Cognition 124 (2012) 107–116

Contents lists available at SciVerse ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Intentional subitizing: Exploring the role of automaticity in enumeration

Hannah L. Pincham *, Dénes Szűcs *

Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, United Kingdom

ARTICLE INFO

Article history:
Received 2 September 2011
Revised 14 February 2012
Accepted 10 May 2012

Keywords:
Automaticity
Enumeration
Counting
Subitizing
Magnitude representation
Numerical cognition

ABSTRACT

Subitizing is traditionally described as the rapid, preattentive and automatic enumeration of up to four items. Counting, by contrast, describes the enumeration of larger sets of items and requires slower serial shifts of attention. Although recent research has called into question the preattentive nature of subitizing, whether or not numerosities in the subitizing range can be automatically accessed is yet to be empirically tested. In the current study, participants searched for two pre-defined digits in a circular visual-search array. Distractor dots of various set sizes were placed at the centre of the array. Despite the relevance of the distractor numerosities to the target detection task, the distractors did not influence target detection, thereby suggesting that their numerosities were not automatically accessed in Experiment 1. In Experiment 2, participants were explicitly instructed to enumerate the distractor dots. Here, congruent and incongruent distractor numerosities influenced the target detection task, thereby revealing that the distractor dots were capable of generating interference. Experiment 3 ensured that dots were attended by asking participants to detect the luminance of dots. Data confirmed that subitizing was not automatic. The present study also supported the alleged discontinuity between the subitizing and counting ranges because an examination of reaction time gradients in Experiment 2 found the counting gradient to be significantly steeper than the subitizing gradient. In sum, the results suggest that subitizing is a distinct but non-automatic style of enumeration.

1. Introduction

The enumeration of visual stimuli appears to be underpinned by two distinct psychological processes. Although lay understandings of numerical cognition suggest that children are explicitly taught to "count" three images on a page, psychological research dictates that *counting* is a process reserved for the enumeration of more than four objects. By contrast, enumeration of four or fewer objects is referred to as *subitizing* (Chi & Klahr, 1975; Kaufman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982). The distinction between subitizing and counting has been motivated by the finding that people almost instantly access the numerosity of displays containing four or fewer items, implying that the numerosity is automatically available without the need for a serial individuation of each item (Trick & Pylyshyn, 1993, 1994). Reaction times (RTs) are typically flat or reveal a shallow gradient as the number of display items increase across the subitizing range (Akin & Chase, 1978; Chi & Klahr, 1975; Jensen, Reese, & Reese, 1950; Mandler & Shebo, 1982; Piazza, Mechelli, Butterworth, & Price, 2002; Sathian et al., 1999; Trick & Pylyshyn, 1994). When displays contain more than four items, enumeration is not automatic and participants must index each item individually in a step-by-step manner. RT gradients are consequently much steeper in the counting range, creating a discontinuity between the subitizing and counting ranges (Jensen et al., 1950; Mandler & Shebo, 1982; Saltzman & Garner, 1948). Interestingly, subitizing is not limited to the enumeration of visual objects by adults, but exists in auditory and tactile domains (Camos & Tillman, 2008; Plaisier, Bergmann Tiest, & Kappers, 2009;

* Corresponding authors.
E-mail addresses: hlp31@cam.ac.uk (H.L. Pincham), ds377@cam.ac.uk (D. Szűcs).

0010-0277/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.cognition.2012.05.010

Riggs et al., 2006), and occurs in pre-verbal infants and animals (Davis & Perusse, 1988; Spelke, 2000; Starkey & Cooper, 1980). Some researchers argue that counting and subitizing are phenomenologically distinct processes because subitizing reflects a preattentive, automatic process that proceeds via parallel processing whereas counting is a more attentionally demanding, conscious mechanism that implicates serial processing (Trick & Pylyshyn, 1993, 1994). The current study focused on investigating the role of automaticity in subitizing.

One of the most popular explanations of enumeration – the fingers of instantiation (FINST) hypothesis – presumes that subitizing occurs, at least in part, via automatic, preattentive mechanisms (Trick & Pylyshyn, 1993, 1994). FINST is rooted in the notion that the visual system is capable of indexing up to four objects before capacity limitations ensue. According to this hypothesis, four FINSTs can be 'attached' to four objects, individuating the objects across space. This process is both goal driven and data driven: it is *automatically* driven by stimuli in the visual field, but is also influenced by the individual's intentions and goals. In other words, aspects of subitizing (for example, the parallel attentive and token indexing stages) are automatic, yet enumeration itself is a deliberate process – people do not automatically enumerate everything that they perceive (Trick & Pylyshyn, 1994). The FINST hypothesis suggests that enumeration of small numbers is rapid because objects are tagged in parallel and the participant simply has to report the number of FINSTs that are bound at that time. Enumeration of more than four items necessitates slower shifts of spatial attention because FINSTs must be serially connected, disconnected, and re-connected until all objects have been tagged and counted. The current study was interested in exploring the nature of automatic processing within subitizing.

Although the role of automaticity in subtizing has not been previously explored, recent research has challenged the notion of subitizing as a preattentive process (Burr, Turi, & Anobile, 2010; Egeth, Leonard, & Palomares, 2008; Olivers & Watson, 2008; Poises, Spalek, & Di Lollo, 2008; Railo, Koivisto, Revonsuo, & Hannula, 2008; Vetter, Butterworth, & Bahrami, 2008; Xu & Liu, 2008). These studies have revealed that attentional demands increase with increasing numbers of to-be-enumerated stimuli, even in the subitizing range. For example, a few experiments have incorporated a subitizing task into the attention blink paradigm in order to explore the relationship between subitizing and attention (Egeth et al., 2008; Olivers & Watson, 2008; Xu & Liu, 2008). The attentional blink describes a deficit in detecting the second of two targets when the second target appears within 500 ms of the first target (Raymond, Shapiro, & Arnell, 1992). Accuracy is poor for this second target because attentional resources are unavailable (Chun & Potter, 1995; Shapiro, Raymond, & Arnell, 1994). If subitizing proceeds preattentively then enumeration should be accurate even when a subitizing task is inserted into the attentional blink paradigm during periods of reduced attentional capacity. However, the empirical evidence counters this logical suggestion. Specifically, the enumeration of small numerosities was found to be significantly delayed or suffered reduced accuracy inside the attentional blink period, hence implicating attention as a critical requirement for subitizing (Egeth et al., 2008; Olivers & Watson, 2008; Xu & Liu, 2008). Given the challenges to the preattentive nature of subitizing, and considering the connection between attention and automaticity, we suggest that the assumption of automaticity within subitizing may also be problematic.

