cortex 73 (2015) 73–79

Available online at www.sciencedirect.com

ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Note

‘How many’ and ‘how much’ dissociate in the parietal lobe

Francesca Lecce [a,b,*], *Vincent Walsh* [a], *Daniele Didino* [c] *and Marinella Cappelletti* [a,d]

[a] *UCL Institute of Cognitive Neuroscience, London, UK*
[b] *Department of Neuropsychology, National Hospital for Neurology and Neurosurgery, London, UK*
[c] *Department of Economics, Tomsk Polytechnic University, Tomsk, Russia*
[d] *Department of Psychology, Goldsmiths College, University of London, UK*

ARTICLE INFO

Article history:
Received 18 March 2015
Reviewed 8 July 2015
Revised 31 July 2015
Accepted 5 August 2015
Action editor H. Branch Coslett
Published online 20 August 2015

Keywords:
Numerosity processing
Continuous quantity
Parietal lobe
TMS

ABSTRACT

We investigated whether two features that are fundamental for quantity processing, namely numerosity and continuous quantity – or 'how many' versus 'how much' – may dissociate in the parietal lobe. Fourteen mathematically-normal participants performed a well-established numerosity discrimination task after receiving continuous theta burst transcranial magnetic stimulation (TBS) over the left or right intraparietal sulcus (IPS) or the Vertex. We performed a detailed analysis of accuracy (based on the Weber Fraction, wf), which distinguished between trials in which numerosity was anti-correlated or 'incongruent' to other continuous measures of quantity, and trials in which numerosity and other continuous features were 'congruent'. Congruent trials can be processed by integrating numerosity or continuous quantity features like cumulative area since they correlate. Instead incongruent trials can only be processed based on numerosity and requires inhibiting cumulative area or other continuous quantity features like dot size and would lead to incorrect judgment if these features are used as a proxy for numerosity.

We found an increase of wf, i.e., weakened numerosity processing in incongruent but not congruent trials following left IPS-TBS, which suggests that numerosity processing was impaired while continuous quantity processing remained unchanged. Moreover, wf increased in congruent but not in incongruent trials following right IPS stimulation. We concluded that left and right parietal are respectively critical for numerosity discrimination, i.e., 'how many' or alternatively for response selection, and for integrating numerosity and continuous quantity features.

* *Corresponding author*. UCL Institute of Cognitive Neuroscience, 17 Queen Square, London, WC1N 3AR, UK.
E-mail addresses: franc.lecce@gmail.com, f.lecce@ucl.ac.uk (F. Lecce).
http://dx.doi.org/10.1016/j.cortex.2015.08.007

1. Introduction

In everyday life we effortlessly indicate how many items are in a set or which set of objects has more elements, for instance which queue has more people at the supermarket, or whether there are more men or women in an audience. This ability, referred to as numerosity discrimination or 'number acuity' (Halberda, Mazzocco, & Feigenson, 2008) and which relies on an 'approximate number system' (Feigenson, Dehaene, & Spelke, 2004), enables us to perform rough numerical estimates and to use this information to guide decisions. Number acuity is typically measured in terms of Weber Fraction (*wf*), which reflects the amount of noise in the underlying approximate number representation (Halberda et al., 2008; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004).

Numerosity tends to correlate with other continuous sensory dimensions, for instance cumulative area, density or size of the individual items. Numerical information can typically be extracted from a visual scene even when numerosity and these continuous dimensions do not correlate (e.g., Gebuis & Reynvoet, 2014), for example we can determine that 5 grapes are more than 2 apples despite being smaller in size (Stavy & Tirosh, 2000). This has been taken as evidence that numerosity estimation (*how many*) is independent from other continuous dimensions (*how much*) (e.g., Halberda & Feigenson, 2008; Halberda et al., 2008; Piazza et al., 2010).

