ARTICLE IN PRESS
Cognition xxx (2011) xxx–xxx
Contents lists available at ScienceDirect
Cognition
journal homepage: www.elsevier.com/locate/COGNIT

Brief article

Subitizing reflects visuo-spatial object individuation capacity

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ARTICLE INFO

Article history:
Received 19 February 2010
Revised 6 May 2011
Accepted 21 May 2011
Available online xxxx

Keywords:
Subitizing
Visuo-spatial working memory
Visuo-spatial attention
Capacity limits
Individuation

ABSTRACT

Subitizing is the immediate apprehension of the exact number of items in small sets. Despite more than a 100 years of research around this phenomenon, its nature and origin are still unknown. One view posits that it reflects a number estimation process common for small and large sets, which precision decreases as the number of items increases, according to Weber's law. Another view proposes that it reflects a non-numerical mechanism of visual indexing of multiple objects in parallel that is limited in capacity. In a previous research we have gathered evidence against the Weberian estimation hypothesis. Here we provide first direct evidence for the alternative object indexing hypothesis, and show that subitizing reflects a domain general mechanism shared with other tasks that require multiple object individuation.

1. Introduction

The exact nature and origin of subitizing, the immediate apprehension of the exact number of items in small sets, is currently debated. One hypothesis posits that it reflects a numerosity estimation process common for small and large sets, which precision decreases as the number of items increases, according to Weber's law (Dehaene & Changeux, 1993; Gallistel & Gelman, 1991). In a previous investigation, however, we have discarded this account by showing that enumeration responses (in terms of accuracy, estimates distributions, and reaction times) dramatically differ for sets of few items compared to sets with a large number of items with identical ratios (e.g. 1, 2, 3, ..., 8 vs. 10, 20, 30, ..., 80). Moreover, according to the single estimation process hypothesis, individual variability in subitizing capacity should correlate with the individual variability in the precision of large numerosity estimation. Thus, for example, a small subitizing capacity should indicate a rough internal representation of numerical quantity, which, in turns, should produce low accuracy in large numerosity estimation. Contrary to this prediction, however, we have shown that the two capacities do not correlate across subjects (Revkin, Piazza, Izard, Cohen, & Dehaene, 2008).

An alternative view on subitizing proposes that it reflects a mechanism of individuating multiple objects in parallel (Trick & Pylyshyn, 1994) that is not specific to the domain of number processing. The term "individuation" is here used to emphasize the fact that items are, through this mechanism, perceived as specific individuals with a given identity and spatial location. According to this view, such parallel individuation mechanism would be common to any tasks requiring multiple objects individuation. One such task is visual working memory (VWM), where subjects encode multiple objects at a time to subsequently compare them to other objects. Like subitizing, visual working memory also shows capacity limits of around three to four items (Luck & Vogel, 1997), even if the exact estimates of such limit are not fixed, but vary depending on the participants and task parameters (Alvarez & Cavanagh, 2004; Bays & Husain, 2008; Melcher, 2001; Melcher & Morrone, 2007).

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doi:10.1016/j.cognition.2011.05.007

In the developmental literature, this multiple object tracking mechanism is sometimes defined as based on "object files", intended as temporary representations of individual objects from a scene (for a review, see (Feigenson, Dehaene, & Spelke, 2004)). Physiologically, we may think of this mechanism as an internal map whereby a limited number of salient objects, as well as their locations can be highlighted in parallel and subsequently used for actions such as grasping or eye movements (Xu & Chun, 2009), or for cognitive tasks such as matching them with other objects or assessing their number (Gottlieb, 2007).

We thus reason that if subitizing relies on such a domain-general process of visuo-spatial individuation, which is not specific to numerical judgements, then the existing inter-individual variability in subitizing (Revkin et al., 2008) and VWM capacity (Vogel & Machizawa, 2004) should tightly correlate, in the absence of correlation between either of these measures with the precision of large numerosity estimation (Halberda, Mazzocco, & Feigenson, 2008; Piazza et al., 2010). We further reasoned that if the individuation process needs to be accessed simultaneously by the requirements of different tasks, as in a dual task condition, then we should observe decreased capacity. According with this idea, even an apparently basic ability like subitizing should be impaired if its core resource (the individuation "map") is being used for another task. To test this hypothesis, we measured enumeration accuracy with and without a concurrent VWM task. Finally, complementary to this prediction, we also reasoned that if large numerosity estimation abilities do not heavily rely on the individuation map, then they should not be impaired by a concurrent individuation task. Thus, we measured large numerosity comparison performance with and without a concurrent VWM task.