Automaticity evades a precise theoretical definition. Numerous descriptions of automatic processing have been suggested, including processing that occurs without conscious control, intention or awareness (Logan, 1988; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In addition, formal definitions of automaticity have been provided by a number of authors (Gibson, 1969; LaBerge, 1973; Logan, 1992; Treisman, Vieira, & Hayes, 1992). Automaticity can be contrasted with processing that is conscious, effortful, intended and controlled. Automatic processing is frequently equated with preattentive processing, and empirical evidence for interactions between the two mechanisms suggest that they are related mechanisms at minimum, and 'different sides of the same coin' at maximum (Logan, Taylor, & Etherton, 1999). Further, Bargh and Chartrand (1999) suggest that preattentive processing is one of the 'major strains' of automaticity. However, while preattentive and automatic processes are related (primarily because they can both occur in the absence of attention), the processes are not identical. For example, the way in which automatic and preattentive processes become independent of attention differs (Treisman et al., 1992). The recent challenge to subitizing as a preattentive process, and the link between preattentive processing and automaticity, suggests that it is prudent to explicitly examine the status of subitizing as an automatic process. Given the similarities between preattention and automaticity, it may be the case that subitizing is not automatic because it is not preattentive. Conversely, the dissociability between these processes means that aspects of subitizing may proceed automatically, but not preattentively.

It is important to note that the current study does not seek to explore whether enumeration proceeds automatically – irrespective of context. It would be unwise to assume that people constantly and persistently enumerate every visual object that they encounter. Similarly, the FINST hypothesis does not suggest that subitizing (or enumeration more generally) is absolutely automatic. While FINST argues that up to four items can be indexed automatically, the mapping of numerosity to number names is not presumed to be automatic but requires a controlled, conscious intention. The current study therefore asked whether the numerical value of a group of dots would be automatically accessed when participants performed a number detection task but were not asked to name the number of dots. In other words, we asked whether numerical value would be accessed when the contextual conditions were highly conducive to such numerical access.

This study required participants to search a circular visual search array and detect whether the Arabic digit "3" or "7" was present. In this manner, "3" and "7" served as targets. The task was designed so as to include one target from the subitizing range and one from the counting range. Distractor stimuli were presented in the centre of the search array and consisted of either two, three, six or seven dots. Distractors were located at fixation in order to ensure that they were positioned within participants' visual fields. If subitizing proceeds automatically, presentation of the three-dot distractor should influence responding by speeding RTs on congruent target-3 trials and slowing RTs on target-7 trials (Henik & Tzelgov, 1982; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Soltesz, Szűcs, & Szűcs, 2010; Soltesz, White, & Szűcs, 2011; Szűcs, Soltesz, Jarmi, & Csepe, 2007). According to our assumptions, enumeration of numerosities in the counting range should not proceed automatically. Therefore, we did not expect to see interference from seven-dot distractors. The neutral two-dot and six-dot distractors were employed in order to prevent participants from anticipating the three or seven dot distractors (the two-dot and six-dot distractors were neutral because '2' and '6' were not target stimuli). Two and six dots were also chosen because they are each very close to the target digits, and fall within the subitizing and counting ranges respectively. Inclusion of the neutral distractors saw that we were able to calculate a gradient for the subitizing range distractors (the gradient between two-dot and three-dot distractor trials) and for the counting range distractors (the gradient between six-dot and seven-dot distractor trials).

We also manipulated attentional load in this study (see Vetter et al., 2008). On high load trials, the target digit was presented amongst numerous different visual-search stimuli whereas the target appeared amongst a single repeated stimulus on low load trials. The perceptual load theory predicts that interference should only occur on low load trials, where attentional resources are available, and not on high load trials where attentional resources are taxed (Lavie, 1995; Lavie & Tsal, 1994). However, if subitizing is preattentive then interference should occur across both high and low loads. Because recent research suggests that subitizing is not preattentive but requires attentional resources, we predicted that interference would be restricted to low load trials, where attentional resources are available to process the distractor dots. In sum, the current experimental design allowed us to investigate three main issues: whether subitizing proceeds automatically, whether subitizing is preattentive, and whether the subitizing and counting gradients are statistically distinct.

2. Experiment 1

Experiment 1 was primarily designed to investigate whether the numerosity of dots in the subitizing range can be automatically accessed, and cause interference on a numerical target detection task. If activation of the numerosity is automatic, it should interfere with target detection due to congruent and incongruent relationships between the target and distractor numerosities. As discussed in Section 1, this experiment did not ask about the automaticity of enumeration in general (under *any* circumstances), and did not presume that the FINSTs would be automatically mapped to number names. For this reason, we did not ask participants to name the number of dots.

2.1. Materials & method

2.1.1. Participants

Nineteen graduate students from the University of Cambridge were compensated £7 for their participation. All participants reported normal or corrected-to-normal vision. The participants (five males) were 18–30 years old. Participants provided informed, written consent before taking part in this experiment. Ethical approval was provided by the Psychology Research Ethics Committee of the University of Cambridge.

