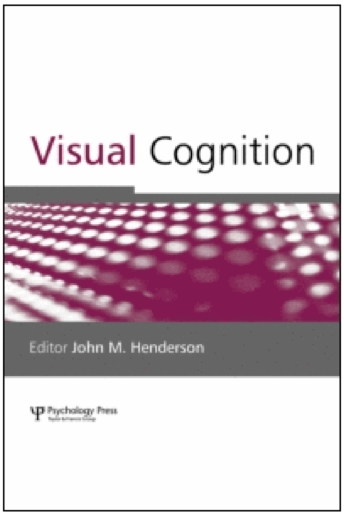

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The role of attention in subitizing: Is the magical number 1?

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The role of attention in subitizing: Is the magical number 1?

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Subitizing, the fast and accurate enumeration of up to about 3 or 4 objects, has often been thought to be dependent on limited-capacity preattentive mechanisms. We used an attentional blink paradigm to investigate the extent to which subitizing requires attentional resources. On each trial, subjects identified a target letter in an RSVP stream and then enumerated dots presented in the stream that were either simultaneous with the target letter or followed it by up to 400 ms. For numerosities from 2 to 9, evidence of an attentional blink was observed; only enumeration of 0 or 1 elements was independent of lag. Thus, even enumeration of 2–3 objects, which is within the traditional subitizing range, appears to require attentional resources. The relation of this work to studies on the attentional requirements of detecting a unique item among distractors, a supposedly preattentive discrimination, is briefly discussed.

Some of the earliest experiments in psychology were studies of enumeration ability, and amounted to demonstrations of the limits of attention. For example, Jevons (1871) picked up handfuls of beans, threw them into a box and, after glancing at them briefly, attempted to say how many he had thrown. He found that he was essentially perfect when there were up to four beans, but beyond four he made progressively more errors. Many variations of this experiment have been conducted. When the time to enumerate objects is measured, that time increases relatively little from one to three or four, and increases more rapidly thereafter. When objects are presented briefly, the accuracy of enumeration decreases relatively little for up to three or four items, and then begins to decline rapidly. This ability to enumerate small

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numbers of items quickly and accurately has been referred to as *subitizing* (e.g., Kaufman, Lord, Reese, & Volkmann, 1949). The limit on subitizing may be related to numerically similar limits found in other tasks, and is one of the bases for the "magical numbers" that have been proposed by some researchers (e.g., Cowan, 2000; Miller, 1956).

The widely, but not universally, accepted explanation of subitizing is that a small number of items can be apprehended simultaneously, and that larger numbers are presumably enumerated serially or, if there is time pressure, their numerosity may be estimated (e.g., Feigenson, Dehaene, & Spelke, 2004; see also Cordes, Gelman, & Gallistel, 2001, and Mandler & Shebo, 1982, for alternative viewpoints). The prominent FINST model holds that subitizing is at least in part a preattentive parallel process (e.g., Trick & Pylyshyn, 1994; see also Dehaene & Cohen, 1994). Cowan (2000) has proposed a model in which subitizing is attributed to a four-item limit of short-term memory capacity. Such models would reasonably predict that if attentional capacity were reduced, there may be a general task impairment due to dual-task constraints, but that this impairment would be the same throughout the subitizing range.

One way to reduce attentional capacity is to present the stimuli that are to be enumerated as the second target in an attentional blink paradigm. The attentional blink (AB) is evidenced by a drop in performance on a second target (T2) that occurs within a short time of the first target (T1) in a rapid stream of visually presented letters (RSVP). It has often been suggested that this impairment is caused by the fact that attention is still involved in processing T1 when T2 arrives (e.g., Raymond, Shapiro, & Arnell, 1992). If subitizing performance is preattentive, then there should be no impairment in the task when it is presented shortly after a T1 target. If attentional capacity above and beyond that minimally required to do the task is needed to enumerate even small numbers of objects, there should be an increasing impairment for each additional object in the subitizing range. This same idea was recently and independently arrived at by Olivers and Watson (2008 this issue); their work and ours should be regarded as a combined effort to determine what role attention plays in enumeration.