2. Methods

2.1. Single task experiment

Sixteen healthy participants (10 males, mean age = 26.2 years), naïve to the scope of the research, gave written informed consent. The experiment took place in a quiet, dimly lit room. Participants sat in front of the computer monitor at a viewing distance of about 50 cm and with their face fixed on a chinrest. Vocal and manual responses were recorded by a microphone and the E-prime response box respectively. Each participant performed the following three tasks, in randomized order.

2.1.1. Dots counting task

Participants were presented with arrays of one to eight colored dots appearing in a central gray circle subtending 3°, and asked to name aloud their number as quickly and accurately as possible (for one exemplar stimulus and the exact trial structure see Fig. 1, panel A). In order to make sure that participants' estimation was based on numerosity and not on other factors, dots were generated so that, across numerosities, half were of constant dot density and the other half of constant dot size (Revkin et al., 2008). Dot colors varied randomly among nine easily discriminable colors, selected without replacement. Responses given within 1600 ms were entered by the experimenter with a keyboard. The experiment started with 10 training trials, and comprised 160 trials, organized in five blocks.

2.1.2. Visual working memory task (hereafter VWM task)

Participants were presented with two arrays (a sample and a target array, separated by a retention interval) of one to eight dots of different colors (selected randomly without replacement), and were asked to perform a vocal same–different judgment. Apparatus and stimuli were the same as the dot counting task (see Fig. 2, panel A). In half of the trials the test array was identical to the sample array, while in the remaining half the color of one item was changed. Responses given within 2000 ms were entered by the experimenter with a keyboard. The experiment started with 10 training trials, and comprised 160 trials, organized in five blocks.

2.1.3. Dots comparison task

Participants were presented with two dots arrays (black, on a gray circular background, presented laterally of a central white fixation cross) and judged, without exact counting, which one contained more dots by pressing the response box button on the side of the larger array. The arrays remained on the screen until subjects gave their response. Dots number varied from 10 to 44, such that the numerical ratio between the two arrays spanned five values: 1.06, 1.14, 1.23, 1.33, or 1.6. The arrays were generated to be equated on half the trials in dot size and in the other half in occupied area (Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). The experiment started with 10 training trials and comprised 140 trials, organized in seven blocks.

2.2. Dual task experiments

Two new groups of subjects performed two separate experiments, one investigating the pattern of interference between VWM and counting, and the other investigating the pattern of interference between VWM and large number estimation.

2.2.1. Dots counting and VWM

Seventeen healthy adult subjects (seven males, mean age = 22.6 years) were tested. In the same trial, they performed two tasks, a counting and a working memory task, in a typical dual task condition. In order to obtain a baseline measure, they also performed the counting task alone while ignoring the working memory stimuli on the screen, and the VWM task alone while ignoring the enumeration stimuli, in separate blocks. Participants were first presented with a memory set of either two or four colored circles displayed near fixation. The circles were 1° in diameter and were in one of eight colors (black, white, red, green, blue, yellow, purple or brown), selected randomly without replacement. The memory set was then replaced with the counting set, consisting in arrays of one to eight Gabor stimuli (oriented contrast gratings windowed by a Gaussian function) displayed against a mean gray background and subsequently masked with 24 randomly oriented Gabor stimuli. Each