2.1.2. Stimuli and apparatus

The experiment was presented on a 17 in. Apple LCD monitor. Visual stimuli were generated using Presentation (Neurobehavioural Systems). All stimuli were presented in black on a white background. Targets were the digits "3" and "7". Non-target visual search stimuli were comprised of the following digits, letters and symbols: 1, 2, 4, 5, 6, 8, 9, 0, A, P, C, X, E, R, H, S, ?, £, &,%, #, =. Stimuli were shown in 'Verdana' font, and subtended a visual angle of 0.6° vertically and 0.4° horizontally assuming a viewing distance of 57 cm. Distractors were images of two, three, six or seven black circular dots. The visual angle diameter of each dot was 0.3°. Three different physical arrangements of dots were created for each of the four distractor set sizes.

2.1.3. Design and procedure

On each trial, a fixation cross (0.4° × 0.4°) was presented in the centre of the monitor for 500 ms. A circular visual search array positioned around the centre of the monitor was then displayed for 150 ms. The search array consisted of eight items located at equidistant intervals around an imaginary circle (diameter 5°). On each trial, only one of the target numbers (3 or 7) appeared in the visual search array. The remaining seven items in the array were either a single repeated item (in the low load block), or seven distinct items (in the high load block). The identities of these non-target items were randomly allocated on each trial. The positions of the stimuli around the imaginary circle were randomised. The distractor dots appeared at the centre of the visual search circle. The set size of the distractor dots was either within the subitizing range (two dots or three dots) or outside the subitizing range (six dots or seven dots). As mentioned in Section 2.1.2, three different versions were created for each of the four distractor set sizes. Additionally, trials with no distractor dots were employed to collect baseline RTs. Within each block, the combination of each target with each of the five distractor conditions was employed with equal frequency. The particular version of the distractor employed was randomised.

On each trial, participants were asked to identify, as quickly as possible, whether "3" or "7" was present on that trial. Participants were instructed to maintain fixation at the centre of the visual search array. In keeping with the mental number line, participants pressed the left ALT key if the target "3" was present and the right ALT key if the target "7" was present. Participants had a maximum of 2000 ms to make their response before the next trial began. Visual feedback was provided using "Correct" or "Incorrect" screens that lasted for 2000 ms.

The experiment contained two blocks (one low load block and one high load block) of 120 trials each. The order of the blocks was counterbalanced across participants. Additionally, the order of trials within each block was randomised. Each block was preceded by ten practice trials, during which time the experimenter was present. Testing occurred individually in a sound-attenuating booth. Fig. 1 shows example stimulus displays.

2.1.4. Data analysis

Reaction times from correctly responded trials were analysed. For each participant, scores more than three standard deviations from mean were excluded as outliers. The current investigation necessitated that different combinations of target and distractor identities be used across conditions. As a result, we were unable to counterbalance target identities across conditions. That is, the target "3" was exclusively a subitizing range target and the target "7" was exclusively a counting range target. To avoid any confusion associated with this inability to counterbalance, we took into account baseline target detection speed by calculating difference scores with the no-distractor trials. For example, the dependent variable on high load/target-3/two-dot trials was calculated by subtracting the average RT on high load/target 3/no-distractor trials from that on high load/target-3/two-dot trials. Consequently, all data reported here are difference scores. The data were initially subjected to a repeated-measures ANOVA with load (high vs. low), target identity (3 vs. 7) and distractor identity (two vs. three vs. six vs. seven) as within subjects factors.

We additionally compared the magnitude of the slope in the subitizing range to that in the counting range. To achieve this, we calculated the gradient between RTs on the two-distractor trials and the three-distractor trials (subitizing gradient), and between RTs on the six-distractor trials and the seven-distractor trials (counting gradient). The data were entered into a repeated-measures ANOVA with gradient type (subitizing vs. counting) and target-identity (3 vs. 7) as within-subjects factors.

2.2. Results and discussion

No effects of load emerged ($F < 1$), so the data were collapsed across high and low load blocks. Only the target main effect reached statistical significance, indicating that distractors in the target-3 condition (indicated by the dashed lines in Fig. 2) slowed RTs more than distractors in the target-7 condition (indicated by the dotted lines in Fig. 2) ($F(1,18) = 5.935$, $p = .025$, $\eta^2 = .248$). Notably, this RT difference occurred even when the baseline speed of detecting "3" or "7" was factored out through the use of difference scores. Therefore, the addition of distractor dots to a target-3 trial slowed baseline responding more so than the addition of distractor dots to a target-7 trial. Given the need to employ specific targets from the subitizing and counting ranges, it was unfortunately not possible to counterbalance target identities.

Interestingly, RTs did not differ across the four distractor conditions and no interactions with distractor condition emerged (Fs < 1). In other words, the distractor dots did not generate interference as hypothesised. There are two possible reasons why the anticipated RT differences did not occur. First, numerical access to the subitizing range may not proceed automatically. In fact, recent challenges to the preattentive nature of subitizing suggest that a challenge to automaticity is not unwarranted. Alternatively, distractor dots may be incapable of *ever* generating interference in a numerical target detection task. This second possibility was explored in Experiment 2 where participants were instructed to identify the distractor dots' numerosity.

Finally, no differences were found between the magnitude of the subitizing gradient and the counting gradient ($F < 1$). The absence of a difference between the two gradients may be taken to reflect a continuum (rather than a dissociation) across the subitizing and counting ranges. However, it is more likely that the distractor dots were not processed (automatically or otherwise), such that any comparison across the subitizing and counting ranges is futile. Experiment 2 explicitly asked participants to enumerate the distractor dots, thereby enabling a proper comparison of the subitizing and counting range gradients.

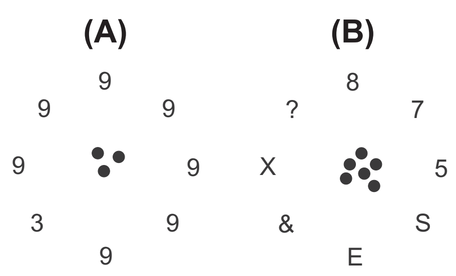

Fig. 1. Example stimulus displays. (A) displays a low load, congruent trial (target-3 and three distractor dots). (B) displays a high load, neutral trial (target-7 and six distractor dots). All combinations of load, target identity and distractor identity were employed in this study.

