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Bilateral and two-item advantage in subitizing

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ABSTRACT

Subitizing refers to people's ability to enumerate small sets of items fast and accurately. The present study examined if the speed and scope of subitizing is improved when the items to be enumerated are presented bilaterally across hemifields rather than unilaterally in a single hemifield. Such an effect, known as the bilateral field advantage, has been observed in a number of other visual tasks. A second aim was to examine whether the speed of subitizing could be explained by the speed it takes to detect the items to be enumerated, as simple reaction times to multiple stimuli are known to be faster than responses to individual items (known as the redundant target effect, RTE). The results revealed a bilateral field advantage even for enumerating two items. Moreover, the two item condition was the optimal subitizing condition – even enumerating one single item took longer – but this effect was not due to the RTE. In fact, the RTE negatively correlated with the speed of enumerating the same stimuli.

1. Introduction

A classical way to study the capacity and speed of visual attention is to ask participants to report the number of visually presented objects as fast as possible (Jevons, 1871; Revkin et al., 2008). The strength of this type of task is that perceptual load, i.e. the number of items, can be parametrically varied while target selection remains undemanding (see, Huang & Pashler, 2007). When the number of items is small (1–3), enumeration is effortless, rapid, and accurate (e.g. Trick & Pylyshyn, 1994). This enumeration process has been termed subitizing to distinguish it from counting which is time-consuming and error-prone (Kaufman et al., 1949).

The very high precision of subitizing when compared to enumerating larger collections of items (Revkin et al., 2008; Choo & Franconeri, 2014) shows that subitizing is more than just fast and accurate estimation of number (cf. Ross & Burr, 2010; Whalen, Gallistel, & Gelman, 1999). Subitizing has been argued to reflect fundamental perceptual (Trick & Pylyshyn, 1994), attentional (Cavanagh & Alvarez, 2005), or cognitive (Cowan, 2001; Piazza et al., 2011) capacity limitations. In addition, subitizing could be based on recognizing stimulus patterns (Mandler & Shebo, 1982; Choo & Franconeri, 2014). In general, an adequate theory of subitizing should explain, first, why subitizing range is limited to 3–4 items, and second, what determines the speed of subitizing (Trick & Pylyshyn, 1994).

The first aim of the present study was to examine whether the hemifield arrangement of the stimuli affects subitizing performance. Many visual tasks reveal a bilateral field advantage where performance is superior when stimuli are presented bilaterally rather than unilaterally (Sereno & Kosslyn, 1991; Delvenne, 2005; Holcombe & Chen, 2012; Kraft et al., 2013). Alvarez and Cavanagh (2005) showed that participants could track almost twice as many items (up to 4) when the items were divided between left and right hemifields, compared to when the items were presented unilaterally. If similar capacity limitations underlie multiple object tracking and subitizing, as is predicted by theories (Pylyshyn, 1989; Cavanagh & Alvarez, 2005) and empirical observations (Chesney & Haladjian, 2011), a bilateral advantage should also be observed in subitizing. A recent study failed to find evidence for bilateral field advantage in subitizing (Delvenne et al., 2011), but only examined enumeration accuracy and variation. However, due to the very high precision of subitizing, it is possible that a bilateral advantage in subitizing may only be observed in enumeration times.

The present study tested if a bilateral field advantage could be observed already in the subitizing range when reaction times (RT) are measured from verbal responses by a voice key. If a bilateral field advantage is observed it could give new insight into the mechanisms of subitizing. Enumeration times have been reported to increase slightly already in the subitizing range (Trick &

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Pylyshyn, 1994; Oyama, Kikuchi, & Ichihara, 1981; Folk, Egeth, & Kwak, 1988), but other studies have reported constant enumeration times (Sagi & Julesz, 1985; Revkin et al., 2008). Constant enumeration times were originally taken as evidence for parallel preattentive processing (Trick & Pylyshyn, 1994), but research has since revealed that subitizing is dependent on attention (Railo et al., 2008; Olivers & Watson, 2008; Egeth, Carly, & Palomares, 2008; Poise, Spalek, & Di Lollo, 2008; Vetter, Butterworth, & Bahrami, 2008; Burr, Turi, & Anobile, 2010). The increase in enumeration times in the subitizing range could thus be caused by increased attentional demands (Duncan, 1980; Oksama & Hyönä, 2008; Railo et al., 2008). Bilateral presentation of items may be beneficial for subitizing as the workload of attention is divided between different representational maps (Franconeri, Alvarez, & Cavanagh, 2013). This could enable parallel multifocal selection of items to be enumerated (Cavanagh & Alvarez, 2005; Huang & Pashler, 2007).

