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Bilateral Advantages in Subitizing With Visual Masking

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Abstract

Performance on a range of visual-processing tasks has been shown to improve when information is split bilaterally across the left and right visual hemifields rather than being restricted to a single visual hemifield. However, a recent study by Delvenne et al. found no such bilateral advantage for subitizing, which is our ability to rapidly and accurately enumerate small quantities of objects. This finding is particularly surprising, as it contradicts the prediction of FINgers of INSTantiation theory that subitizing should benefit from bilateral presentation. Our study investigated the issue by determining if there are any circumstances where a bilateral advantage for subitization occurs. Contrary to Delvenne et al., we found that subitizing could show bilateral advantages, but only when the display was backward-masked. We discuss these findings in relation to how the rate of encoding and the time available for this encoding may affect bilateral advantages in subitizing. A general model is proposed under which bilateral advantages could be explained.

Keywords

subitizing, bilateral advantages, backward masking

Enumeration is often viewed as involving either a slow, serial process of accurately counting objects or a rough but rapid estimation of quantity. However, we can enumerate 1 to 4 objects both rapidly and accurately. This ability to rapidly and accurately enumerate small quantities has been termed *subitizing* (Kaufman, Lord, Reese, & Volkmann, 1949). Understanding the factors that impact subitizing performance may help us better understand this ability. One factor found to influence performance on a range of visual processing tasks is whether a display is presented across the visual hemifields (bilateral presentation) or restricted to a single hemifield (unilateral presentation). An important theory of subitizing, FINgers of INSTantiation (FINST) theory, predicts that subitizing should also benefit from bilateral presentation (Trick & Pylyshyn, 1994). Surprisingly, Delvenne, Castronovo, Demeyere, and Humphreys (2011) recently found no bilateral advantage for subitizing, bringing this theory into question.

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FINST theory proposes that subitizing is an emergent property of the visual system's ability to mark and index (i.e., individuate) the location of up to four objects, simultaneously (Trick & Pylyshyn, 1994). The theory suggests that objects are individuated by indexes known as FINgers of INSTantiation (i.e., FINSTs). Individuated objects can then easily be attended to, encoded, and enumerated. If the number of objects to be enumerated exceeds the number of FINSTs that the observer possesses, then the observer can only enumerate a subset of the display at once before having to shift their FINSTs to new objects that were not previously enumerated. This shifting of the individuation mechanism is thought to take time and increase the likelihood of an error as the observer must now remember which objects have already been enumerated so that they do not enumerate them again. Avoiding this need to shift the individuation mechanism and remember already encoded objects is thought to be why observers are better at enumerating four or fewer objects as this is the maximum number of FINSTs that most observers possess (Trick & Pylyshyn, 1994).

Importantly, this object-individuation mechanism is thought to be the same mechanism that underlies multiple object tracking (MOT) and spatial visual short term memory (VSTM; Pylyshyn, 1989; Xu & Chun, 2009). In support of the idea that MOT, VSTM, and subitizing all rely on FINSTs, Chesney and Haladjian (2011) found that for each additional moving object that had to be tracked whilst subitizing, estimated subitizing capacity decreased by one. Furthermore, Piazza, Fumarola, Chinello, and Melcher (2011) found that people who are better at subitizing also tend to have a larger VSTM capacity. If subitizing relies on the same mechanism as MOT and VSTM, then it should be similarly affected by factors that affect MOT and VSTM performance.

One factor found to affect performance on a range of tasks is whether a display is presented unilaterally, to a single visual hemifield or bilaterally, across both the left and right visual hemifields. Information presented to someone's left visual hemifield (i.e., to the left of their centre of vision) is initially processed in their right cortical hemisphere and vice versa for information presented in their right visual field (Sperry, 1968). This contralateral processing means that information must be integrated between the hemispheres via the corpus callosum whenever the important information is presented bilaterally. Integration of information between cortical hemispheres has been found to be less efficient than integration within a hemisphere (Large, Culham, Kuchinad, Aldcroft, & Vilis, 2008; Murray, Foxe, Higgins, Javitt, & Schroeder, 2001; Pillow & Rubin, 2002). For example, Murray et al. (2001) found that the neural representations of two visually-presented objects took approximately 10 ms longer to interact, as measured by evoked potentials, when the objects were presented bilaterally rather than unilaterally. This finding reflects the cost of between-hemisphere integration relative to within-hemisphere integration and suggests that bilateral presentation could hinder performance on visual tasks. Despite this potential for unilateral presentation advantages, bilateral presentation has actually been found to benefit performance for many forms of visual processing (e.g., Alvarez & Cavanagh, 2005).

Crucially, bilateral advantages have been found for MOT and VSTM. For example, Alvarez and Cavanagh (2005) found that participants could keep track of approximately twice as many moving objects when the objects were split across visual hemifields than when the objects were restricted to a single hemifield. Similarly, Kraft et al. (2013) and Delvenne (2005) both found greater VSTM capacities when the visual information to be remembered was split bilaterally rather than unilaterally. These bilateral advantages may seem somewhat surprising given the cost of between-hemisphere integration. However, what these findings suggest is that we are able to process information from each visual hemifield independently in the contralateral cortical hemispheres, prior to between-hemisphere integration (Alvarez & Cavanagh, 2005). Consequently, bilateral presentation allows the early stages of processing to engage separate resources from the left and right cortical hemispheres, reducing the maximum load on any single hemisphere. When the advantage of engaging both hemispheres during the early stages of processing outweighs the cost of between-hemisphere integration, we can expect bilateral advantages to occur.

