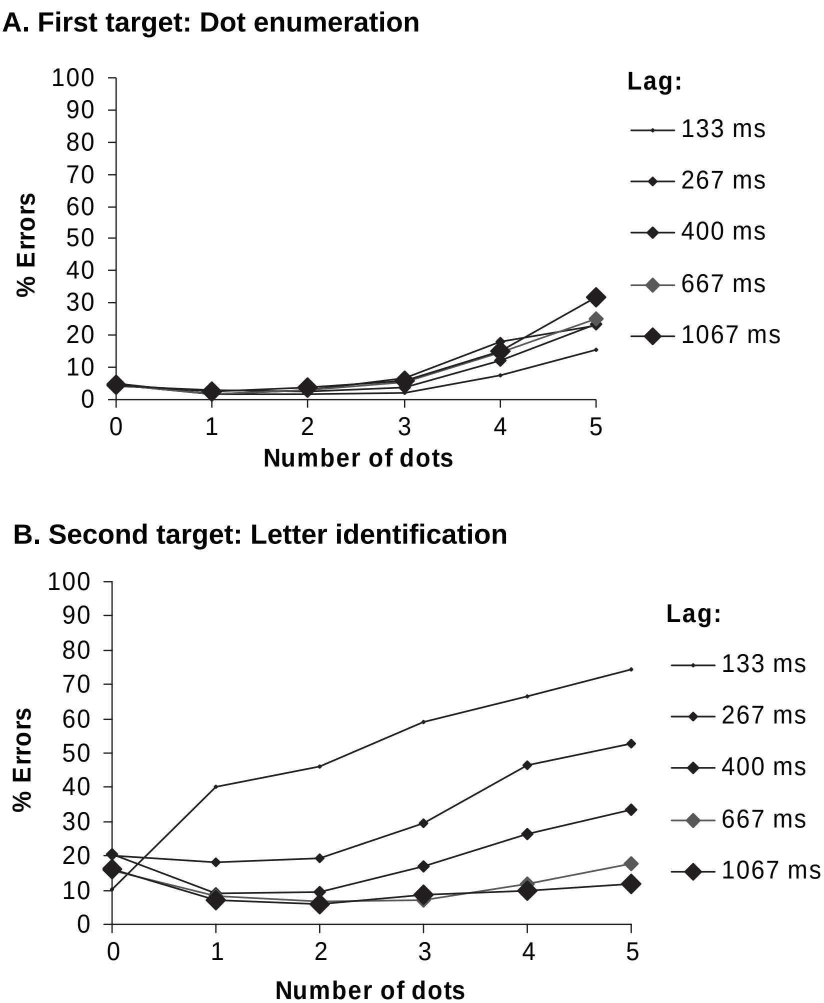

Figure 4. Performance in Experiment 3, as a function of the number of dots and the lag between the first (dot pattern) and second (letter) target. (A) Error percentages for the first target (dot enumeration task). (B) Error percentages for the second target (letter identification task).

Experiment 3b, resulting in an Experiment × Lag interaction, $F(4,112) = 2.99$, $MSE = 0.006$, $p < .05$. There were no other significant effects involving experiment, all Fs < 1. There was a significant Number of dots × Lag interaction, $F(20, 560) = 4.49$, $MSE = 0.005$, $p < .001$. The number of dots had a stronger effect when lag was long than when it was short, with especially a difference between the longest (1067 ms) and shortest lags (133 ms). For the shortest lag, there were no significant differences for the first three dots (all ts < 1), whereas for four and five dots errors increased significantly relative to the one dots condition, ts > 3.9, ps < .001. For the longer lag, errors increased slightly but significantly for two dots relative to one dot, $t(29) = 2.34$, $p < .05$, as well as for three, four, and five dots relative to one dot, ts > 3.9, ps < .001.