EXPERIMENT 1

In this experiment a red target letter appeared at some point within a rapid serial visual presentation of variously coloured letters. Either simultaneous with the target letter or at a variable lag of 100 to 400 ms, a display consisting of a ring of green dots was flashed briefly on the screen. The number of dots was varied from 0 to 9. The dot display was followed by a masking field. At the end of the letter stream the subject had to indicate the identity of the red letter and the number of green dots.

Method

Subjects. Twenty-four Johns Hopkins undergraduates with self-reported normal or corrected-to-normal visual acuity and colour perception participated in a session lasting about 50 min. Participation was voluntary and subjects received extra credit in a course for participating.

Apparatus and stimuli. Stimuli were generated on an Apple iMac G3 computer and displayed on a 19-inch NEC monitor using MATLAB with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Subjects viewed the stimuli in a dimly lit room at a distance of approximately 71 cm. All stimuli were presented on a black background. The letters in the RSVP stream were presented at the centre of the computer screen. These letters were approximately 0.6° high and 0.6° wide, with a stroke width of 0.16°. Letters were presented at a rate of 10 per second, with each letter displayed for 50 ms and followed by a 50 ms blank period. One of the frames containing a letter was accompanied by a ring of from 0 to 9 green dots; these dots were 0.7° in diameter and were presented 8.6° from fixation. The next letter in the stream was accompanied by a masking display that consisted of 24 multicoloured masks covering all 24 of the potential dot locations, each larger than the to-be-enumerated dots. The dot display and the mask display were each presented for as long as the letter that they appeared with (i.e., 50 ms). The luminances of the display elements were measured with a Pritchard PR-1980A Photometer, and reported here in cd/m^2. The screen background was 0.092, the fixation cross was 49.98, the green dots were 31.52, the red target letter was 10.78, and the nontarget letters in the stream varied from 5.30 to 48.96, depending on their colour. The nontarget letters in the stream could be blue, yellow, aqua, magenta, orange, or green.

The RSVP stream was 16 letters long and the red target letter appeared randomly and approximately equally often in positions 4, 5, 6, 7, or 8. The enumeration display appeared randomly and approximately equally often at lags of from 0 to 400 ms (i.e., either simultaneously with the red target letter or 1, 2, 3, or 4 letters later).

Design and procedure. Participants were instructed that after the stimulus stream was completed they were to report the red letter in the stream by pressing the appropriate key on the computer keyboard, and to then indicate how many green dots had been presented by pressing the appropriate key on the numerical keypad. There were 10 practice trials followed by 10 blocks of 64 trials each. Within blocks, trials were random with respect to numerosity, serial position of the red target, and lag. See Figure 1 for an illustration of the displays and timing used on a trial.

Results

To show that subitizing was possible during a dual-task with our stimuli, we examined performance separately at lag 4, as any impairment caused by AB should be greatly diminished by this point. An ANOVA on the numerosities from 0 to 3 showed no significant effect of number, $F(3, 69) = 1.32$, $p > .1$. An ANOVA on the numerosities from 0 to 4 showed a significant effect of number, $F(4, 92) = 8.81$, $p < .001$. An analysis of selected contrasts showed this effect was largely driven by the difference between 3 and 4, $F(1, 23) = 7.6$, $p = .011$.