Interestingly, a recent study by Delvenne et al. (2011) found no such bilateral advantage for subitizing. They had participants fixate on a central cross and then briefly presented two to eight dots spread either across the visual hemifields (bilateral presentation) or all within a visual hemifield (unilateral presentation). They found that average enumeration accuracy was equivalent across bilateral and unilateral conditions for quantities within the typical subitizing range, specifically for two to four dots. This finding suggests that subitizing is relatively unaffected by whether a display is presented bilaterally or unilaterally. How can we reconcile this finding with the theory that subitizing relies on the same mechanism as MOT and VSTM, both of which showed a bilateral advantage?

A limitation of Delvenne et al.'s (2011) study may explain their lack of bilateral advantage. Accuracy for enumeration of two and three dot displays was close to 100%. Performance this high prevents bilateral advantages from showing in accuracy measurements because bilateral presentation cannot offer any advantage over the near perfect accuracy on unilateral trials. These ceiling effects were not apparent on four-item trials though, which still showed no bilateral advantage. However, their results represented group-averaged data, and so it is possible that a subset of participants still performed at ceiling on four-item trials, reducing any bilateral advantages in the group-averaged data. Group-averaged accuracy may have only appeared below ceiling because another subset of participants had a subitizing capacity less than four items, which is not uncommon (Basak & Verhaeghen, 2003; Reeve, Reynolds, Humberstone, & Butterworth, 2012), and so struggled to enumerate this quantity. One simple way of overcoming any such ceiling effects is by measuring response times (RTs). In line with the idea that bilateral presentation engages both cortical hemispheres, making processing more efficient, bilateral presentation should allow for faster RTs. Therefore, measuring RTs may provide a simple way of detecting bilateral advantages for subitizing even when accuracy is near perfect.

Another potential way of dealing with ceiling effects is to bring subitizing performance below ceiling by making the task more difficult. One simple way to increase the difficulty of subitizing a display is by backward-masking the display. Although Delvenne et al. (2011) only presented their displays for 150 ms, participants could have processed this information for longer by using iconic memory. Iconic memory refers to our ability to maintain highly detailed representations of visual information for a few hundred milliseconds after its presentation (Sperling, 1960). Consequently, participants may have found the task easier due to eased time constraints, resulting in ceiling effects. Backward-masking involves presenting new visual information to replace the information in iconic memory. This prevents further processing of the display and subsequently should reduce subitizing accuracy by limiting the amount of time participants have to accurately enumerate the display.

If it is the case that subitizing does not benefit from bilateral presentation, then this poses a problem for FINST theory. FINST theory predicts that subitizing should show a similar bilateral advantage to that seen for MOT and VSTM, as it proposes that subitizing, MOT, and VSTM all rely on object individuation, achieved via FINSTs (Trick & Pylyshyn, 1994). The fact that a bilateral advantage is shown for MOT and VSTM implies that these FINSTs are hemifield-specific, with approximately two FINSTs assigned to each hemifield (Alvarez &

Cavanagh, 2005; Delvenne, 2005; Kraft et al., 2013). A similar bilateral advantage should also be found for subitization if it relies on FINSTs too (Trick & Pylyshyn, 1994). The aim of this study was, therefore, to determine whether subitizing could show bilateral advantages when bilateral advantages were not limited by ceiling performance. In Experiment 1, RT was measured as a way of detecting bilateral advantages even when accuracy is at ceiling levels. Experiment 2 attempted to see whether bilateral advantages could be seen for subitizing when the display is backward-masked such that stricter time-constraints on processing bring accuracy below ceiling. In line with the predictions of FINST theory, it was hypothesized that participants would show greater subitizing accuracy when objects were presented bilaterally rather than unilaterally.

Experiment 1

Method

Participants. A total of 15 volunteers (mean age = 18.4, range: 17–22), primarily University of Melbourne students, participated in this experiment. All participants gave informed consent. All participants had normal or corrected-to-normal vision as verified by scoring 20/25 or better on a 40 cm Good-Lite® eye chart and successfully completing an Ishihara color blindness test.

Stimuli and Apparatus. Stimuli were presented using software coded in MATLAB R2010a using Psychtoolbox v3.0.8 on a 40 cm CRT monitor with a refresh rate of 85 Hz. Participants viewed the display from a distance of 60 cm in a dimly-lit, quiet room. The stimuli were presented on a black background ($Y = 1.69\,cd/m^2$, $x = 0.34$, $y = 0.36$)[11] and consisted of a white fixation cross ($Y = 29.99\,cd/m^2$, $x = 0.32$, $y = 0.34$) and red target objects ($Y = 7.15\,cd/m^2$, $x = 0.60$, $y = 0.33$). The fixation cross had a height and width of 1.05°. The targets were circular dots with a diameter subtending 0.67° with a minimum center-to-center distance of 0.86°.

Procedure. A within-subjects design was used, with all participants completing the same experimental task. Participants completed 20 training trials before commencing the main experiment, which consisted of 200 trials. Between each trial, participants were able to take a break and were told how many trials remained.

Participants were instructed to maintain focus on a central fixation cross throughout each trial. Around the fixation cross, at a vertical and horizontal distance of 1.48° of visual angle from the fixation cross, were four invisible quadrants, each subtending 7.88° × 7.88° (see Figure 1). After the fixation cross had been presented on its own for 1 sec, the fixation cross remained on the screen while one to three target dots were presented on the screen for 150 ms. The display was then replaced by a black screen for 3 sec or until the participants responded, whichever came first.

