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Differential effects of left parietal theta-burst stimulation on order and quantity processing

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ABSTRACT

Numbers can be used to represent different meanings, including order information ('Steve lives at house number 24') and quantity ('Steve is paid 24 pounds'). The few previous neuroimaging studies that investigated order and quantity processing reported conflicting evidence as to whether same or partially overlapping brain systems are engaged in these processes. Such inconsistencies may be related to the use of neuroimaging techniques which do not allow causal inference regarding brain-behaviour relationships. To overcome this problem, the present study employed continuous theta-burst stimulation (TBS) to investigate whether interference to either the left or right parietal regions affected order and quantity in similar or different ways. Results revealed that following TBS to the left intraparietal sulcus, quantity processing was impaired and order facilitated; TBS to the contralateral brain region led to no specific effects in either order or quantity processing. These findings suggest that there are at least partially different neuronal populations involved in order and quantity processing, and that the left parietal cortex is critical for both processes.

Introduction

In everyday life we effortlessly use different meanings of numbers, including *quantity* (e.g. 'Steve is paid 24 pounds') and *order*, sometimes called rank (e.g. 'Steve lives at house number 24'). Very few studies have explored order processing and in particular the issue of whether this is distinct from quantity or not. Findings from these studies are in support of either one of the following not mutually exclusive positions: (1) order and quantity are processed in similar ways [1–3] or (2) processing order and quantity information require at least partially distinct cognitive mechanisms [4–7].

A common representation for order and quantity has been suggested by studies reporting similar brain regions activated by processing order and quantity information. For instance, the bilateral intraparietal sulci (IPS) have been reported to be activated by both a numerical quantity task and an order task that used letters of the alphabet as stimuli [1]. Similarly, it was found that both order and quantity processing involve left IPS activation, although they showed different numerical distance effects which may suggest independent cognitive mechanisms being used [2]. On the other hand, evidence supporting distinct representations for order and quantity comes from an event-related potentials (ERPs) study. This reported only partially overlapping neural courses for order and quantity, the latter associated with brain signals in the left parietal cortex, the former with bilateral and delayed parietal signal [6]. Support for separable order and quantity processes also comes from a few single-case studies of neurological patients showing double dissociations between these processes [8–10]. The inconsistencies between studies supporting common or distinct representations between order and quantity may be methodological. It is possible that some early functional imaging studies claiming common brain regions involved in order and quantity processing may have used methods that did not allow us distinguishing between order and quantity-related areas. Indeed, based on a more sophisticated method such as multivariate pattern recognition [11], a recent re-analysis of the data reported in a previous study which supported the 'common' position [1] has in fact identified separable sets of voxels within the IPS for order and quantity processing [7].

Functional imaging is essential to identify the brain regions involved in order and quantity processing, but it does not allow us

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Table 1
Examples of the experimental trials used and corresponding answers for the order and quantity tasks. (For interpretation of the references to colour in this table, the reader is referred to the web version of this article.)

Order Correct order?	Correct response?	Quantity More red or green Xs?	Correct response?
← X4XXXXX3X	Yes	↔ XX3XX6XXX	Green
→ X4XXXXX3X	No	↔ X4XXXXX3X	Red

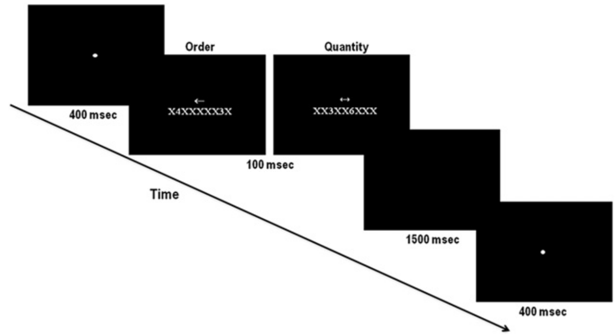

Figure 1. Timeline of a single experimental trial.