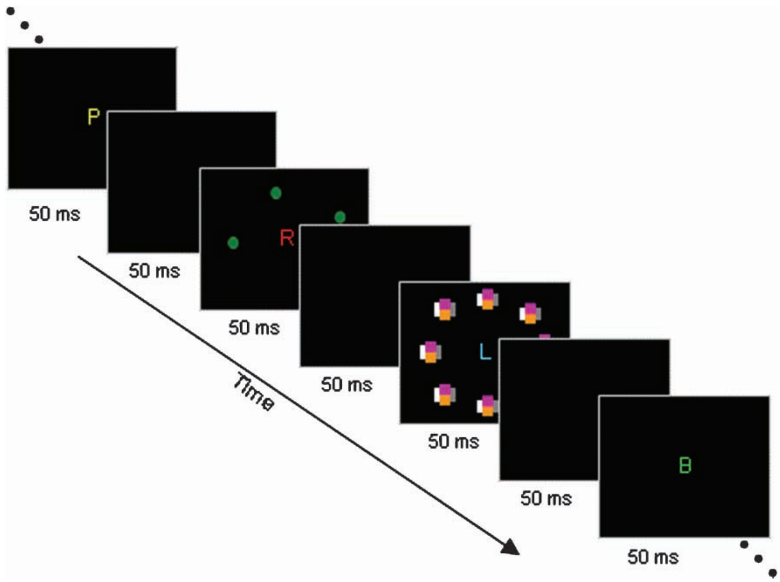

Figure 1. A portion of a complete trial from Experiment 1. In this example, both T1 and T2 occur simultaneously (lag 0). For other lags, the to-be-enumerated dots appeared in the same frame as a distractor letter. The frames in the RSVP stream, such as those containing a letter, the to-be-enumerated dots (or both, as above), and mask, appear for 50 ms each and are always followed by an ISI of 50 ms. While similar in appearance, the actual mask contained 24 individual coloured splotches, one at each target location. To view this figure in colour, please see the online issue of the Journal.

For those trials on which letter identification was correct, Figure 2a shows accuracy of report of numerosity judgements as a function of lag collapsed into two groups, one including data from our subitizing range (0 to 3), and the other the higher numerosities (4 to 9). Analysis of variance (on the uncollapsed data) confirmed the unsurprising decline in accuracy as numerosity increased, $F(9, 207) = 279.86$, $p < .001$. Analysis of variance also

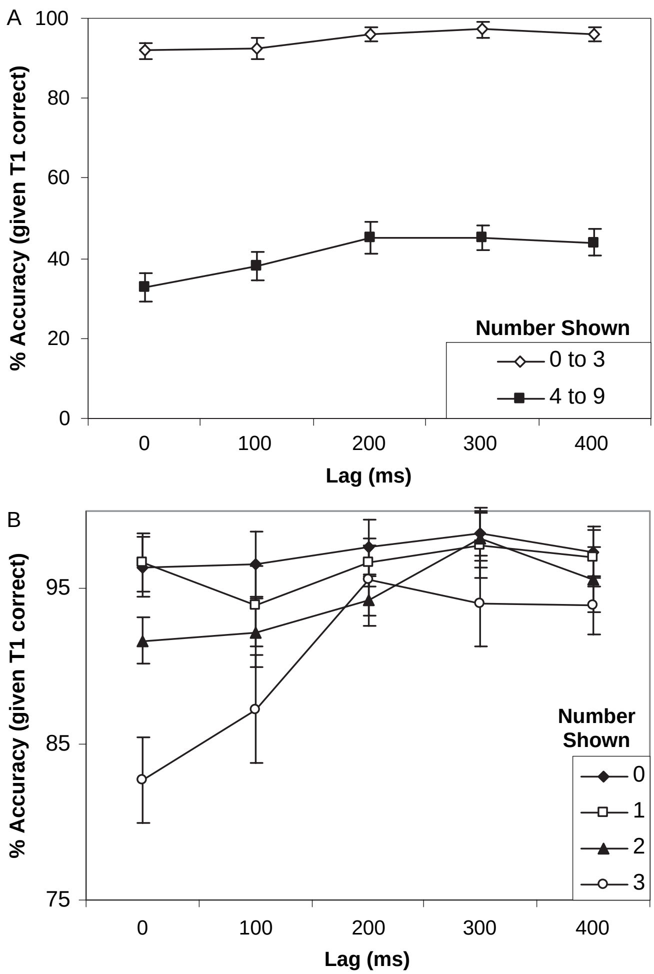

Figure 2. (A) Accuracy for the T2 enumeration task, given T1 correct, plotted as a function of lag. Data has been collapsed within the subitizing range (0–3) and above the subitizing range (4–9). Errors bars here and in other figures represent the standard error of the mean as calculated by the procedure suggested by Cousineau (2007) for a repeated-measures design. (B) Accuracy shown for each numerosity within the subitizing range.