3. Experiment 2

Experiment 2 reacted to the finding that the distractor dots did not interfere with the target detection task in Experiment 1. We therefore questioned whether distractor dots are *ever* able to influence RTs in this paradigm. To that end, this experiment was identical to Experiment 1 with one exception; participants were requested to verbally enumerate the distractor dots after they responded to the target detection task. If the distractor dots successfully generate interference in this task, the absence of interference in Experiment 1 cannot be due to the distractor dots' inability to influence RTs. Instead, the absence of interference in Experiment 1 is likely because numerical access to the subitizing range was not automatic.

3.1. Materials & method

3.1.1. Participants

Nineteen graduate students from the University of Cambridge who had not participated in Experiment 1 were

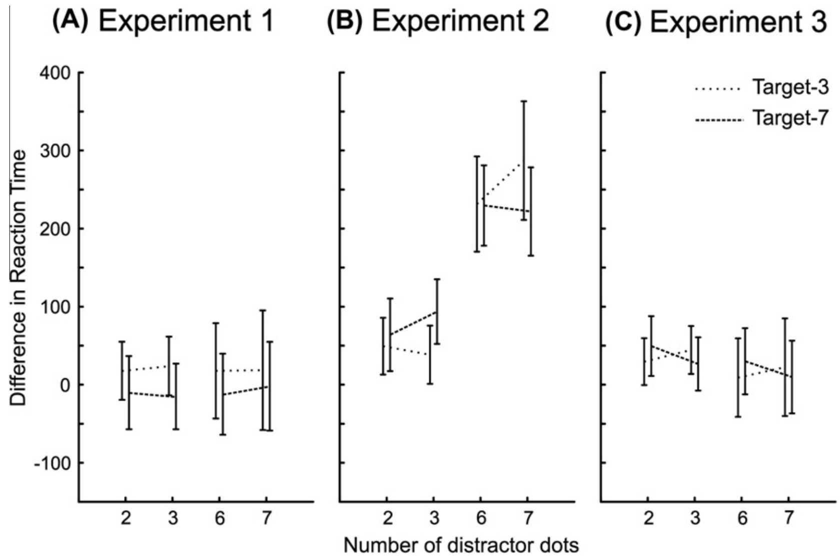

Fig. 2. RT difference scores for the two target identities (target-7 and target-3) and the four distractor dot numerosities (two, three, six and seven). (A) displays data from Experiment 1: possible attention to distractors, no intention to enumerate. (B) displays data from Experiment 2: attention to distractors, intention to enumerate. (C) displays data from Experiment 3: attention to distractors, no intention to enumerate. Interference only occurred in Experiment 2, and only on the three-dot and seven-dot distractor trials. Error bars display 95% confidence intervals.

compensated £7 for their participation. All participants reported normal or corrected-to-normal vision. The participants (six males) were 18–30 years old. Participants provided informed, written consent before taking part in this experiment. Ethical approval was provided by the Psychology Research Ethics Committee of the University of Cambridge.

3.1.2. Design and procedure

This experiment was identical to Experiment 1 except for the requirement to enumerate the distractor dots. In this experiment, participants verbalised the number of dots presented at fixation after making their target detection response. An experimenter located outside the booth listened to ensure that participants were verbally enumerating. Participants were still instructed to respond to the targets as quickly as possible, but the verbal responses were not recorded. Data analysis was as per Experiment 1.

3.2. Results and discussion

As in Experiment 1, the data were collapsed across high and low load blocks because no significant load effect emerged ($F < 1$). In this experiment, RTs were influenced by the type of distractor stimulus and the specific combination of target and distractor identities (distractor main effect: $F(3,54) = 14.817$, p<.001, $\eta^2 = .452$; interaction effect: $F(3,54) = 4.976$, $p = .004$, $\eta^2 = .217$). In other words, the distractor dots successfully generated interference in Experiment 2. Fisher's LSD post hoc comparisons were used to probe the significant interaction effect. Specifically, RTs on target-3 trials were compared with RTs on target-7 trials for each of the four distractor conditions. This investigation confirmed that the neutral distractors did not interfere with responding, regardless of whether the numerosity of those neutral distractors was inside the subitizing range (two-dots: $p = .517$) or inside the counting range (six-dots: $p = .936$). Interestingly, both the three-dot and seven-dot distractors caused strong interference on the target-detection task. Detection of the number "3" was faster when the distractor was a congruent three-dots distractor ($p = .017$). Conversely, detection of the number "7" was faster with a congruent seven-dots distractor ($p = .005$). Experiment 2 clearly reveals that distractor dots are capable of interfering with the target detection task, thereby suggesting that the absence of interference in Experiment 1 was due to the null requirement for enumeration. The finding that only the three-dot and seven-dot distractors generated interference in Experiment 2 is useful because it indicates that participants were able to differentiate between the numerosities of the distractor dots – if participants were unable to distinguish the numerosities, the distractor dots should have caused generalised, rather than specific, interference. Experiment 2 further suggests that participants enumerated the dots accurately because interference was contingent on the numerosity of the distractor dots being congruent or incongruent with the target.

Analysis of the gradients revealed that the gradients did not differ on average according to target identity or range (Fs < 1). However, gradients were influenced by specific combinations of range and target identity ($F(1,18) = 8.985$, $p = .008$, $\eta^2 = .333$). Fisher's LSD post hoc comparisons confirmed that, on trials where target identity was "3", the subitizing range gradient was significantly smaller than the counting range gradient ($p = .014$). By contrast, when target identity was "7", gradients did not differ between the subitizing and counting ranges ($p = .145$). The distractors were arguably responsible for the gradients differing on target-3 trials but not on target-7 trials. For target-3 trials, the typically small subitizing gradient would have been further reduced because congruent three-dot distractor trials speeded RTs, making RTs on two-dot and three-dot trials more similar to one another. The large counting range gradient would have been further enhanced on target-3 trials as incongruent seven-dot distractors slowed RTs further. Consequently, the gradients across the subitizing and counting ranges would have become more different from one another in the target-3 trials. The opposite pattern was true for target-7 trials: the small subitizing gradient would have been enhanced by incongruent interference and the large counting gradient would have been reduced by congruent interference, making the subitizing and counting gradients more similar to one another.