Exactly two targets were presented on 50% of the trials, whilst 25% of the trials had just one target, and the remaining 25% of trials had three targets. No more than two targets were ever presented within a single quadrant.

Participants were instructed to answer whether "summing across the array, were there exactly 2 targets in total?" by pressing the "Y" key on a keyboard if they believed that there were two targets presented and to press the "N" key if either one or three targets were presented. Correct responses were defined as responding "Y" on the two-target trials and "N" on any other trials. Participants were told that their RTs would be measured, and that they should respond as rapidly as possible but to focus primarily on maximizing accuracy.

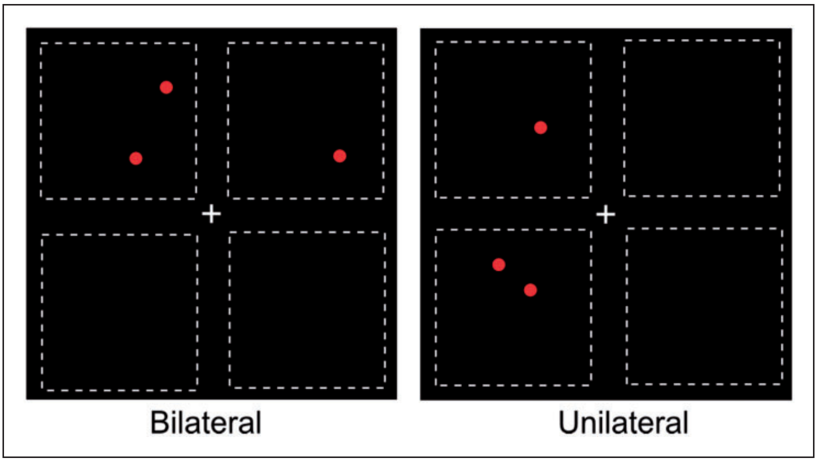

Figure 1. Samples of the dot displays used in Experiment 1 for the bilateral and unilateral presentation conditions. The dotted lines are depicted here to show the boundaries of the four quadrants and were not actually presented during the experiment.

Participants could respond at any point after the display appeared. The accuracy and RTs of their responses were the primary dependent variables of interest.

When estimating participants' RTs, trials where an incorrect response was made were excluded from analysis. Trials where RT was two *SD* above or below the participant's mean RT were also excluded as outliers.

The primary experimental variable was whether the two arrays of dots were both on one side of the fixation cross (unilateral presentation) or split across the left and right sides of the display (bilateral presentation) as shown in Figure 1. Of the 200 trials, each participant completed 100 bilateral and 100 unilateral trials in a random, interleaved order. On bilateral trials, the dots were presented entirely above and entirely below the fixation cross at equal frequencies. Likewise, unilateral trials had dots presented to the left and to the right of the fixation cross at equal frequencies.

Results and Discussion

The mean and spread of accuracy and RT for the unilateral and bilateral conditions are presented in Figure 2. No significant difference in accuracy or RT was seen for unilateral displays presented to the left or right hemifield or for bilateral displays presented above or below the fixation cross (see Appendix A). All participants performed at or near ceiling in terms of accuracy. It is, therefore, unsurprising that a paired-samples t test found no significant difference in accuracy between the unilateral and bilateral conditions, mean difference = 1.2%, $t(14) = 1.72$, $p = .108$, 95% CI [−0.30, 2.7]. To account for the possibility that accuracy could be affected by a response bias toward, for example, responding "two targets present," d' was also intended to be analysed as a measure of sensitivity unaffected by such a response bias.

A response of "two targets present" is defined as a hit on two-target trials and defined as a false alarm on any other trial. However, because many participants made few or no false alarms, there was not enough data to reliably calculate d' and so no analysis of d' was

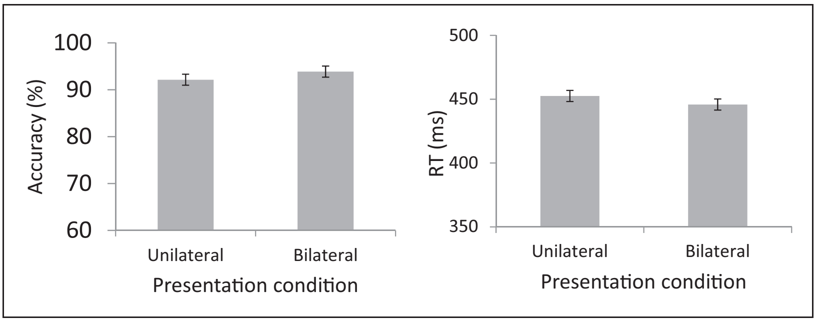

Figure 2. Mean and 95% CI for accuracy and RT in the unilateral and bilateral presentation conditions in Experiment 1. The confidence intervals have been adjusted to remove between-subjects variation, in line with the recommendations of Cousineau (2005) and Morey (2008).

conducted. The low false alarm rate and high hit rate suggest that response biases are unlikely to have affected accuracy here anyway (see Appendix B).

Due to ceiling performance, response time was the primary dependent variable of interest. The number of trials removed due to incorrect responses or outlier RTs when estimating participants' mean RTs is shown in Appendix C. Interestingly, a paired-samples t test revealed no significant difference in RT for the unilateral and bilateral conditions, mean difference $= -5.29$ ms, $t(14) = -1.70$, $p = .112$, 95% CI [−12.0 ms, 1.3 ms].

