Cognition 121 (2011) 147–153

Contents lists available at ScienceDirect

Cognition

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

Brief article

Subitizing reflects visuo-spatial object individuation capacity

Manuela Piazza[a,b,c,*], Antonia Fumarola[a,d], Alessandro Chinello[a,b], David Melcher[a,b]

[a] Center for Mind/Brain Sciences, University of Trento, Italy
[b] Department of Cognitive Sciences, University of Trento, Italy
[c] INSERM, U562, Cognitive Neuroimaging Unit, Gif/Yvette, France
[d] Department of Psychology "Gaetano Kanizsa", University of Trieste, Italy

ARTICLE INFO

Article history:
Received 19 February 2010
Revised 6 May 2011
Accepted 21 May 2011
Available online 15 June 2011

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).

* Corresponding author at: INSERM, Cognitive Neuroimaging Unit, NeuroSpin Center, CEA Saclay, 91191 Gif-sur-Yvette, France. Tel.: +33 (0)1 69 08 19 06.
E-mail address: manuela.piazza@gmail.com (M. Piazza).

0010-0277/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
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