4. Experiment 3

Experiments 1 and 2 collectively suggest that participants accessed the distractor dots' numerical values only when there was an explicit intention for enumeration. However, it is important to rule out alternative interpretations of these findings. For example, although we argue that attention was directed towards the distractor dots in Experiment 1 (given their location at fixation – see Section 1), we cannot guarantee that the distractors were attended in that experiment. It is therefore possible that participants failed to access the distractors' numerical values in Experiment 1 due to inattention, and not due to the null requirement for enumeration. Importantly, interference would not be expected by unattended items because attention is required for subitizing to occur (Egeth et al., 2008; Olivers & Watson, 2008). Experiment 3 was therefore conducted to test whether the distractor dots would generate interference when attention was explicitly directed towards those dots, but there was no intention to enumerate them.[1]

To achieve this aim, Experiment 3 was identical to Experiment 2 with one exception; the distractor dots appeared in either a light grey colour or a dark grey colour and participants were asked to verbally assess the dots' luminance. Attention to the distractor dots was hence required for successful completion of the task. The three experiments in the current study therefore captured the range of attention and enumeration combinations: Experiment 1 (possible attention, no intention to enumerate), Experiment 2 (attention, intention to enumerate), Experiment 3 (attention, no intention to enumerate). If the distractor dots fail to generate interference in Experiment 3 (despite being attended), this task will provide novel evidence against the automaticity of subitizing. In other words, this study will reveal that numerical access – even for attended items within the subitizing range – requires an intention to enumerate. On the other hand, if the distractor dots generate interference as per Experiment 2, this study will not speak to the role of automaticity in subitizing, but will support the necessary role of attention in enumeration as previously reported (for example Egeth et al., 2008; Olivers & Watson, 2008).

4.1. Materials & method

4.1.1. Participants

Twenty-eight young adults from the University of Cambridge community who had not participated in Experiments 1 or 2 were compensated £7 for their participation. All participants reported normal or corrected-to-normal vision. The participants (seven males) were 18–30 years old. Participants provided informed, written consent before taking part in this experiment. Ethical approval was provided by the Psychology Research Ethics Committee of the University of Cambridge.

4.1.2. Design and procedure

This experiment was identical to Experiment 2 except for the following changes: participants were required to identify the luminance of grey distractor dots (light or dark), and were not required to enumerate the dots. On each trial, the dots were either light or dark grey. No single trial contained a mixture of light and dark distractor dots. Participants were exposed to the light and grey luminances before the experiment began. As in Experiment 2, participants made a speeded target detection response by a button press. After making their speeded response, participants verbalised the luminance of the dots using the words "light" or "dark." Participants were asked to use the word "absent" for the no-distractor trials. An experimenter located outside the booth listened to ensure that participants were verbally identifying the shade of the dots. As in Experiment 2, participants were instructed to respond to the targets as quickly as possible, but their verbal responses were not analysed. Data analysis was as per Experiments 1 and 2.

4.2. Results and discussion

Similarly to Experiments 1 and 2, the data were collapsed across high and low load blocks because no significant effect of load emerged ($F < 1$). The data were additionally collapsed across the light and dark distractor dot trials because no significant effect of luminance emerged ($F < 1$). Despite attention being explicitly directed at the distractor dots in this experiment, the dots did not generate enumeration-related interference. Specifically, RTs did not differ across the four distractor conditions, nor did any interactions with distractor condition emerge (largest $F = 2.445$). Further, RTs did not differ across the two target conditions ($F < 1$). Finally, like Experiment 1, no differences were found between the magnitude of the subitizing gradient and the counting gradient (largest $F = 3.228$). This experiment therefore confirms that the numerical value of attended distractor dots was not accessed in the absence of an intention to enumerate. It is important to reiterate that the absence of interference in Experiment 3 cannot result from the distractors being unattended because participants were required to attend to those dots, and make a decision based on their physical appearance. Experiment 3 therefore confirms our claim –

[1] The authors thank Chris Olivers for this useful suggestion.

that access to numerical information within the subitizing range is not automatic, but requires an intention to enumerate.

4.2.1. Comparison across Experiments 1–3

In order to directly compare responding across the three experiments, a mixed ANOVA was employed with target identity (3 vs. 7) and distractor identity (two vs. three vs. six vs. seven) as within subjects factors and experiment as a between subjects factor. This analysis revealed differences in response speed across the three experiments ($F(2,63) = 19.386$, $p < .001$, $\eta^2 = .381$). Fisher's LSD post hoc contrasts confirmed that enumerating participants were generally slower to respond than non-enumerating participants (Experiment 1 vs. Experiment 2: $p < .001$; Experiment 2 vs. Experiment 3: $p < .001$). However, speed of responding across non-enumerating participants in Experiments 1 and 3 did not differ ($p = .334$). These findings are not particularly surprising because, even though enumerating participants were instructed to quickly respond to the target detection task as a first priority, the requirement to enumerate obviously interfered with their target detection performance. RTs also differed across distractor types (distractor main effect: $F(3189) = 13.190$, $p < .001$, $\eta^2 = .173$; distractor $\times$ group interaction: $F(6189) = 17.612$, $p < .001$, $\eta^2 = .359$; target $\times$ distractor interaction: $F(3189) = 2.857$, $p = .038$, $\eta^2 = .043$). Importantly, the three-way interaction was significant, confirming that distractor interference did not occur equally across the three experiments ($F(6189) = 3.819$, $p = .001$, $\eta^2 = .108$). Further probing of this interaction effect indicated significant differences in distractor interference across Experiments 1 and 2, and Experiments 2 and 3, but not between Experiments 1 and 3 ($F(3108) = 5.605$, $p = .001$, $\eta^2 = .135$; $F(3135) = 4.311$, $p = .006$, $\eta^2 = .087$; $F(3135) = 1.136$, $p = .337$, $\eta^2 = .025$ respectively). In other words, the between-experiment analyses confirmed that the numerosities of the distractor dots were only accessed in Experiment 2, when participants were explicitly required to enumerate the dots. As a result, it appears that numerical access to items within the subitizing range is not automatic.