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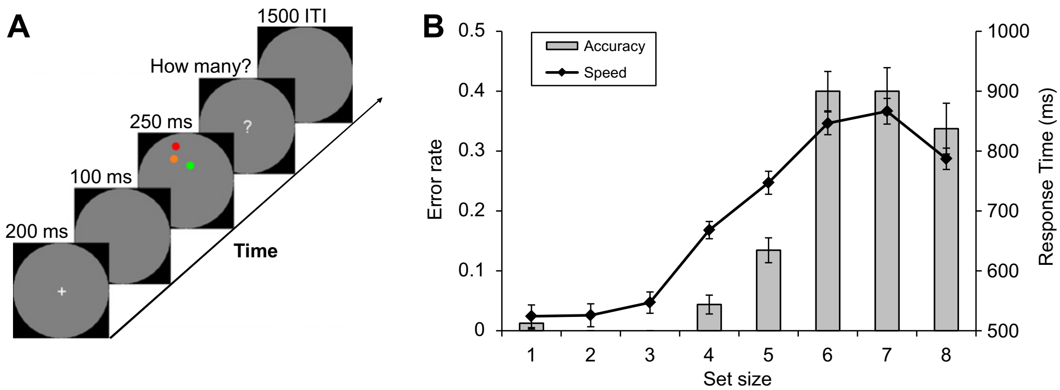

Fig. 1. Dots counting task. Example of stimuli, trial structure and timing (panel A). Performance (RTs and error rate) as a function of set size (panel B). Error bars are SEM.

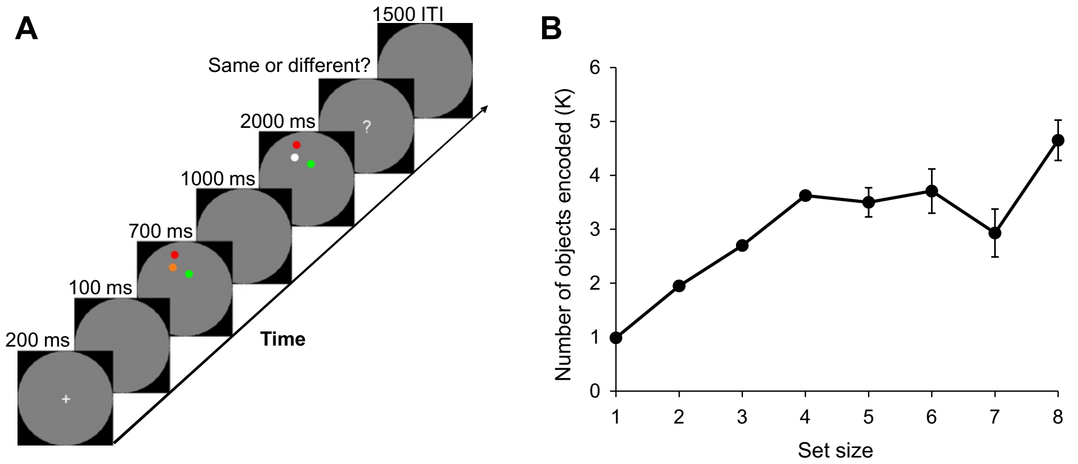

Fig. 2. Visual working memory task. Example of stimuli, trial structure and timing (panel A). Performance (in terms of number of objects encoded) as a function of set size (panel B). Error bars are SEM.

Gabor stimulus subtended 2° in visual angle and was located within a radius of 8° from the center of the screen. After the mask, the memory test set was shown. At the end of the trial participants were asked to first report the number of Gabor stimuli by typing in the number of items using the keyboard (primary task) and then report whether the two colored circle displays were identical or different (secondary task), again via key press (see Fig. 4, panel A). On 90% of trials, there were 1, 2, 4, 6 or 8 stimuli presented. The other 10% of trials, 3, 5, 7 or 9 stimuli were presented to ensure that participants did not always guess an even number when unsure (the first trial was set to always show 3, 5, 7 or 9 stimuli, for this reason). The counting and the VWM stimuli never spatially overlapped, as the area within a 3° radius from fixation was reserved to the VWM stimuli. The experiment started with 20 training trials and comprised 330 experimental trials, organized in three blocks.