It is possible that this lack of bilateral advantage was simply due to the bilateral advantage effect being split between RT and accuracy, given participants may have switched between focusing on maximizing accuracy on some trials and minimizing RT on other trials. A repeated measures multiple analysis of variance was run to assess bilateral advantages on a linear combination of accuracy and RT that maximizes the differences between bilateral and unilateral conditions. If the lack of significant results in Experiment 1 were due purely to a splitting of the effect between RT and accuracy, then a repeated measures multiple analysis of variance should reveal a significant bilateral advantage. No such bilateral advantage was found, $F(2, 13) = 2.77$, $p = .099$.

It is worth briefly discussing the possibility that our experimental design allowed participants to use an alternate strategy that allowed them to avoid enumerating the display. Participants may have simply been determining whether one or more than one target was present on each trial. Such a strategy could allow participant to achieve up to around 75% accuracy even without distinguishing between two-item and three-item trials. However, our replication of Delvenne et al.'s (2011) findings and the high observed accuracy in this experiment indicate that, like in Delvenne et al.'s study, participants were actually subitizing the display. Furthermore, if, as this strategy suggests, participants were not distinguishing between two-item and three-item displays, then a response of "two items present" should have been just as likely on three-item displays as on two-item displays. Contrary to this, the false alarm rate on three-item trials (i.e., incorrectly responding "two items present" on three-item trials) was significantly lower than the hit rate (i.e., correctly responding "two items present" on two-item trials), mean difference $= 80.7\%$, $t(14) = 37.0$, $p < .001$, 95% CI [76, 85], Cohen's $d = 9.5$. This shows that participants were distinguishing between two and three item trials, suggesting that they were actually enumerating the display.

Overall, these results provide a strong replication of Delvenne et al. (2011), suggesting that their failure to find a bilateral advantage for subitizing holds even when ceiling effects are circumvented by measuring RTs. Of course, this failure to find a bilateral advantage for subitizing may be specific to the conditions used here and by Delvenne et al. (2011). Our next experiment looks at whether subitizing will show a bilateral advantage when the difficulty of the task is manipulated such that performance is no longer near ceiling levels.

Experiment 2

Previous studies of bilateral advantages have found that a variety of tasks show bilateral advantages under some experimental conditions but not under others (Belger & Banich, 1992; Chakravarthi & Cavanagh, 2009; Delvenne & Holt, 2014; Reardon, Kelly, & Matthews, 2009; Weissman & Banich, 2000). The general pattern of these findings is that by making processing of the stimuli more difficult, bilateral advantages are more likely to occur. These findings will be considered in more detail when discussing our results. Importantly, these findings open up the possibility that the lack of bilateral advantage for subitizing observed in Experiment 1 and by Delvenne et al. (2011) is limited to the simple conditions present in those experiments. Experiment 2, therefore, looks at whether subitizing will show bilateral advantages under more difficult conditions.

Specifically, we increased the difficulty of processing the stimuli by backward-masking the display to instill stricter time-constraints on processing. Backward-masking was used here, as it provides an important control over how long participants process the display for. By removing information from iconic memory, backward-masking allows for consistency in the duration of visual presentation length across participants rather than having performance influenced not only by their subitizing ability but also the persistence of information in iconic memory. On the basis of premise that tasks are more likely to exhibit bilateral advantages under difficult conditions and FINST theory's prediction that subitizing will show bilateral advantages, we expect a bilateral advantage to occur for subitizing when the task is made more difficult by backward masking the display.

Method

Participants. Out of 17 new University of Melbourne Psychology students who volunteered for this study, data from 15 participants were used (mean age = 19.4, Range: 18–23). Two participants were excluded from the analysis for having accuracy no better than chance performance. All participants gave informed consent. All participants had normal or corrected-to-normal vision as verified by scoring 20/25 or better on a 40 cm Good-Lite® eye chart and successfully completing an Ishihara color blindness test.

Apparatus and procedure. The exact same experimental design was used as in Experiment 1, except a mask was presented immediately after the 150 ms display presentation, followed by a black screen. The stimulus sequence is shown in Figure 3. The masking array consisted of a grid of red and green squares that flashed on and off twice over the course of 60 ms (see Figure 3).

Results and Discussion

The mean RT and accuracy in the bilateral and unilateral conditions for the remaining 15 participants are presented in Figure 4. Appendix A shows that accuracy and RT were not significantly impacted by the location of dot presentations within unilateral trials or within bilateral trials.

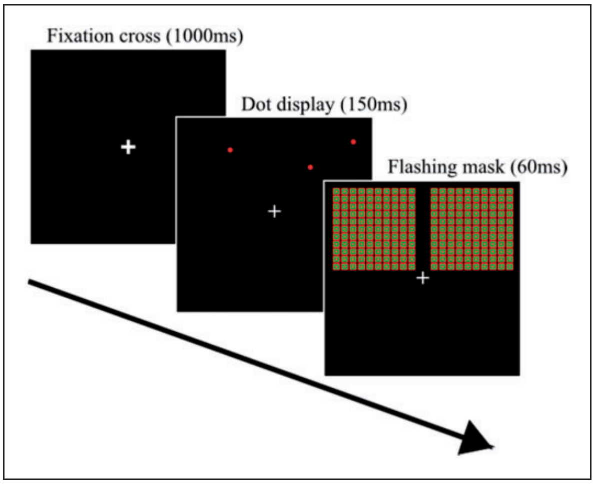

Figure 3. A visual example of the sequence and timing of displays presented for a trial in Experiment 2.