Letter identification errors. Figure 4b shows the proportion of letter identification errors as a function of lag and the number of first target dots. Note that in this experiment letter identification was the *second* task. Overall more errors were made in Experiment 3a than in Experiment 3b, $F(1, 28) = 6.73$, $MSE = 0.298$, $p < .05$. No other effects involving experiment were significant, Fs < 2.2. Errors increased with increasing number of dots in the first set, $F(5, 140) = 58.00$, $MSE = 0.017$, $p < .001$, and increased with shorter lags, $F(4, 112) = 147.13$, $MSE = 0.021$, $p < .001$. There was also a significant Number of dots × Lag interaction, $F(20, 560) = 29.23$, $MSE = 0.008$, $p < .001$ (note that this interaction was also significant when the zero dots condition was excluded, $p < .001$). The proportion of errors increased more steeply with the number of dots under short lag conditions than under long lag conditions, especially in the lower range of one to four dots. To assess this interaction in more detail, we analysed the error rates for the longest lag (1067 ms) and the shortest lag (133 ms) separately, and compared performance for each number of dots against performance when only one dot was present. For the longest lag (1067 ms), from zero to one dot there was a significant decrease in letter identification errors, $t(29) = 4.83$, $p < .001$. Between one and two dots there was virtually no difference, $t < 0.5$, *ns*, and neither was there between one and three dots, $t < 1$, *ns*. Letter identification errors increased between one and four dots, $t(29) = 2.50$, $p < .05$, and increased more between one and five dots, $t(29) = 3.84$, $p = .001$. For the shortest lag (133 ms), there was a significant increase in letter identification errors between zero and one, one and two, one and three, one and four, and one and five dot displays, all ts(29) > 3.0, all ps < .005.

The dot enumeration task had a profound effect on letter identification. Overall, across the various dot numbers, error levels increased steeply with the shorter lags (i.e., 133 ms, and, to a lesser extent, 267 ms and 400 ms). Of particular interest, erroneous identifications of the second (letter) target increased with the number of dots in the first target, even when this number fell within the subitizing range. For these groups, subitizing again ranged from one to around three items, as was apparent from performance on the dot enumeration task (the first target). Yet, even within the range of one to three the number of dots affected subsequent letter identification, suggesting that not only overhead processes, but also the subitizing process per se requires attentional resources.

The occurrence of overall costs (across the dot numbers) is an interesting difference relative to Experiment 2. There we found that a letter identification task did not affect the enumeration of a single dot. Here, on the other hand, we find that enumerating even a single dot does affect identification of a subsequent letter. There may be several explanations for this difference. One is the possibility for asymmetrical task switch costs (Allport, Styles, & Hsieh, 1994). For example, the overhead processes associated with subitizing may require more resources or last longer than those involved in letter recognition (the latter perhaps being more automatic). Another possibility is that, with sparser dot displays, attention is attracted to a single dot location. With the attentional focus being elsewhere, letter recognition may be relatively more impaired. The fact that there were no costs for zero dot displays may provide some evidence for this latter hypothesis, though note that this may also stem from a response bias (i.e., the tendency to report zero when no dots are perceived).

GENERAL DISCUSSION

To our knowledge, our study, that of Egeth et al. (2008 this issue), and that of Poiese et al. (2008 this issue) are the first to show that the enumeration of small numbers—subitizing—is under attentional control. This is not surprising, given that subitizing tasks usually require higher cognitive functions such as mapping the percept to an often arbitrary verbal or manual response. Experiment 3 provided evidence for such attentional overhead costs: At short lags, letter identification suffered from a preceding subitzing task, across the range of dot numbers. What is more interesting is that the attentional costs also depended on the number of dots, even though this number fell within the subitizing range (which in our experiments was estimated at about 1 to 3; see Experiment 1, second target performance at long lags in Experiment 2, and first target performance of Experiment 3). In Experiment 3, letter identification suffered more with increasing dot numbers in the preceding subitizing task. Vice versa, in Experiment 2, the more dots there were, the more enumeration suffered from the preceding letter identification task—a finding that has proven robust (Egeth et al., 2008 this issue; Poiese et al., 2008 this issue; see also Olivers & Watson, 2006, for a partial manipulation). Also, in Experiment 2, observers were fine at enumerating just a single dot, showing that the letter identification task did not simply result in complete inattentional blindness for the dot patterns (viz. Rock et al., 1992). Again, the same was found by Egeth et al. (2008 this issue). Thus, whatever the limitations imposed by the attentional blink, these do not appear to affect the simple detection of a single object.

The finding that a secondary task affects subitizing is corroborated by a recent study of Di Lollo, Smilek, Kawahara, and Ghorashi (2005; see also Di Lollo, Kawahara, Zuvic, & Visser, 2001), who were primarily interested in visual search, but also employed a task similar to ours. In one of their conditions they asked observers to first decide on the exact shape of a centrally presented hexagon. The second task was then to enumerate up to four line segments presented inside the hexagon, followed by a masking pattern. At short intervals between the two tasks, the enumeration task suffered with increasing number of lines, even though the number fell within the subitizing range. Di Lollo et al. argued that performance suffered from the need to reconfigure tasks between shape judgment and enumeration. At short lags, no appropriate input filter for the enumeration task has been set up yet. Such an input filter, once instantiated, allows for relatively rapid, automatic template matching processes. Without such a filter, however, the system needs to revert to a slow explicit perceptual hypothesis-testing mode requiring the focusing of attention on single objects. This is consistent with our conclusion that subitizing is under attentional control.