Some more recent studies have, however, challenged this view suggesting that instead numerosity processing is intrinsically dependent from or modulated by continuous quantity (Cappelletti, Didino, Stoianov, & Zorzi, 2014, 2015; Dakin, Tibber, Greenwood, Kingdom, & Morgan, 2012; Gebuis & Gevers, 2011; Gebuis & Reynvoet, 2012a, 2012b, 2014; Henik, Leibovich, Naparstek, Diesendruck, & Rubinsten, 2012; Hurewitz, Gelman, & Schnitzer, 2006; Mix, Huttenlocher, & Levine, 2002; Szucs, Devin, Soltesz, Nobes, & Gabriel, 2013). These studies are based on the distinction between '*congruent*' and '*incongruent*' numerosity trials, whereby numerosity either correlates with or instead is inversely correlated to continuous variables (Cappelletti et al., 2014, 2015; Gebuis & Gevers, 2011; Gebuis & Reynvoet, 2012a, 2012b, 2014; Szucs et al., 2013). While congruent numerosity trials benefit from integrating different visual cues (i.e., numerosity and continuous quantity information) since they correlate, in incongruent numerosity trials continuous variables anti-correlating with numerosity need to be inhibited (Cappelletti et al., 2014, 2015; Dakin et al., 2012; Geibus & Reynvoet, 2011, 2012a, 2012b, 2014; Henik et al, 2012; Szucs et al., 2013), an operation which is especially demanding in ageing (Cappelletti et al., 2014, 2015), in dyscalculia (Szucs et al., 2013), and in infants (Suanda, Thompson, & Brannon, 2008). Neuroimaging studies have typically not distinguished between congruent and incongruent numerosity trials (e.g., Dehaene, Piazza, Pinel, & Cohen, 2003; Piazza et al., 2004; Pinel, Piazza, Le Bihan, & Dehaene, 2004), but an exception is a recent EEG study showing that the left parietal lobe can detect lack of co-variation between numerosity and continuous quantity in a stimulus display (i.e., incongruent numerosity trials), but it is not involved when these dimensions co-vary (Gebuis & Reynvoet, 2014). In this study, participants were asked to passively view sets of visual stimuli increasing or decreasing in numerosity. When numerosity and its sensory properties were manipulated in different directions (i.e., one dimension increased while the other decreased) a left parietal activation was observed. These results show that numerosity is not processed independently from sensory cues and suggest a critical role for the left parietal cortex in detecting a violation of this expectation (Gebuis & Reynvoet, 2014).

It is however not clear whether the parietal cortex is equally critical for processing numerosity and continuous quantity, i.e., whether these dimensions may dissociate in the parietal cortex. Here we addressed this issue using continuous theta burst transcranial magnetic stimulation (TBS), a safe technique capable of producing consistent and rapid behavioural changes in the function of the human motor (e.g., Huang, Edwards, Rounis, Bhatia, & Rothwell, 2005) and parietal systems (e.g., Cheng, Tang, Walsh, Butterworth, & Cappelletti, 2012). We used TBS to the left and right parietal lobes in young, mathematically-normal participants, and combined it with an established numerosity discrimination paradigm (Halberda et al., 2008) whereby intermixed trials requiring or not to inhibit continuous quantity variables were used. We reasoned that if the left parietal lobe is involved in detecting lack of co-variation between numerosity and its sensory properties, then left parietal-TBS may modulate performance in incongruent numerosity trials more specifically. This result would indicate that the left parietal lobe may be more critical for discriminating numerosities –'how many'– but not for continuous quantity dimensions –'how much'. We expected that right parietal-TBS may be more involved in integrating different visual cues and therefore may specifically modulate performance in congruent trials since they benefit from such integration (Cappelletti, Barth, Fregni, Spelke, & Pascual-Leone, 2007; Cohen Kadosh et al., 2007).

2. Methods

Stimulus presentation and data collection were controlled using the Cogent Graphics toolbox (http://www.vislab.ucl.ac.uk/Cogent) and MATLAB 7.3 software on a Sony PCG laptop computer with video mode of 640 × 480 pixels, and 60 Hz refresh rate.

2.1. Participants

Fourteen right-handed participants (mean age 26.7 years; range 19–40; 5 males) with normal or corrected-to-normal vision were recruited according to exclusion criteria used for Transcranial Magnetic Stimulation and gave written consent to participate in our study approved by the local Ethics Committee. Data were collected in three testing sessions, 2–7 days apart.

2.2. Experimental task: numerosity discrimination

2.2.1. Stimuli and procedure

The numerosity discrimination task required judging which of two intermixed collections of blue and yellow 5 to 16 dot stimuli each was more numerous (Halberda, Lya, Wilmerb, Naimana, & Germine, 2012; Halberda et al., 2008; Cappelletti