A second aim of the present study (Experiment 2) was to investigate whether subitizing speed could in part be explained by the speed it takes to simply detect the items to be enumerated. Simple speeded RTs are known to decrease when two items are presented instead of one – this is known as the *redundant target effect (RTE*; Miller, 1982; Miniussi, Girelli, & Marzi, 1998; Murray et al., 2001; Iacoboni & Zaidel, 2003). According to the statistical facilitation model a single item is detected faster when there are more alternatives to choose from (Miller, 1982). The neural summation model states that the RTs decrease because multiple targets produce a stronger neural activation than one target (Miniussi, Girelli, & Marzi, 1998; Murray et al., 2001). The RTE could decrease subitizing slopes by speeding up the detection of items. Note that from the behavioral point-of-view the crucial difference between a simple detection and an enumeration task is that items need to be processed as separate entities only in the latter case.

2. Experiment 1

2.1. Method

2.1.1. Participants

Thirty volunteers (mean age 22, 21 females) took part in Experiment 1. All participants had normal or corrected-to-normal vision. One participant was left-handed (Oldfield, 1971). All experiments of the present study were carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.2. Stimuli and procedure

Stimuli were presented using a 21-inch CRT-screen and E-prime 1.2 software. The stimuli to be enumerated were light grey dots (95 cd/m^2) presented on a white (109 cd/m^2) background for 160 ms. The dots were presented following a fixation mark displayed at the center of the screen for 800–1600 ms. The fixation mark was also visible when the dots were presented.

The participants' task was to fixate their eyes on the center of the screen, and report the number of dots as fast and accurately as possible by speaking to a microphone (AKG D40S). The participants were encouraged to maintain a central fixation, but eye-movements or fixation location was not registered. The microphone was attached to a voice key (Psychology Software Tools, model 200A), which recorded the participants' reaction times (relative to stimulus onset). After the participant's response the experimenter logged it by pressing a corresponding number on a keyboard. A separate control experiment (N = 9) showed no statistically significant RT differences in pronouncing number words 1–4 ($F_{3,\ 24}$ = 1.20, p = .33; see Table 1).

The locations of the dots were calculated as follows: Each hemifield was divided into three sectors which were in addition divided into three different eccentricity portions (approximately 1.4°, 2.5°, and 5° from fixation), yielding nine possible locations per hemifield (Fig. 1A). On each trial the dots were randomly assigned to any of these predetermined (invisible) locations. To ensure that each dot configuration was novel, the exact locations where the dots were presented (within a sector) varied slightly from trial to trial. Depending on the condition, all dots were presented to either to the left or right hemifield (unilateral condition), or distributed to both hemifields (bilateral condition). On bilateral trials, when the number of dots was odd, one hemifield contained one extra dot compared to the other hemifield. When the number was even (on bilateral trials), both hemifields had an equal number of dots. In order to counteract the limitation of spatial resolution (Palomares et al., 2011), and to minimize crowding effects (Chakravarthi & Cavanagh, 2009), the size of the dots increased with eccentricity. The size of a dot presented near fixation was 0.4°, 0.7° for intermediate eccentricity, and 1.2° for the highest eccentricity.

The number of dots varied from 1 to 6. Each number was presented 16 times in each experimental condition (unilateral vs. bilateral). In addition, the experiment included filler trials that were not included in the analysis. To discourage the participants from guessing the highest number of stimuli, seven dots were presented 16 times (8 unilaterally, and 8 bilaterally) during the experiment. Also, on eight filler trials, when four dots were presented bilaterally, the number of dots was not equally divided between the hemifields (e.g. 1 dot in the left and 3 dot in the right hemifield). The experiment was divided into 4 blocks, and conducted in a quiet room. Each participant completed 10 practice trials before the experiment.

2.2. Results

Data was analyzed using a 5 (Number: 2–6) × 2 (Condition: unilateral vs. bilateral) repeated measures ANOVA. The one item condition was excluded from the ANOVA because it was always presented unilaterally.

2.2.1. Enumeration times

Median reaction times of trials where the number was reported correctly within 100–2000 ms were analyzed. This meant that for numbers 1–4, on average 2% of trials were excluded from the analysis per participant, and for numbers 5 and 6 on average four trials were excluded per participant.

Results are shown in Fig. 2A. ANOVA revealed main effects of Number ($F_{4,\ 116}$ = 195.7, p < .001) and Condition ($F_{1,\ 29}$ = 30.8, p < .001), and their interaction ($F_{4,\ 116}$ = 5.1, p = .006). Bilateral presentations relative to unilateral presentations reduced reaction times for number two (t_{29} = 2.8, p = .04), but not for number three (uncorrected p = .25; multiple comparisons are Bonferroni corrected unless otherwise stated). A bilateral advantage was also

Table 1
Mean RTs of the control experiment (Experiment 4).

Response word	Mean RT (ms)	SEM
"One"	256.57	13.30
"Two"	257.31	13.10
"Three"	269.39	13.10
"Four"	272.24	13.90