Magical number 1?

An intriguing finding in Experiment 2 was that enumeration performance for a single dot was fine, regardless of lag. It did not appear affected by the lack of attention. The exact same finding is reported by Egeth et al. (2008 this issue), and they make the tentative but tantalizing proposal that in terms of attention and/or working memory capacity, there may be a "magical number 1", rather than, or in addition to, earlier proposed magical numbers 4 (Cowan, 2000) and 7 (Miller, 1956). Might the unaffected performance for the single dot condition have been caused by a floor effect? We cannot exclude this possibility, but a number of findings may make it unlikely. For one, Egeth et al. explicitly controlled for floor effects by making the enumeration task overall more difficult. Again, performance for a single dot was unaffected by lag. Furthermore, corroborating evidence has been reported by Ghorashi, Di Lollo, and Klein (2006): Perception of a single dot does not seem to be impaired during the AB when that dot functions as a spatial cue for the upcoming second target. Finally, also Olivers (2004) found that detecting and localizing a single cue, or the first of two cues, was not affected, while the second of two cues was strongly affected by the attentional blink.

The fact that one dot could virtually always escape the attentional blink also appears to go against the idea that the attentional blink leads to "an all-or-none bifurcation" in consciousness, as proposed by Sergent and Dehaene (2004). According to this account, the second target is either fully perceived, or not at all. In the present Experiment 2, participants virtually always saw something (i.e., at least one dot). Futhermore, a closer look at the errors shows a pattern of underestimation: Observers mostly reported one or two fewer dots than were actually present. This too suggests a more gradual decrease in consciousness.

Implications for theories of enumeration

The finding that the magnitude of the blink was systematically affected by the number of dots provides evidence against the idea that subitizing reflects a purely parallel process with a fixed capacity. Such a parallel process is hypothesized under the STM account, which supposes that attentional processes form the basis of short-term memory capacity, but that within a single attentional focus or episode, up to four objects can be processed simultaneously. Also according to the FINST hypothesis, the process underlying subitizing occurs in parallel. The assignment of spatial indexes (FINSTs) is thought to occur preattentively, in an automatic, and stimulus-driven fashion (Pylyshyn, 2001).

The STM hypothesis may be easily saved by supposing that the capacity of the initial parallel stage can be further limited by an additional attentional task, but remains parallel in essence, with four as the upper limit. However, our data here suggest that capacity may be reduced to a single object, at which point the limited-capacity parallel model becomes indistinguishable from a serial model. Furthermore, one may then wonder if four really is the upper limit. The limit of around four may simply stem from the fact that almost every task requires some attention, taking resources away from the limited-capacity parallel process. If we could find a way to reduce overhead costs, we may find that initial perceptual processing capacity increases.

The FINST hypothesis may be saved by assuming that the initial assignment of preattentive FINSTS occurs in parallel, but that transfer of this information to higher order processes such as STM is a serial process. Alternatively, the idea of preattentive parallel assignment could be abandoned. For example, Watson and colleagues have proposed that FINST assignment is rapid but serial or parallel, but not preattentive (Watson & Humphreys, 1999; Watson & Maylor, 2002; Watson et al., 2007). By this view, any manipulation that reduces available attentional resources can potentially impact on the efficiency with which FINSTs can be assigned or reassigned over time. It follows that subitization ability will be reduced during an attentional blink. However, as argued previously (Watson & Humphreys, 1999), an STM account and a FINST account of subitization then essentially become functionally equivalent: Each has a limit of four, which gives rise to the subitizing phenomena. Each allows for further reductions of this limit under conditions of attentional strain. Serial enumeration beyond this limit then arises as a need to empty STM or as a result of having to disengage and reassign FINSTs (but see also Watson, Maylor, & Bruce, 2005, for further relevant findings). In any case, by either account, the present work has demonstrated that subitization is susceptible to a reduction in attentional resources and therefore should not be viewed as a strictly automatic, preattentive process. In this sense then, it becomes indistinguishable from the counting of higher numbers. Whether the seriality occurs as a result of interactions within STM, or as a result of early serial tagging by a FINST mechanism (or some combination of both), poses a difficult question for future research.