2.2.2. Dots comparison and VWM

Fifteen healthy adult subjects (four males, mean age = 28 years), were tested. In the same trial, participants performed both a dot comparison and a working memory task, in a typical dual task condition. In order to obtain a baseline measure, they also performed the dot comparison task alone, while ignoring the working memory stimuli on the screen, in a separate block. The condition order (dual task first or control task first) was randomized across participants. Trials started with the presentation of a memory set consisting in one to eight colored dots which were displayed within a central gray circle (subtending 4.8°) for 500 ms. Dots were identical to the ones used in the single WM task (see description above). The memory set was then cleared from the screen and replaced after 500 ms with the comparison sets, consisting of two arrays of black dots, appearing in two lateral white circles at an offset of 5.7° from fixation bilaterally. Dots were identical to the ones used in the single dots comparison task (see description above). The comparison sets were presented for 1000 ms, and followed by 500 ms blank. Finally, the memory test set appeared in the central circle, for 250 ms, and was followed by 250 ms blank, marking the end of the trial. Participants were asked to first judge which lateral array contained more dots by pressing the mouse keys on the same side as the larger array (primary task), and then report whether the two colored circles sets displayed centrally were identical or different (secondary task), via keyboard key press. The experiment started with 10 training trials and comprised 200 trials, organized in five blocks.

3. Results

3.1. Single task experiments

In all three tasks we observed the expected patterns of results. In the dots counting task, mean correct response times (RTs) and errors increased with set size ($F(7, 105) = 155.279$, $p = 0.001$, and $F(7, 105) = 55.95$, $p = 0.000$, respectively), but only starting from numerosity 3 onwards (see Fig. 1, panel B).

We estimated, for each subject, the subitizing capacity (hereafter *S*) by fitting the full RTs curve with a sigmoid function of numerosity and taking the inflexion point of that curve (Revkin et al., 2008). Data fit was very good ($R^2 = 0.89$, SD = 0.09) and yielded a mean estimate across subjects of 4.47 (range = 3.81–5, SD = 0.36; Shapiro–Wilk test ($p = 0.57$) confirmed that data was normally distributed). While such sigmoid fit appeared to be the most appropriate approach to the present data (see Fig. 1, panel B), the numerical output used to estimate subitizing (e.g. the flex of the sigmoid) grossly overestimates the actual subitizing range (Revkin et al., 2008). Such overestimation should not be considered as a problem in this study because the scope of the fitting is to capture the inter-individual differences, and this method does this very well. However, in order to thoroughly check the consistency and reliability of our estimated inter-individual differences, we also fitted a bilinear function to the data and took the intersection between the two lines as another estimate of subitizing (Green & Bavelier, 2003). Given the drop in RTs for the large numerosity, probably due to guessing end-effects, we excluded the last data point, and fitted RTs for numerosities 1–7. This model also fit the data well ($R^2 = 0.94$, SD = 0.03), and gave an estimated subitizing range of 2.2 (range = 1.39–2.78, SD = 0.5, data not normally distributed, Shapiro–Wilk $p = 0.005$). Importantly, as expected, the ranges estimated with these two methods highly correlated across subjects ($R = 0.83$, $p = 0.000$).

In the VWM task, accuracy declined with increased set size (set size 1:99%; 2:98%; 3:95%; 4:95%; 5:85%; 6:81%; 7:73%; 8:78) ($F(7, 105) = 32.93$, $p = 0.000$) especially starting from sets with more than four objects.

The number of objects encoded at each set size (*N*), estimated with Cowan's *K* formula (Cowan, 2001), increased up to set size 4, and levelled off thereafter (see Fig. 2, panel B). For each subject, we took the average *K* across set sizes as an estimate of their capacity. Across subjects, the average estimated *K* was 3.01 (range = 1.6–4.1, SD = 0.62, data normally distributed, Shapiro–Wilk test $p = 0.69$).

In the dots comparison task, performance was modulated by the ratio between the sets, according to Weber's law. Accuracy was used to estimate the internal Weber fraction (hereafter *W*), a measure of the precision of the numerical estimation, for each participant, using a method previously described (Dehaene, 2007; Piazza et al., 2004). Data fit was very good (average $R^2 = 0.90$, SD = 0.12), and yielded a mean estimate of 0.20 (range = 0.09–0.32, SD = 0.067, normally distributed, Shapiro–Wilk test $p = 0.85$), in excellent agreement with previous reports (Piazza et al., 2010).