showed a significant main effect of lag, $F(4, 92) = 24.80$, $p < .001$, and a significant interaction of lag and numerosity, $F(36, 828) = 1.892$, $p = .001$.

More detailed analyses were performed within the subitizing range of 0–3, which are plotted in Figure 2b. An ANOVA limited to those numerosities showed that the interaction between lag and numerosity was significant, $F(12, 276) = 2.53$, $p < .01$. That interaction was not significant in an ANOVA limited to the numerosities of 0 and 1, $F(4, 92) = 0.37$, $p > .05$. Finally, we determined whether there was an effect of lag at each level of numerosity. This analysis showed that for 0 and 1 dots there was no effect of lag. However, statistically significant effects of lag emerged for numerosities of 2 and greater. This pattern of results indicates increasing impairment for each additional object to be enumerated within the subitizing range.

Letter identification accuracy decreased somewhat with lag; for the lags 0, 1, 2, 3, and 4, respectively, the values were 0.97, 0.91, 0.91, 0.92, and 0.90, $F(4, 92) = 14.28$, $p < .001$. The effect of numerosity was significant, $F(9, 207) = 2.9$, $p < .003$, although a meaningful pattern is not obvious in the data. The interaction of numerosity and lag was not significant, $F < 1$.

Discussion

Along with the results of the Olivers and Watson study (2008 this issue), these data are among the first to show that enumeration of small numbers is under attentional control (see also Poiese, Spalek, & DiLollo, 2008), and suggest that there are capacity demands when as few as two items must be enumerated. This stands in contrast to the expectation from Trick and Pylyshyn (e.g., 1994) and Cowan (2000) that that the critical limit is four. It is an interesting question whether such a circumscribed capability deserves its own special label, i.e., subitizing.

It is not entirely clear how to interpret the finding that T1 accuracy gets worse with increasing lag. Most AB studies do not report T1 accuracy as a function of lag. Of those that do, some show that T1 is missed most often at the shortest lag (e.g., at lag 1 in Chun & Potter, 1995), while others show that T1 is missed least often at the shortest lag (e.g., lag 1 in Olivers & Watson, 2008 this issue). The basis of this difference is not yet known, and is beyond the scope of this paper.

Accuracy with 0 and 1 items in the display is so high in Experiment 1 that one might well suspect a ceiling effect, which might obscure an underlying dependence of performance on lag. Thus, in an effort to drive performance down, in Experiment 2 the targets were presented along with distractors. Several studies in the literature have reported that the presence of preattentively discriminable distractors (i.e., Treisman & Gelade, 1980) reduces the speed and/or accuracy of enumeration (e.g., Di Lollo, Kawahara, Zuvic, &

Visser, 2001; Folk, Egeth, & Kwak, 1988; Olivers & Watson, 2006; Trick & Pylyshyn, 1993). Note that according to the FINST model, even though overall performance may be reduced by the presence of distractors, as long as those distractors are preattentively discriminable from the targets, evidence of subitizing should still be obtained (e.g., Trick & Enns, 1997, p. 195).

EXPERIMENT 2

This experiment was identical to Experiment 1, with the exception that the ring of dots now contained distractors. Twenty-four subjects were again asked to enumerate the number of green dots (N) presented on a trial (which varied from 0–9), but the remaining locations (24–N) contained white dots (luminances were 9.27 cd/m^2 for green dots and 14.4 cd/m^2 for white dots).

Results and discussion

The presence of distractors clearly impacted performance overall. Importantly, accuracy for 0 and 1 was significantly reduced from 96% and 97% in Experiment 1 to 85% and 87% in Experiment 2, which is well below "ceiling".