To examine the influence of experiment on gradient magnitude, we subjected the data to an ANOVA with target identity (3 vs. 7) and range (subitizing vs. counting) as within subjects factors and experiment as a between subjects factor. Only the three-way target $\times$ range $\times$ experiment interaction attained statistical significance ($F(2,63) = 6.346$, $p = .003$, $\eta^2 = .168$). Like the between-experiment analysis reported above, further probing of this interaction revealed significant gradient effects between Experiments 1 and 2, and Experiments 2 and 3, but not between Experiments 1 and 3 ($F(1,36) = 9.969$, $p = .003$, $\eta^2 = .217$; $F(1,45) = 7.664$, $p = .008$, $\eta^2 = .146$; $F < 1$ respectively). These findings therefore confirm that the gradients differed across the subitizing and counting ranges for the enumerate participants (Experiment 2) but not the non-enumerate participants (Experiments 1 and 3). Again, these results indicate that the distractor dots only influenced performance when enumeration was required.

5. General discussion

The current study examined the role of automaticity in subitizing by presenting distractor dots within a numerical target detection task. The results suggested that accessing numerical information in the subitizing range is not automatic because the numerosity of the distractor dots was only accessed when participants were explicitly asked to enumerate those stimuli. Our study also contributed to the ongoing controversy concerning whether or not subitizing and counting are distinct phenomena. The current data suggest that the processes underpinning enumeration differ when two or three items are enumerated vs. six or seven items. This is because, under certain conditions, the RT gradients significantly differed across the subitizing and counting ranges.

Overall, data from the three experiments argue against the automatic access to numerical information by subitizing items. As mentioned in Section 4, it cannot be excluded that subitizing proceeded in an automatic fashion in Experiment 1, but the automatic processing effects were hidden because participants did not perceive the distractors. However, in our opinion, it is unlikely that the distractor dots were not perceived because they were positioned at fixation, in the centre of the visual search array. In that sense, even though the distractors may not have received covert attention, they would have fallen within participants' visual fields. Further, previous research indicates that distractors at fixation are perceived, and influence responding on a numerical target detection task – at least under low attentional load (Beck & Lavie, 2005). It therefore seems reasonable to argue that the distractor dots were perceived in Experiment 1, but their numerical value was not automatically accessed. However, any concerns about distractor perception are alleviated by Experiment 3. Here, the distractor dots were attended and perceived because participants were required to perform a visual judgment on those stimuli. This judgment task required attention because examples of light and dark luminances were not always present on the monitor, thereby preventing employment of a simple visual matching strategy.

The current results are not wholly inconsistent with the FINST hypothesis because FINST does not suggest that people always enumerate every object set that they encounter. However, FINST does posit that certain aspects of the subitizing process (the parallel attentive and token indexing stages) are automatic. Although the current study did not target specific sub-stages of the subitizing process, our data – along with findings that subitizing is not preattentive – point to the possibility that no aspects of subitizing are automatic. Additional research is required to confirm whether specific sub-stages of the subitizing process are preattentive and/or automatic.

While it was not our main goal to study the effects of the attentional load manipulation, given that prior research has successfully manipulated attentional load in a very similar numerical target detection task, it is interesting to question why no RTs differences were observed across the low and high load blocks. It is probably the case that the high load block was not difficult enough to sufficiently tax attentional resources and cause RT differences across the two blocks (see Experiment 1 in Forster & Lavie, 2008). Because the load manipulation did not appear to strain attentional resources, we were unable to examine whether subitizing can occur in the absence of attention. The weight of recent research strongly suggests that, in contrast to the predictions made by the FINST model, subitizing is not a preattentive mechanism, but relies on the availability of attentional resources (Burr et al., 2010; Egeth et al., 2008; Olivers & Watson, 2008; Poises et al., 2008; Railo et al., 2008; Vetter et al., 2008; Xu & Liu, 2008).

The accumulating evidence against subitizing's preattentive status bolsters our finding that subitizing numerosities were not automatically accessed in the current task. Despite the functional dissociations between automaticity and preattentive processing, the similarities between them are many (see Logan, 1992; Treisman et al., 1992). Hence, theoretically, it would not be particularly surprising for subitizing to be neither preattentive nor automatic. We provide empirical evidence for this theoretical position by demonstrating a lack of interference (and hence a lack of automatic subitizing) in Experiments 1 and 3. One could argue that the null result in Experiments 1 and 3 were due to a lack of power, and that interference may have emerged with a more powerful design. However, the analyses did not even approach statistical significance. Further, the between-experiment statistical comparisons indicated that strong interference can emerge in this task provided that participants have an intention to enumerate the distractor dots. This demonstrates that our experiments did possess enough statistical power to observe potential effects. Finally, even when participants explicitly attended to the distractor stimuli in Experiment 3, interference did not occur. At this stage, it is important to highlight that the current findings are distinct from previous work concerning the requirement for attention in subitizing (Egeth et al., 2008; Olivers & Watson, 2008). Our study indicates that, even when attention is directed towards enumerable stimuli, numerical information is not automatically accessed. As noted in Section 1, the FINST model does not suggest that subitizing automatically and consistently interferes with visual processing under all circumstances. It does, however, suggest that aspects of the subitizing process (the parallel attentive and token indexing stages) are automatic (Trick & Pylyshyn, 1994). In our opinion, if the automatic (and perhaps non-conscious) influences of subitizing were to emerge under any circumstances, they would be most apparent during a task that specifically required participants to focus on numerical information. Because the effects of subitizing were not obvious in this task in Experiments 1 or 3, we propose that access to numerical information in the subitizing range is neither preattentive nor automatic.