We conducted correlation analysis between the estimated measures: subitizing capacity (*S*), VWM capacity (*K*) and the numerosity estimation precision (*w*). If subitizing relies on a single process of visuo-spatial individuation, used for multiple tagging of objects in parallel in various tasks, then subitizing range and VWM capacity should tightly correlate, in the absence of correlation between these measures and the precision of numerosity comparison (*w*). Results clearly confirmed these predictions. First, we replicated the absence of correlation between subitizing capacity and numerosity comparison precision first observed by Revkin et al. (2008) ($R = 0.13$, $p = 0.63$, and $R = 0.12$, $p = 0.64$ for *S* calculated with the sigmoid and the bilinear fit respectively). Second, we confirmed that numerosity comparison precision was also unrelated to VWM capacity ($R = 0.07$, $p = 0.80$). Finally, and crucially, we observed a significant linear correlation between subitizing capacity and VWM capacity ($R = 0.73$, $p = 0.001$; 95% confidence interval, 0.37–0.9, and Kendall's Tau correlation coefficient = .370, $p = 0.04$, for the sigmoid and the bilinear fit for deriving *S*, respectively) (see Fig. 3).

We statistically confirmed that the correlation between *S* and VWM is significantly higher that the correlation between *S* and *W*, by performing a Z_1bar^* test (Steiger, 1980) ($Z = 2.228$, $p = 0.02$).

3.2. Dual task experiments

3.2.1. Dots counting and VWM

Without any added VWM load, counting performance was near perfect for up to four items, with a drop in proportion correct when six or eight items were presented. Thus, the subitizing range was around four items, consistent with previous reports. The addition of the VWM load

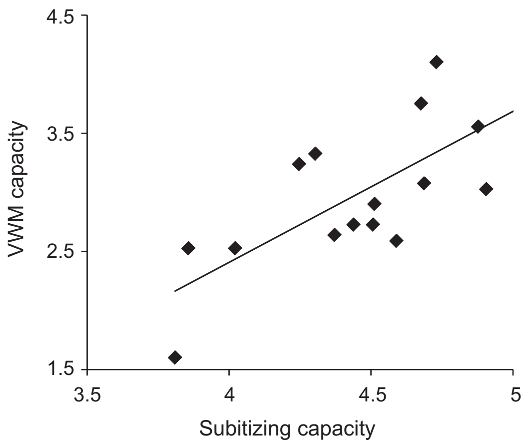

Fig. 3. Correlation between visual working memory and subitizing capacity across subjects.

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strongly modulated counting performance (ANOVA main effect of VWM load ($F(2,32) = 21.78$, $p < 0.001$)) (see Fig. 2, panel B). The effect of VWM increased for larger numbers of items (interaction between VWM load and set size ($F(8,32) = 2.35$, $p = 0.037$). The main effect of VWM load was significant for a memory load of two items ($F(1,16) = 13.01$, $p = 0.002$) and for the larger memory load of four items ($F(1,16) = 47.54$, $p < 0.001$).

In order to more directly test the hypothesis that subitizing capacity can be modulated by concurrent working memory load, we estimated, for each subject, the subitizing capacity (*S*) by fitting the accuracy curve with a sigmoid function of numerosity, closer to the accuracy data available in this experiment then a bilinear function fit (see Fig. 4, panel B). Data fit ($R^2 = 0.89$, SD = 0.16) yielded a average estimate of S across subjects and the three load conditions of 4.7 (SD = 0.97). Subitizing capacity correlated across subjects in the no load vs. load conditions ($R = 0.70$, $p = 0.002$), suggesting that our measure is a reliable one. Despite such inter-subject consistency, however, in confirmation to our hypothesis we observed that the estimated *S* was higher in the no load condition and decreased proportionally with VWM load (ANOVA main effect of VWM load $F(2,32) = 15.72$, $p < 0.001$, pairwise planned comparisons all $p < 0.001$).