Figure 3a reports accuracy as a function of lag collapsed into two groups (subitizing range and above), for those trials when letter identification was correct. Once again, analysis of variance (on the uncollapsed data) confirms a decline in accuracy as numerosity increases, $F(9, 207) = 261.44$, $p < .001$. Analysis of variance also shows a main effect of lag, $F(4, 92) = 9.67$, $p < .001$, and a significant interaction of lag and numerosity, $F(36, 828) = 1.89$, $p = .001$. We then examined whether there was a significant effect of lag at each level of numerosity. Performance for each numerosity in the subitizing range is plotted individually in Figure 3b. Statistically significant effects of lag emerged for 2, 3, and 4 dots. Additionally, as performance reached low overall levels of accuracy for 5 or more dots the effect of lag was eliminated, presumably due to a floor effect. Critically, this analysis shows that for the enumeration of 0 and 1 dots there was no effect of lag.

Letter identification accuracy once again was better for shorter lags, $F(4, 92) = 140.7$, $p < .001$. The effect of numerosity and the numerosity by lag interaction were not significant, $p > .05$.

ANCILLARY EXPERIMENT

We conducted another experiment designed to reduce performance below ceiling for 0 and 1 items. Twenty-four subjects were tested in a design that was identical to that of Experiment 1 (no distractors) except that target

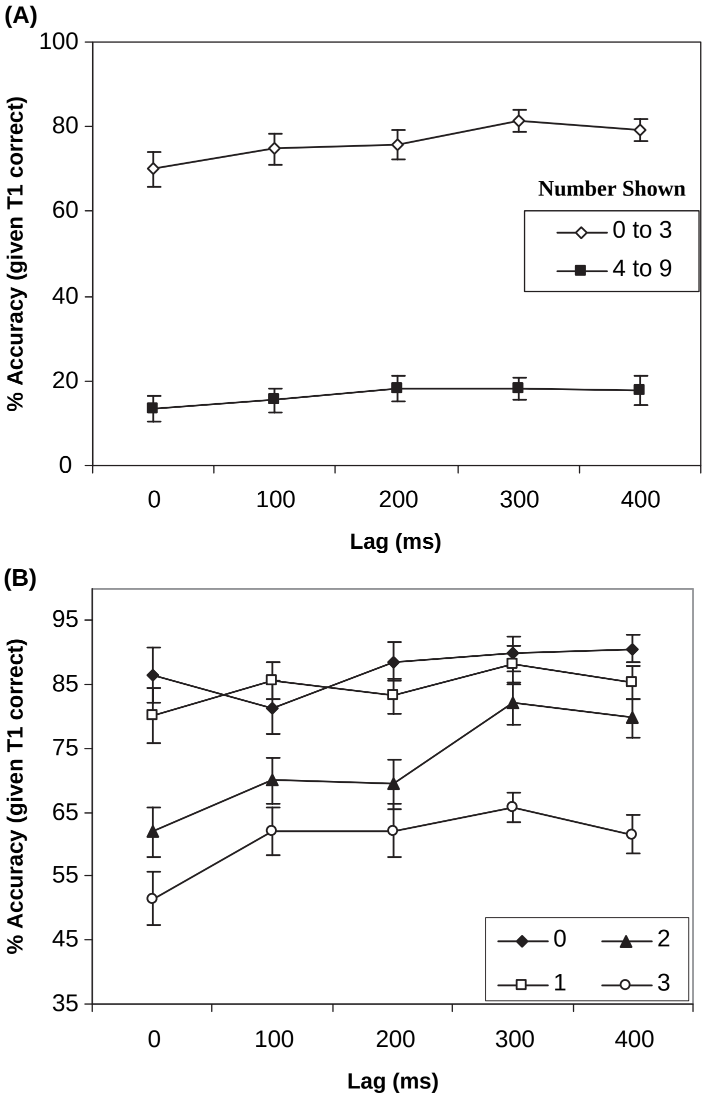

Figure 3. (A) Accuracy for T2 enumeration task, given T1 correct, for Experiment 2, in which distractors where intermixed with to-be-enumerated items. Shown as a function of lag, once again collapsed within the subitizing range (0 to 3) and above (4 to 9). (B) Accuracy shown for each numerosity within the subitizing range.