Experiment 2 confirmed that the lack of interference in Experiments 1 and 3 was not due to an insurmountable inability for interference in this task. In Experiment 2, a coherent pattern of data emerged because interference was not generated by the neutral distractors but was confined to trials on which the distractor dots were congruent or incongruent with the target stimulus. Specifically, when three-dot distractors appeared, RTs were slower for target-7 trials compared with target-3 trials. When seven-dot distractors appeared, the pattern was reversed: RTs were slower for target-3 trials. The specificity of the interference effect suggests that participants accurately enumerated the distractor dots. We anticipated that interference would only occur for the three-dot distractor trials, because three dots can be subitizied whereas seven dots must be serially counted. However, interference occurred for both three-dot and seven-dot distractors. This result indicates that participants attempted to balance the target detection and enumeration tasks, rather than reacting as quickly as possible to the target stimulus before directing their attention to the enumeration task. Slower RTs for the six and seven-dot distractor trials confirms this suggestion. As seven items cannot be subitized, we must ask how the seven-dot distractors generated interference. The fact that only three different configurations of each distractor dot numerosity were used may have enabled participants to map configurations to numerosities and apply a pattern-matching approaches to enumerate the dots (Logan and Zbrodoff, 2003). Further, participants' attentional sets (Folk, Remington, & Johnston, 1992) would have been tuned to process 'three' and 'seven' numerosities, and this may have seen that both three-dot and seven-dot distractors generated interference.

The final question posed by the current study concerned whether subitizing and counting are distinct processes, or at different ends of an 'enumeration continuum'. The existing evidence pertaining to this question is mixed (Balakrishnan & Ashby, 1991; Nan, Knosche, & Luo, 2006; Piazza et al., 2002; Watson, Maylor, & Bruce, 2007; Wender & Rothkegel, 2000). Fisher (1984) identifies that the number '4' has emerged as an important turning point in a range of phenomena including subitizing, visual search and iconic memory. Numerous subitizing experiments with neurologically intact participants, as well as single case studies support this dissociation (Dehaene & Cohen, 1994; Demeyere, Lestou, & Humphreys, 2010; Trick, Enns, & Brodeur, 1996). Additionally, patients with simultagnosia show a dissociation between their ability to subitize and inability to accurately enumerate in the counting range (Dehaene & Cohen, 1994). More recently, the discontinuity between subitizing and counting has been revealed for both visual and auditory modalities (Camos & Tillman, 2008). Using manipulations that differentially influence the subitizing and counting ranges, Trick (2008) argues that subitizing and counting are related but distinct processes. In spite of the body of work supporting a distinction between subitizing and counting, Piazza et al. (2002) employed positron emission tomography to reveal that activity in the extrastriate and parietal brain regions do not show dissociations but are modulated by numerosity along a continuum. Similarly, Balakrishnan and Ashby's (1991, 1992) large scale statistical reviews reject the notion that subitizing is a unique numerical ability. The competing views may be underpinned by the different methodologies used to investigate enumeration. For example, Haladjian and Pylyshyn (2011) asked participants to indicate the locations (rather than the numerosity) of briefly displayed discs. A comparison of the data obtained using this technique and the standard enumeration technique suggested that the turning point is six items with the new technique but only four items with the standard technique. Hence, if the subitizing limit changes with across methodologies, it is possible that the apparent existence of a discontinuity also changes with technique. The present study contributed to this debate using another novel examination method. Instead of using dots as target stimuli, we positioned the to-be-enumerated dots as distractors and measured RTs on a target detection task. Our data are suggestive of a discontinuity, at least for the target-3 trials, because the counting range gradient was significantly steeper than the subitizing range gradient.

5.1. Conclusions

To conclude, the current study reveals a number of important aspects of enumeration. In line with recent research addressing preattentive processing, access of numerical information in the subitizing range does not appear to proceed automatically. Subitizing requires an explicit intention to enumerate even when participants are operating in an environment that is conducive to enumeration, and even when participants explicitly attend to enumerable items. When participants intended to enumerate in the current task, congruent and incongruent distractor dots successfully generated interference. Further, the data supported the view that subitizing and counting are subserved by different mechanisms. We therefore suggest that subitizing is a distinct but non-automatic type of enumeration.

Acknowledgements

This research was funded by a Grant to DS from the Medical Research Council (G0900643), and a Gates Cambridge studentship to HP. The authors would like to thank Alison Nobes for her assistance in collecting data for these experiments.

References

Akin, O., & Chase, W. (1978). Quantification of three-dimensional structures. *Journal of Experimental Psychology: Human Perception and Performance, 4*, 397–410.

Balakrishnan, J., & Ashby, F. (1991). Is subitizing a unique numerical ability? *Perception and Psychophysics, 54*, 80–90.

Balakrishnan, J., & Ashby, F. (1992). Subitizing: Magical numbers of mere superstition? *Psychological Research, 50*, 555–564.

Bargh, J., & Chartrand, T. (1999). The unbearable automaticity of being. *American Psychologist, 54*(7), 462–479.

Beck, D. M., & Lavie, N. (2005). Look here but ignore what you see: Effects of distractors at fixation. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 592–607.

Burr, D., Turi, M., & Anobile, G. (2010). Subitizing but not estimation of numerosity requires attentional resources. *Journal of Vision, 10*(6), 20.

Camos, V., & Tillman, B. (2008). Discontinuity in the enumeration of sequentially presented auditory and visual stimuli. *Cognition, 107*, 1135–1143.

Chi, M., & Klahr, D. (1975). Span and rate of apprehension in children and adults. *Journal of Experimental Psychology, 19*, 434–439.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 21*(1), 109–127.

Davis, H., & Perusse, R. (1988). Numerical competence in animals: Definitional issues, current evidence, and a new research agenda. *Behavioural and Brain Scieneces, 11*, 561–615.

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

Demeyere, N., Lestou, V., & Humphreys, G. W. (2010). Neuropsychological evidence for a dissociation in counting and subitizing. *Neurocase, 16*(3), 219–237.