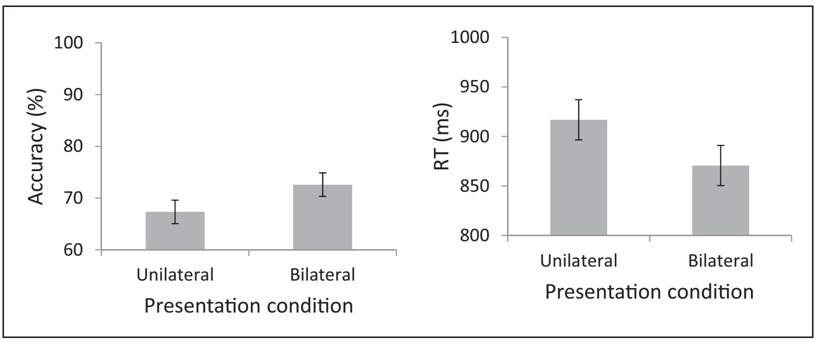

Figure 4. Mean and 95% CI for accuracy and RT in the unilateral and bilateral presentation conditions in Experiment 4. The confidence intervals have been adjusted to remove between-subjects variation, in line with the recommendations of Cousineau (2005) and Morey (2008).

Unlike in Experiment 1, a paired-samples t test revealed a bilateral advantage, with accuracy being significantly higher in the bilateral condition than the unilateral condition, mean difference = 5.3%, $t(14) = 3.517$, $p = .003$, 95% CI [2.1, 8.5], Cohen's $d = 0.91$. Unlike in Experiment 1, d' could be calculated here thanks to the higher false alarm rate (see Appendix B). Analysis of d' conformed with this finding, showing a significant bilateral advantage, mean difference = 0.32, $t(14) = 3.33$, $p = .005$, 95% CI [0.11, 0.53], Cohen's $d = 0.86$.

Appendix C shows that a relatively large number of trials were excluded from the analysis of RT due to the lower accuracy. Although this likely increased the standard deviation of the RT estimates, the assumptions of the paired samples t test were still met so it is presented here. Excluding these trials, a paired-samples t test still revealed that RTs were significantly faster when the display was presented bilaterally rather than unilaterally, mean difference = 46.2 ms, $t(14) = 3.45$, $p = .004$, 95% CI [17 ms, 74 ms], Cohen's $d = 0.89$.

As in Experiment 1, to confirm that people were actually enumerating the displays, a paired-samples t test was run, showing that the false alarm rate on three-item trials was significantly lower than the hit rate on two-item trials, mean difference = 31.30%, $t(14) = 6.02$, $p < .001$, 95% CI [20.2, 42.4], Cohen's $d = 1.56$. This shows that participants were not simply checking whether one or more than one item was present on each trial and were actually distinguishing between two- and three-item trials.

It should be noted that the difference in performance between the unilateral and bilateral conditions cannot be attributed to differences in eye movements between the two conditions. Because the trials were randomly interleaved, the observer did not know in advance where the visual stimulus would appear. Because the stimulus was displayed for only 150 ms there was not enough time to make any eye movements after the stimulus appeared before it disappeared again. As such, we can be sure that our data represent a pure measure of bilateral versus unilateral processing.

Crucially, these findings provide strong evidence that subitizing can exhibit bilateral advantages. This suggests that a substantial portion of subitizing processing occurs independently in each cortical hemisphere. It, therefore, remains possible that, as predicted by FINST theory, subitizing relies on the same object-individuation mechanism as MOT and VSTM (Trick & Pylyshyn, 1994), given that studies have shown that MOT and VSTM also benefit from bilateral presentation (Alvarez & Cavanagh, 2005; Delvenne, 2005; Kraft et al., 2013).

The finding of a bilateral advantage when masking was present, in combination with the lack of bilateral advantage when masking was absent, suggests that backward-masking affected the occurrence of bilateral advantages for subitizing. In support of this conclusion, a Mixed analysis of variance was run with bilateral versus unilateral presentation as the within-subjects factor and presence of backward-masking (Experiment 1 vs. 2) as the between-subjects factor. This found a significant interaction, with the bilateral advantage when backward-masking was present being significantly larger than the bilateral advantage seen when backward masking was absent for both accuracy, $F(1,28) = 6.06$, $p = .020$, partial $\eta^2 = .178$ and RT, $F(1,28) = 8.87$, $p = .006$, partial $\eta^2 = .241$. To our knowledge, no such effect of backward-masking on bilateral advantages has thus far been reported. Potential explanations for these findings are discussed below.

General Discussion

This study set out to test whether independent resources are engaged in each cortical hemisphere when subitizing a display. We found that subitizing can benefit from bilateral presentation, contrasting with the lack of a bilateral advantage for subitizing reported by Delvenne et al. (2011). This finding implies that some portion of subitization processing can occur independently in each cortical hemisphere. This finding is particularly important for FINST theory as this theory predicts that subitizing should be able to benefit from bilateral presentation. This prediction is based on FINST theory's assertion that subitizing relies on the same mechanism as MOT and visual short term memory (VSTM), both of which have shown bilateral advantages (Alvarez & Cavanagh, 2005; Delvenne, 2005; Kraft et al., 2013; Trick & Pylyshyn, 1994).

This finding also suggests that it may be important to control for how a display is presented when studying or assessing subitizing ability, especially if the display is being backward-masked. If performance is worse when a display is presented unilaterally then assessing subitizing ability without bilaterally presenting the display may hinder performance. For example, a recent study by Ester, Drew, Klee, Vogel, and Awh (2012) presented a subitizing display to just a single hemifield so as to detect the neural response in the contralateral hemisphere. Such unilateral presentation may unintentionally limit the ability of participants to subitize a display. Being aware of how subitizing performance can be affected by such factors is particularly important given recent suggestions that subitizing ability may offer a useful way of diagnosing numerical difficulties in children (Butterworth, 2005). The better we understand the factors impacting subitizing performance, the more accurately we can assess people's subitizing ability. However, our results suggest that bilateral advantages are not a stable feature of subitizing tasks. Instead, these advantages appear to occur only under certain conditions.