luminance was reduced from 31.52 cd/m^2 to 0.17 cd/m^2. We were successful in driving performance below ceiling (accuracy was 91% and 87% for 0 and 1, respectively) and yet again there was an effect of lag for 2 or more dots, but not for 0 or 1.

GENERAL DISCUSSION

Our results suggest that attentional processes, above and beyond general task demands, are necessary to enumerate accurately within the subitizing range. Similar to Olivers and Watson (2008 this issue), we reached this conclusion by showing impairments in enumeration during the AB. Further, these data point to a marked discrepancy within the range of numerosities often referred to as the subitizing range. For the stimuli we used, the enumeration of a single item is unaffected by the AB, but enumeration of as few as two or three items is impaired during the AB. Over several decades estimates of the "magical number" have varied from 7 (Miller, 1956) to 4 (Cowan, 2000). In the absence of attention, the present data and those of Olivers and Watson (2008 this issue) suggest that, if there is a magical number, it is 1.

The basic effects we have described would appear to be quite robust. We have shown that the results obtain when the target items are alone in the field or are accompanied by preattentively discriminable distractors, and when target luminance is varied by a factor of 185. Robustness is further suggested by the fact that the pattern of results was unaffected by the large number of differences in methodological details between our studies and those of the independently conceived studies of Olivers and Watson (2008 this issue). These include differences in the sizes and colours of stimuli, lags, presentation rates, and spatial organizations of the to-be-enumerated elements. Also, for our subjects the target in the first task was a letter of a specific colour in a stream of heterogeneously coloured letters, whereas for Olivers and Watson the target letter differed in colour from the other letters in a homogeneously coloured stream. This latter design permits the use of singleton detection mode, whereas the former does not (e.g., Folk, Leber, & Egeth, 2002).

Our results and those of Olivers and Watson (2008 this issue) show that the attentional blink has a more pronounced effect the greater the number of items to be enumerated, even in the subitizing range. This indicates that subitizing is not solely a fixed-capacity parallel process as in the models proposed by Trick and Pylyshyn (e.g., 1994) and by Cowan (2000). It is not clear exactly what aspects of these models would need to be changed for them to accommodate our data. It might be that there are fewer FINSTs or short-term memory slots available when attentional capacity is stressed in the AB paradigm. Alternatively, there might be four available but a rapid serial process may be required to gain access to them for enumeration. For a more detailed discussion of models of enumeration and subitizing, see Olivers and Watson, 2008 this issue.

Discriminating between 0 and 1, the simplest case of enumeration, is also the fundamental task involved in discriminating an object's presence from its absence. In this connection it is interesting to note just how strikingly different our results are from those of Joseph, Chun, and Nakayama (1997). They used an attentional blink paradigm in which the second task was to indicate if a ring of Gabor patches was uniform in orientation or whether one patch was misoriented by 90°. Preliminary data from a visual search task suggested that preattentive processing should obtain. Nevertheless, they found a very marked attentional blink. While on the face of it a detection task is quite different from an enumeration task, it does not take a great leap of the imagination to see some important underlying similarities. Why is it that subjects suffer no blink when they indicate whether there is a single green dot present among white dots, but do suffer a (severe) blink when they indicate whether or not there is one misoriented Gabor patch? This particular question may be subsumed by a broader question: Which kinds of information survive the attentional blink and which do not? (For other examples of information surviving the attentional blink see, e.g., Ghorashi, Di Lollo, & Klein, 2006; Maki, Frigen, & Paulson, 1997) This promises to be a fruitful topic for further investigation.

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