Alternative accounts of subitizing

There are other explanations of the differences in counting performance for small and large numbers of items. The discrimination account (van Oeffelen & Vos, 1982) states that smaller numbers are more easily discriminated from each other than larger numbers. For example, the difference between 1 and 2 is 100%, whereas between 10 and 11 it is only 10%. The pattern matching account (Logan & Zbrodoff, 2003) states that patterns consisting of small numbers are more similar to patterns experienced in the past. That is, a pattern consisting of four dots resembles other patterns of four dots more than a pattern of eight dots resembles other patterns of eight dots. In a sense, patterns of smaller numbers are more canonical (Mandler & Shebo, 1982). Both accounts assume there is no real dichotomy in counting processes, just a nonlinear decrease in discriminability or similarity to previous patterns. We cannot exclude these accounts on the basis of the present data. In fact, one could argue that the present data offer direct evidence for these accounts by showing that, like counting, subitizing is not immune to attentional manipulations. It is possible that as the patterns become less discriminable from adjacent patterns or less similar to previously encountered patterns, more attention is needed, and processing is therefore suffering more from (or inducing more strongly) an attentional blink.

However, we would like to point out that the FINST and short-term memory accounts on the one hand, and the discriminability and pattern matching accounts on the other, may not be that incompatible with each other. For instance, why are patterns consisting of small numbers of dots rated more similar than patterns consisting of large numbers of dots, when larger numbers are less discriminable? One explanation is that small numbers (up to 4) can be grabbed by the FINST/STM system in only one way (i.e., all dots are picked up simultaneously). In contrast, larger numbers of dots can be grabbed in multiple ways by the FINST/STM system. For example, with a capacity of four, five dots can be grabbed in five different ways, with a different set of four dots being grabbed each time (leaving one different residual dot every time). Similarly, a set of four dots can be chosen from a set of six dots in 15 different ways and from a set of ten dots in 210 different ways. Thus, beyond the initial capacity limit, the informational load (i.e., the number of possible different memory interpretations) of a pattern rapidly increases with the number of dots, leading to a reduction in perceived similarity. If the number of different interpretations becomes too big, dot patterns may not be actively interpreted at all, making them less discriminable. One could imagine that whether there are 126 different interpretations (for nine dots) or 210 different interpretations (for ten dots), the attentional system just gives up and treats both sets as containing “many dots”. In any case, much of the relationship between enumeration, attention, and short-term memory remains to be explored.

REFERENCES

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 421–452). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Atkinson, J., Campbell, F. W., & Francis, M. R. (1976). The magic number 4 + / − 0. *Perception*, *5*, 327–334.

Balakrishnan, J., & Ashby, F. (1991). Is subitizing a unique numerical ability? *Perception and Psychophysics*, *50*, 555–564.

Burkell, J. A., & Pylyshyn, Z. W. (1997). Searching through subsets: A test of the Visual Indexing Hypothesis. *Spatial Vision*, *11*, 225–258.

Cowan, N. (2000). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 87–185.

Dehaene, S., & Cohen, L. (1994). Dissociable mechanisms of subitizing and counting: Neuropsychological evidence from simultanagnosic patients. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(5), 958–975.

Di Lollo, V., Kawahara, J., Ghorashi, S. M. S., & Enns, J. T. (2005). The attentional blink: Resource depletion or temporary loss of control? *Psychological Research*, *69*, 191–200.

Di Lollo, V., Kawahara, J., Zuvic, S. M., & Visser, T. A. W. (2001). The preattentive emperor has no clothes: A dynamic redressing. *Journal of Experimental Psychology: General*, *130*, 479–492.

Di Lollo, V., Smilek, D., Kawahara, J.-I., & Ghorashi, S. M. S. (2005). System reconfiguration, not resource depletion, determines the efficiency of visual search. *Perception and Psychophysics*, *67*, 1080–1087.

Egeth, H., Leonard, C. J., & Palomares, M. (2008). The role of attention in subitzing: Is the magical number 1? *Visual Cognition*, *16*, 463–473.

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 103–134). Cambridge, UK: Cambridge University Press.

Gallistel, C. R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition*, *44*, 43–74.

Ghorashi, S., Di Lollo, V., & Klein, R. M. (2006). Attentional orienting in response to peripheral cues survives the attentional blink. *Visual Cognition*, *15*, 87–90.

Ives, H. E. (1912). Studies of the photometry of different colours: I. Spectral luminosity curves obtained by equality of brightness photometer and the flicker photometer under similar conditions. *Philosophical Magazine*, *24*, 149–188.

Kaufman, E. L., Lord, M. W., Reese, T. W., & Volkman, J. (1949). The discrimination of visual number. *American Journal of Psychology*, *62*, 498–525.