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

Fisher, D. L. (1984). Central capacity limits in consistent mapping, visual search tasks: Four channels or more? *Cognitive Psychology, 16*, 449–484.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 1030–1044.

Forster, S., & Lavie, N. (2008). Failures to ignore entirely irrelevant distractors: The role of load. *Journal of Experimental Psychology: Applied, 14*(1), 73–83.

Gibson, E. J. (1969). *Principles of perceptual learning and development*. New York: Appleton-Century-Crofts.

Haladjian, H., & Pylyshyn, Z. (2011). Enumerating by poitning to locations: a new method for measuring the numerosity of visual object representations. *Attention Perception and Psychophysics, 73*(2), 303–308.

Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relation between physical and semantic size in comparison tasks. *Memory and Cognition, 10*, 389–395.

Jensen, E., Reese, E., & Reese, T. (1950). The subitizing and coutning of visually presented fields of dots. *Journal of Psychology, 30*, 363–392.

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

LaBerge, D. (1973). Attention and the measurement of perceptual learning. *Memory and Cognition, 1*(3), 268–276.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 451–468.

Lavie, N., & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual-attention. *Perception and Psychophysics, 56*, 183–197.

Logan, G. D. (1988). Towards an instance theory of automatization. *Psychological Review, 95*, 492–527.

Logan, G. D. (1992). Attention and preattention in theories of automaticity. *American Journal of Psychology, 105*, 317–339.

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

Logan, G. D., Taylor, S., & Etherton, J. (1999). Attention and automaticity: Toward a theoretical integration. *Psychological Research, 62*, 165–181.

Mandler, G., & Shebo, B. (1982). Subitizing: An analysis of its component processes. *Journal of Experimental Psychology: General, 111*, 1–21.

Nan, Y., Knosche, T. R., & Luo, Y.-J. (2006). Counting in everyday life: Discrimination and enumeration. *Neuropsychologia, 44*, 1103–1113.

Olivers, C. N. L., & Watson, D. G. (2008). Subitizing requires attention. *Visual Cognition, 16*(4), 439–462.

Piazza, M., Mechelli, A., Butterworth, B., & Price, C. (2002). Are subitizing and counting implemented as separate or functionally overlapping processes? *NeuroImage, 15*, 435–446.

Plaisier, M. A., Bergmann Tiest, W. M., & Kappers, A. M. L. (2009). One, two, three, many – Subitizing in active touch. *Acta Psychologica, 131*, 163–170.

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

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

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 18*(3), 849–860.

Riggs, K. J., Ferrand, L., Lancelin, D., Fryziel, L., Dumur, G., & Simpson, A. (2006). Subitizing in tactile perception. *Psychological Science, 17*(4), 271–272.

Rubinsten, O., Henik, A., Berger, A., & Shahar-Shalev, S. (2002). The development of internal representations of magnitude and their association with Arabic numerals. *Journal of Experimental Child Psychology, 81*(1), 74–92.

Saltzman, I. J., & Garner, W. R. (1948). Reaction time as a measure of span of attention. *Journal of Psychology, 25*, 227–241.

Sathian, K., Simon, T. J., Peterson, S., Patel, G. A., Hoffman, J. M., & Gratton, S. T. (1999). Neural evidence linking visual object enumeration and attention. *Journal of Cognitive Neuroscience, 11*, 36–51.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing. I. Detection, search and attention. *Psychological Review, 84*, 1–66.

Shapiro, K. L., Raymond, J. E., & Arnell, K. M. (1994). Attention to visual pattern information produces the attentional blink in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 20*(2), 357–371.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing. II. Perceptual learning, automatic attending and a general theory. *Psychological Review, 84*, 127–190.

Soltesz, F., Szűcs, D., & Szűcs, L. (2010). Relationships between magnitude representation, counting and memory in 4- to 7-year-old children: a developmental study. *Behavioral and Brain Functions, 6*, 13.

Soltesz, F., White, S., & Szűcs, D. (2011). Event-related brain potentials dissociate the developmental time-course of automatic numerical magnitude analysis and cognitive control functions during the first three years of primary school. *Developmental Neuropsychology, 36*(6), 682–701.

Spelke, E. S. (2000). Core knowledge. *American Psychologist, 55*, 1233–1243.

Starkey, P., & Cooper, R. G. (1980). Perception of numbers by human infants. *Science, 210*, 1033–1035.

Szűcs, D., Soltesz, F., Jarmi, E., & Csepe, V. (2007). The speed of magnitude processing and executive functions in controlled and automatic number comparison in children: an electro-encephalography study. *Behavioral and Brain Functions, 3*, 23.

Treisman, A., Vieira, A., & Hayes, A. (1992). Automatic and preattentive processing. *American Journal of Psychology, 105*, 341–362.

Trick, L. (2008). More than superstition: differential effects of featural heterogeneity and change on subitizing and counting. *Perception and Psychophysics, 70*(5), 743–760.

Trick, L., Enns, J. T., & Brodeur, D. A. (1996). Lide span changes in visual enumeration: The number discrimination task. *Developmental Psychology, 32*(5), 925–932.

Trick, L., & Pylyshyn, Z. (1993). What enumeration studies can show us about spatial attention: Evidence for limited capacity preattentive processing. *Journal of Experimental Psychology: Human Perception and Performance, 19*(2), 331–351.

Trick, L., & Pylyshyn, Z. (1994). Why are small and large numbers enumerated differently: A limited-capacity stage in vision. *Psychological Review, 101*(1), 80–102.

Vetter, P., Butterworth, B., & Bahrami, B. (2008). Modulating attentional load affects numerosity estimation: Evidence against a pre-attentive subitizing mechanism. *PLoS ONE, 3*(9), e3269.

Watson, D. G., Maylor, E. A., & Bruce, L. A. M. (2007). The role of eye movements in subitizing and counting. *Journal of Experimental Psychology: Human Perception and Performance, 33*(6), 1389–1399.

Wender, K. F., & Rothkegel, R. (2000). Subitizing and its sub-processes. *Psychological Research, 64*, 81–92.

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