Factors Affecting Bilateral Advantages

Although Experiment 2 found a bilateral advantage to occur for subitizing when backward-masking was present, no such bilateral advantage was observed in Experiment 1, when backward-masking was absent. Likewise, Delvenne et al. (2011) found no bilateral advantage for subitizing under similar, simple conditions. To our knowledge, our study is the first to identify an apparent impact of backward-masking on the occurrence of bilateral advantages. We develop here a potential explanation for this impact of backward-masking on bilateral advantages.

Previously, studies have found that changes in whether bilateral advantages occur could be attributed to the computational complexity of the task (Belger & Banich, 1992; Chakravarthi & Cavanagh, 2009; Delvenne & Holt, 2014; Reardon et al., 2009; Weissman & Banich, 2000). The term computational complexity was used to simply refer to the relative amount of processing required to generate an appropriate response from an initial stimulus in these studies. For example, Belger and Banich (1992) explored the role of computational complexity, showing that bilateral advantages only occurred on a letter-matching task for the more computationally complex task of matching letters with the same name (e.g., b and B) and not on the computationally simpler task of identifying physically-identical matches (e.g., B and B). Under lower computational-complexity conditions, the amount of processing the stimuli had to undergo may have been so low that engaging additional resources from bilateral presentation had little impact on the final performance. We propose that a similar explanation can be applied to our observed impact of backward-masking on bilateral advantages.

We propose that, like computational complexity, backward-masking influences the occurrence of bilateral advantages through making it more difficult to encode visual information. However, rather than influence the amount of processing that a stimulus must undergo, as computational complexity does, backward-masking removes information from iconic memory, reducing the amount of information available for processing. We propose that this reduction in the time available to process a display may make performance more dependent on the early, hemifield-independent stages of processing a display. After a backward-mask is presented, any subsequent processing is dependent on what has already been encoded into VSTM (Sperling, 1960). Backward-masking, therefore, may make final performance more dependent on the rate at which information is encoded through limiting the time available to encode a display. Because bilateral presentation allows information to be processed in both the left and right hemispheres, it can be assumed to increase the rate of encoding. Therefore, bilateral presentation may be particularly beneficial when a display is masked because it increases the amount of information encoded before the mask is displayed, making the subsequent task of subitizing a display easier.

It is worth noting that MOT and VSTM tasks did not require backward-masking in order to show bilateral advantages. This might seem surprising given these tasks are thought to rely on the same object-individuation mechanism as subitizing, which did not show bilateral advantages when the display was not masked. We propose that this can be attributed to the higher computational complexity of MOT and VSTM tasks. Delvenne's (2005) VSTM task required participants to remember the spatial arrangement of objects whilst MOT tasks require participants to constantly update information about the spatial location of moving objects (Alvarez & Cavanagh, 2005). Conversely, our subitizing task only required that participants encode the presence of objects, not other information such as their location. Without backward-masking, it may simply be that encoding information on MOT and VSTM tasks, but not on subitization tasks, is difficult enough that bilateral presentation can offer an advantage.

A General Model of Bilateral Advantages

Smith and Ratcliff (2009) formulated a computational model that explained differences in performance as stemming from changes in the strength of VSTM representations. We suggest that this model could be adapted to explain our findings. In their integrated model of signal detection, Smith and Ratcliff (2009) propose that information from a visual display is gradually encoded and accumulates in VSTM toward some maximum level. Backward-masking stops this accumulation process and, therefore, prevents the VSTM representation from reaching its maximum strength. The strength of the VSTM representation then determines the drift rate in a diffusion process. This diffusion process represents the process of repeatedly sampling information in VSTM (Ratcliff, 1978). When correct information is sampled, the process will move toward a correct-response threshold. Conversely, sampling random noise may shift the process toward an incorrect-response threshold. A correct response is made if the process reaches the correct-response threshold. A high drift rate occurs when there is a high likelihood that correct information is sampled, thereby reducing the time taken to make correct responses and increasing the frequency of correct responses. However, if the amount of information in VSTM is low then the drift rate will be low, leading to slower RTs and lower accuracy. We believe that a similar model could be applied to our finding that bilateral advantages may be influenced by backward-masking.

We propose that the occurrence of bilateral advantages in our study could be modeled based on the accumulation of evidence into VSTM. For simplicity, we describe the accumulation process using an exponential equation

$$S = S_{max}\left(1 - e^{\left(\frac{-t}{\lambda}\right)}\right) \quad (1)$$

This equation states that the strength of the VSTM representation (S) accumulates toward some theoretical maximum (S_{max}) at an accumulation rate determined by a positive constant (λ) and the time (t), as the participant began processing the visual information. The strength of the VSTM representation in turn determines the drift rate in some decision process, such as a diffusion process, toward one of two thresholds, in this case corresponding to the response that there either were or were not two targets present. Both accuracy and RT are proportional to this drift rate, so will also be proportional to the amount of information in VSTM, as modeled by equation (1).

This model attempts to explain bilateral advantages as stemming from changes in the accumulation rate. As described earlier, bilateral processing is assumed to approximately double the accumulation rate because it allows information to be independently processed in the two cortical hemispheres. This higher accumulation rate allows the VSTM representation to approach the maximum level more rapidly, resulting in a higher average drift rate (see Figure 5). A higher average drift rate then leads to faster RTs and higher accuracy, that is, a bilateral advantage.