Consistent with the hypothesis that VWM and enumeration would interfere with each other based on a shared capacity limit, performance on the VWM task was best when the number of items to enumerate was low (especially when there was only one item) and much worse when there were many items to enumerate. There was a main effect of the number of items to enumerate on VWM performance ($F(4,13) = 56.31$, $p < 0.001$). The presence of an interaction between the VWM set size and the number of items to enumerate ($F(4,13) = 8.35$, $p = 0.001$) may be explained by the particularly good performance when there were few items and a small set size (performance was near perfect for the VWM set size of two items when there was only one item to enumerate). This overall trend can be seen by plotting percent correct in the VWM task as a function of the total number of items presented during the trial, including both the memory set and the enumeration stimuli (see Fig. 4, panel C). The flex in the curve between three and four items suggests that here was a trade-off in performance consistent with a limited, shared resource for the two tasks.

3.2.2. Dots comparison and VWM

One subject responded quasi randomly in the dots comparison task, in both the no load and the load task, such that his psychometric curves were not fittable, and we thus excluded the data from further analysis. The significant correlation of the weber fraction across subjects in the no load

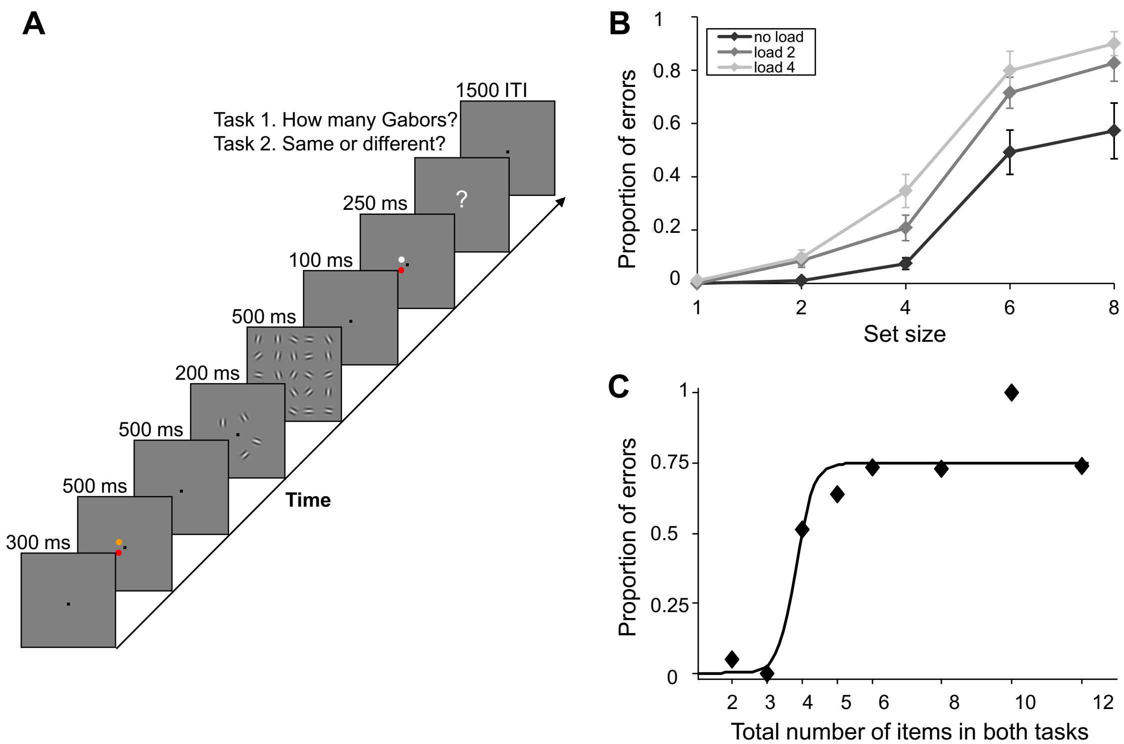

Fig. 4. Dual-task experiments. Example of stimuli, trial structure and timing (panel A). The Gabor stimuli were presented at 60% contrast, in order to maintain good visibility but avoid afterimages. Pilot testing revealed that up to nine stimuli could be accurately counted given unlimited time. Performance in the dots counting task as a function of set size (panel B). Separate lines show performance without a VWM load (black), with a concurrent memory load of two items (dark gray) or of four items (light gray). Performance in the VWM task as a function of total number of items presented during the memory set and enumeration set (panel C). Note that data for two and four items includes that found in the control condition in which the participants ignored the enumeration task and concentrated only on the VWM task. Error bars are SEM.