Klahr, D. (1973). Quantification processes. In W. G. Chase (Ed.), *Visual information processing* (p. 555). Oxford, UK: Academic Press.

Logan, G. D., & Zbrodoff, N. J. (2003). Subitzing and similarity: Toward a pattern-matching theory of enumeration. *Psychonomic Bulletin and Review*, *10*(3), 676–682.

Logie, R. H., & Baddeley, A. D. (1987). Cognitive processes in counting. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 310–326.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281.

Mandler, G., & Shebo, B. J. (1982). Subitizing: An analysis of its component processes. *Journal of Experimental Psychology: General*, *111*, 1–22.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81–97.

Nieuwenstein, M. R., & Potter, M. C. (2006). Temporal limits of selection and memory encoding: A comparison of whole versus partial report in rapid serial visual presentation. *Psychological Science*, *17*, 471–475.

Olivers, C. N. L. (2004). Blink and shrink: The effect of the attentional blink on spatial processing. *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 613–631.

Olivers, C. N. L. (2007). The time course of attention: It's better than we thought. *Current Directions in Psychological Science*, *16*, 11–15.

Olivers, C. N. L., van der Stigchel, S., & Hulleman, J. (2007). Spreading the sparing: Against a limited-capacity account of the attentional blink. *Psychological Research*, *71*, 126–139.

Olivers, C. N. L., & Watson, D. G. (2006). Input control processes in rapid serial visual presentation: Target selection and distractor inhibition. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 1083–1092.

Pashler, H. (1988). Familiarity and visual change detection. *Perception and Psychophysics*, *44*, 369–378.

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception and Psychophysics*, *16*, 283–290.

Poiese, P., Spalek, T., & Di Lollo, V. (2008). Attentional involvement in subitizing: Questioning the preattentive hypothesis. *Visual Cognition*, *16*, 474–485.

Pylyshyn, Z. (1989). The role of location indexes in spatial perception: A sketch of the FINST spatial-index model. *Cognition*, *32*, 65–97.

Pylyshyn, Z. (2001). Visual indexes, preconceptual objects, and situated vision. *Cognition*, *80*, 127–158.

Pylyshyn, Z., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, *3*, 179–197.

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.

Rock, I., Linnett, C. M., Grant, P., & Mack, A. (1992). Perception without attention: Results of a new method. *Cognitive Psychology*, *24*, 502–534.

Sergent, C., & Dehaene, S. (2004). Is consciousness a gradual phenomenon? Evidence for an all-or-none bifurcation during the attentional blink. *Psychological Science*, *15*(11), 720–728.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs*, *74*(Whole No. 11).

Trick, L. M., & Pylyshyn, Z. W. (1993). What enumeration studies can show us about spatial attention: Evidence for limited preattentive processing. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 331–351.

Trick, L. M., & Pylyshyn, Z. W. (1994a). Cueing and counting: Does the position of the attentional focus affect enumeration? *Visual Cognition*, *1*, 67–100.

Trick, L. M., & Pylyshyn, Z. W. (1994b). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Review*, *101*, 80–102.

Tuholski, S. W., Engle, R. W., & Baylis, G. C. (2001). Individual differences in working memory capacity and enumeration. *Memory and Cognition*, *29*(3), 484–492.

Van Oeffelen, M. P., & Vos, P. G. (1982). A probabilistic model for the discrimination of visual number. *Perception and Psychophysics*, *32*, 163–170.

Watson, D. G., & Humphreys, G. W. (1999). The magic number four and temporo-parietal damage: Neurological impairments in counting targets amongst distractors. *Cognitive Neuropsychology*, *16*(7), 609–629.

Watson, D. G., & Maylor, E. A. (2002). Aging and visual marking: Selective deficits for moving stimuli. *Psychology and Aging*, *17*, 321–339.

Watson, D. G., Maylor, E. A., Allen, G., & Bruce, L. A. M. (2007). Early visual tagging: Effects of target-distractor similarity and old age on search, subitization, and counting. *Journal of Experimental Psychology: Human Perception & Performance Learning and Memory*, *33*, 549–569.

Watson, D. G., Maylor, E. A., & Bruce, L. A. M. (2005). The efficiency of feature-based subitization and counting. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(6), 1449–1462.

Watson, D. G., Maylor, E. A., & Manson, N. J. (2002). Aging and enumeration: A selective deficit for the subitization of targets among distractors. *Psychology and Aging*, *17*(3), 496–504.

Yantis, S., & Johnson, D. N. (1990). Mechanisms of attentional priority. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 812–825.

Manuscript received April 2007
Manuscript accepted November 2007
First published online April 2008