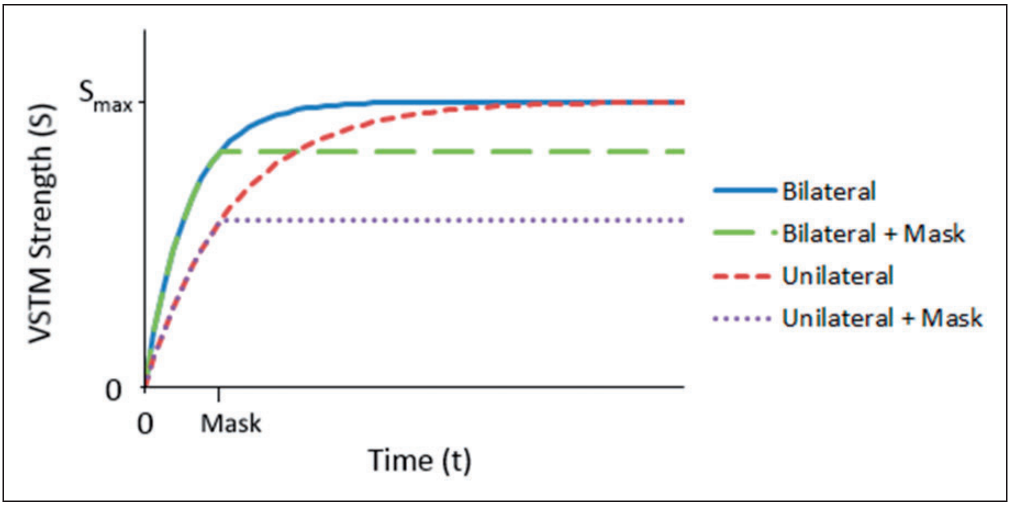

Figure 5. An example of the accumulation of information into VSTM as modeled by equation (1) for displays presented bilaterally and unilaterally, with or without masking. This diagram depicts the slower accumulation rate for unilaterally processed displays. Both bilateral and unilateral processing approach S_{max} but backward-masking stops the accumulation process before this maximum is reached. As can be seen, this effect of masking results in a larger difference in the final VSTM strength between bilateral and unilateral displays.

Under this model, the impact of backward-masking on bilateral advantages is attributed to the accumulation process stopping before it reaches the maximum VSTM strength. A faster accumulation rate, as comes with bilateral processing, means that more information will be encoded into VSTM before the process is stopped by backward-masking. Consequently, rather than unilateral and bilateral processing reaching the same maximum VSTM strength, the final VSTM strength for a bilateral trial is typically higher than that of a unilateral trial, as depicted in Figure 5. This higher VSTM strength leads to a higher drift rate for the decision process which can explain the faster RTs and higher accuracy that we found when backward-masking was present.

The impact of computational complexity on bilateral advantages could also be described using the above model. Increasing computational complexity increases the amount of time taken to reach the maximum VSTM strength. Accordingly, under this model, low computational complexity tasks such as our subitizing task have less room to benefit from bilateral presentation because they reach the maximum VSTM strength faster, at which point bilateral presentation offers no advantage. At this stage, such a model is purely hypothetical and further work is needed to better determine whether the effects we found could be attributed to the accumulation of evidence in VSTM. For example, this model makes the testable prediction that there will be an interaction between backward-masking and computational complexity such that the effect of backward-masking on bilateral advantages will be greater when the task is more computationally complex and vice versa.

Conclusions

In line with the predictions of FINST theory, our study found that subitizing can benefit from bilateral presentation. This finding suggests that part of the processing underlying subitization occurs independently in the left and right cortical hemispheres. The potential for subitizing to be affected by bilateral or unilateral presentation emphasizes the importance of controlling for such hemifield effects when assessing subitizing ability. Furthermore, our results suggest that backward-masking can affect the occurrence of bilateral advantages. We expect that future studies could identify a similar effect of backward-masking on bilateral advantages in a range of other tasks. We have proposed a general model that may explain bilateral advantages and the effects of backward-masking on bilateral advantages through focusing on the time available to encode visual information and the rate of this encoding. Quantitative and qualitative analysis of this model against data should help to determine its utility for explaining bilateral advantages in both subitizing and other visual processing tasks.

Conflict of interest

None declared.

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Note

1. All colors are defined in the CIE Yxy color space.

References

Alvarez, G. A., & Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual hemifields. *Psychological Science*, *16*, 637–643.

Basak, C., & Verhaeghen, P. (2003). Subitizing speed, subitizing range, counting speed, the Stroop effect, and aging: Capacity differences and speed equivalence. *Psychology and Aging*, *18*, 240–249.

Belger, A., & Banich, M. T. (1992). Interhemispheric interaction affected by computational complexity. *Neuropsychologia*, *30*, 923–929.

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry*, *46*, 3–18.

Chakravarthi, R., & Cavanagh, P. (2009). Bilateral field advantage in visual crowding. *Vision Research*, *49*, 1638–1646.

Chesney, D. L., & Haladjian, H. H. (2011). Evidence for a shared mechanism used in multiple-object tracking and subitizing. *Attention, Perception, & Psychophysics*, *73*, 2457–2480.

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology*, *1*, 42–45.

Delvenne, J.-F. (2005). The capacity of visual short-term memory within and between hemifields. *Cognition*, *96*, B79–B88.

Delvenne, J.-F., Castronovo, J., Demeyere, N., & Humphreys, G. W. (2011). Bilateral field advantage in visual enumeration. *PLoS One*, *6*, e17743.