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vs. load conditions ($R = 0.82$, $p = 0.001$), suggests that our measure is a reliable one. Without any added VWM load, subjects were quit precise in the dots comparison task, yielding to an estimated weber fraction of 0.21 (SD = 0.09). For the condition with the additional VWM load, the weber fraction was equal to 0.26, (SD = 0.14), slightly higher than the no load condition ($t(13) = -2.371$, $p = 0.034$). Crucially, however, the weber fraction was not modulated by VWM load ($R = 0.187$, $p = 0.657$). In order to fit the psychometric functions at the individual subject level, we collapsed trials corresponding to low working memory load (1–4) vs. high WM load (5–8), in the dual task and the control task condition separately. Results showed no effect of working memory load ($F(1, 13) = 0.323$, $p = 0.679$), nor an interaction between task condition (single vs. dual) and working memory load ($F(1, 13) = 0.059$, $p = 0.811$).

Performance in the VWM task itself (the secondary task) remained extremely high, confirming that subjects were not ignoring the secondary task (average Cowan's $K = 3.5$, range = 0.6–6, SD = 1.41), despite the concurrent numerosity comparison task.

4. Discussion

In conflict with the idea that small numerosities are processed by a Weberian mechanism for extracting numerical information common for large and small numerosity, we found that individual differences in subitizing capacity do not correlate with individual difference in large number estimation precision. Thus, the two mechanisms seem to be of a different nature. This result is in line with recent work in favor of the notion of a dissociation between large and small numerosity processing in terms of attentional resources, showing that while subitizing is influenced by a concurrent attentional task, numerosity estimation is not (Burr, Turi, & Anobile, 2010).

Indeed, in agreement with the idea that small numerosities are processed by an object individuation mechanism dedicated to multiple objects processing, we observed that individual differences in subitizing capacity tightly correlated with the individual differences in VWM capacity. These results suggest that subitizing and visuo-spatial working memory share some key components, in particular those components that exhibit a capacity limit. Interestingly, independent work on the neural basis of capacity limits point to posterior parietal cortex as the locus of capacity limits, accounting for the inter-individual variability in performance in both subitizing (Piazza, Giacomini, Le Bihan, & Dehaene, 2003) and visuo-spatial working memory (Todd & Marois, 2004; Vogel & Machizawa, 2004). According to the object individuation hypothesis, at the origin of capacity limitations common to subitizing and visuo-spatial memory is the architecture of our sensory-motor system that generates maps of a limited number of salient objects and their locations in parallel. These maps are instrumental for keeping track of multiple items in order to guide cognition and action (Drew & Vogel, 2008; Gottlieb, 2007; Melcher, 2001; Melcher & Colby, 2008). Eventually, these maps support perceptual and numerical judgments of the sort explored in the present study.

By using a dual task paradigm, we provide further evidence that subitizing and visuo-spatial working memory share common resources. Indeed, we showed that the maintenance of two or four items in VWM interfered with enumeration by reducing the subitizing range. Likewise, the enumeration task interfered with the VWM task in a predictable manner, consistent with a common capacity limit. Complementary to this observation, and in agreement with our correlational results, we also show that loading VWM does not result in a decrease in precision of large numerosity estimation. This confirms the relative independence between object indexing processes (subitizing VWM) and numerosity estimation processes, and even suggests the possibility that these mechanisms rely on separable neural systems (see Piazza (2010) for a review of current imaging data).

The results of this study are also in line with previous research showing that subitizing is not fully automatic or "pre-attentive", in that its capacity can be reduced by concurrent visuo-attentive tasks (Egeth, Leonard, & Palomares, 2008; Olivers & Watson, 2008; Vetter, Butterworth, & Bahrami, 2008; Xu & Liu, 2008). Beyond the debate related to the nature of subitizing, these results also inform the working memory literature in that they suggest that the ability to store items in memory is closely related to the ability to quickly select individual. This individuation/selection step seems to form a first bottleneck which serves as an upper limit on the ability to track multiple items or maintain them in memory. Thus, the central capacity limitation on the number of items we can eventually recall might be crucially determined by the number of items we can initially encode (Drew & Vogel, 2008).

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