Delvenne, J.-F., & Holt, J. L. (2014). A bilateral advantage in controlling access to visual short-term memory. *Experimental Psychology*, *61*, 127–133.

Ester, E. F., Drew, T., Klee, D., Vogel, E. K., & Awh, E. (2012). Neural measures reveal a fixed item limit in subitizing. *The Journal of Neuroscience*, *32*, 7169–7177.

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

Kraft, A., Dyrholm, M., Bundesen, C., Kyllingsbæk, S., Kathmann, N., & Brandt, S. A. (2013). Visual attention capacity parameters covary with hemifield alignment. *Neuropsychologia*, *51*, 876–885.

Large, M. E., Culham, J., Kuchinad, A., Aldcroft, A., & Vilis, T. (2008). fMRI reveals greater within- than between-hemifield integration in the human lateral occipital cortex. *European Journal of Neuroscience*, *27*, 3299–3309.

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorial in Quantitative Methods for Psychology*, *4*, 61–64.

Murray, M. M., Foxe, J. J., Higgins, B. A., Javitt, D. C., & Schroeder, C. E. (2001). Visuo-spatial neural response interactions in early cortical processing during a simple reaction time task: A high-density electrical mapping study. *Neuropsychologia*, *39*, 828–844.

Piazza, M., Fumarola, A., Chinello, A., & Melcher, D. (2011). Subitizing reflects visuo-spatial object individuation capacity. *Cognition*, *121*, 147–153.

Pillow, J., & Rubin, N. (2002). Perceptual completion across the vertical meridian and the role of early visual cortex. *Neuron*, *33*, 805–813.

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

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, *85*, 59–108.

Reardon, K. M., Kelly, J. G., & Matthews, N. (2009). Bilateral attentional advantage on elementary visual tasks. *Vision Research*, *49*, 691–701.

Reeve, R., Reynolds, F., Humberstone, J., & Butterworth, B. (2012). Stability and change in markers of core numerical competencies. *Journal of Experimental Psychology: General*, *141*, 1–18.

Smith, P. L., & Ratcliff, R. (2009). An integrated theory of attention and decision making in visual signal detection. *Psychological Review*, *116*, 283–317.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74*, 1–29.

Sperry, R. W. (1968). Hemisphere deconnection and unity in conscious awareness. *American Psychologist*, *23*, 723–733.

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

Weissman, D. H., & Banich, M. T. (2000). The cerebral hemispheres cooperate to perform complex but not simple tasks. *Neuropsychology*, *14*, 41.

Xu, Y., & Chun, M. M. (2009). Selecting and perceiving multiple visual objects. *Trends in Cognitive Sciences*, *13*, 167–174.

Appendix A

Paired-samples *t* tests were conducted within each experiment to confirm that accuracy and RT were not affected by whether a display was presented to the left or right of the fixation cross on unilateral trials and whether the display was presented above or below the fixation cross on bilateral trials.

Table A1. Output of Two Paired-Samples *t* Tests Comparing Accuracy Between Presentation Locations in Experiment 1. The Following Two Tests Were Conducted Using a Bonferroni-Adjusted Alpha Level of 0.0125 Per Test (0.5/4).

	t	df	*p*
Accuracy left–accuracy right	0.378	14	.711
Accuracy above–accuracy below	1.033	14	.319
RT left–RT right	−0.368	14	.719
RT above–RT below	0.052	14	.959

Note. RT = response times.

Table A2. Output of Four Paired-Samples *t* Tests Comparing Accuracy and RT Between Presentation Locations in Experiment 2a. The Following Four Tests Were Conducted Using a Bonferroni-Adjusted Alpha Level of 0.0125 Per Test (0.5/4).

	t	df	*p*
Accuracy left–accuracy right	2.192	14	.046
Accuracy above–accuracy below	2.836	14	.014
RT left–RT right	−0.434	14	.671
RT above–RT below	−1.631	14	.125

Note. RT = response times.

Appendix B

Table B1. Summary of the Average False Alarm Rate and Hit Rate for Each Experiment Where a Response of "two targets present" Is Classified as a Hit on Two-Target Trials and a False Alarm on Trials Without Two Targets (i.e., One or Three Targets). This Table Shows the Percentage of Trials That a "two target present" Response Was Made for Each Quantity, Split According to Unilateral or Bilateral Presentation.

	Unilateral			Bilateral		
	1-target	2-targets	3-targets	1-target	2-targets	3-targets
Experiment 1	3.5%	82.0%	6.8%	3.7%	91.4%	5.1%
Experiment 2	21.0%	61.0%	43.0%	21.8%	65.3%	32.5%

Appendix C

Table C1. Summary of the Number of Trials Removed When Estimating Participants' Mean RTs for the Bilateral and Unilateral Presentation Conditions. This Table Shows the Percentage of Total Trials Excluded due to Incorrect Responses and due to RTs More Than Two Standard Deviations Above and Below the Mean. The Range Reflects the Minimum and Maximum Percentage of Trials Excluded From any Single Participant for the Bilateral and Unilateral Conditions for Each Study.

		Percentage of trials removed due to:			Range (%)	
		RT > 2*SDs* below mean	RT > 2*SDs* above mean	Incorrect responses	Min	Max
Exp. 1	Bilateral	0	2.73	6.13	3	16
	Unilateral	0	3.73	7.33	4	18
Exp. 2	Bilateral	0	2.80	27.40	17	44
	Unilateral	0	2.47	32.67	19	52

Note. RT = response times.