to establish whether these regions are also critical for those processes. Transcranial magnetic stimulation (TMS) has been successfully used to establish the causal involvement of a brain region in a cognitive function. For instance, the IPS has been shown to be critical for number quantity processing [12], but so far no study investigated whether this is also the case for order processing. The aim of the present study was therefore to investigate the interplay between order and quantity processing by testing the brain regions that may be critical for them. To achieve this, TMS in the form of continuous theta-burst stimulation (TBS) was used to investigate the extent to which the IPS may be equally critical for order and quantity processing. The bilateral IPS were chosen as target regions since: (i) previous functional imaging studies indicated that this region to be most consistently associated with order processing [1,2]; and (ii) previous transcranial magnetic stimulation studies revealed the IPS to be critically involved in quantity [12]. If order and quantity processing indeed rely on the same neuronal resources, then IPS-TBS should affect performance on both tasks. Conversely, if order and quantity involve different brain areas, then IPS-TBS may result in different effects.

Methods and materials

Participants

Twenty-one neurologically healthy adults participated in the present study. A screening was conducted to ensure that all participants were TMS-compatible, i.e. that they had no history of neurological conditions, seizure, loss of consciousness, or serious illness, and currently not taking any form of medication, suffer from frequent or severe headaches, or having family members with epilepsy. As an additional safety precaution, only one of the targeted brain areas (LIPS, RIPS, vertex) was stimulated per day for participants who were able to come back for more than one testing session. Specifically, 4 participants attended three sessions on three separate days, 5 attended two sessions on two separate days, and 12 attended one session only. For each of the three targeted areas there was an equal number of 11 participants; data from one participant who attended one session only was discarded as he obtained abnormally high error rates (i.e. higher than 40% error). Participants were initially randomly assigned to one of three targeted areas: (i) left IPS (mean age 24.2 $\pm$ 5.20, 2 males); (ii) right IPS (mean age 24.0 $\pm$ 5.39, 3 males); and (iii) vertex (mean age 22.6 $\pm$ 5.20, 2 males). For participants who attended more than one session, the order of stimulation sites was counterbalanced such that the targeted areas were not stimulated in the same order. All participants reported normal or corrected-to-normal vision. The factors that influence individual variability in neuroplasticity induction are becoming increasingly well-established. These factors include age, gender, level of physical exercise, time of day, attention, etc. [13]. Our participants across the different conditions were matched in some of these factors (i.e. age and gender), and other factors were assumed to be matched based on the randomization procedure. The Ethics Committee of the Institute of Neurology, University College London, approved the present study which was performed in accordance with the standard TMS safety procedures [14].

Stimuli and tasks

The current experimental tasks were adapted from a previous study that also investigated order and quantity processing [5]. Each stimulus consisted of an array of nine items presented side-by-side at the centre of a computer screen on a black background. Two of these nine items were single-digit numbers (ranging from 1 to 7); the other seven items were ‘X’s. Some of the items were presented in red, others in equiluminant green. The array subtended a visual angle of approximately 11.9° (width) and 0.96° (height). For the order task, a white arrow pointing either left- or right-ward was presented directly above and at the same time as the stimulus. For the quantity task, a similar arrow pointing simultaneously at both left and right was presented; this aimed to match the visual presentation of the order task.

In the order task, participants decided whether the two numbers in the array were in the correct ascending order according to the direction of the arrow. Prior to the beginning of this task, participants were instructed to ignore the ‘X’s in the array. In the quantity task, participants decided whether there were more green ‘X’s or red ‘X’s in the array. Participants were instructed to ignore the arrow and the two numbers in the array. One number was always presented in green while the other in red so the correct answer did not change even if participants included the numbers in their judgements. The larger number was always in the colour of the larger set so that any incongruent numerical Stroop effect could be avoided [15,16]. The numerical distance of stimuli was manipulated [17]. In the order task, the distance between the two presented numbers referred to the numerical difference between them. There were two possible distances: 2 (i.e. 1–3; 3–5; 4–6) and 4 (i.e. 1–5; 2–6; 3–7). In the quantity task, the manipulation of distance referred to the difference between the number (or numerosity) of green and red ‘X’s. The distances were always 1 (small) or 3 (large), namely, for each array there were always either 3 ‘X’s in one colour and 4 ‘X’s in the other colour (for distance 1); or 2 ‘X’s in one colour and 5 ‘X’s in the other colour (for distance 3). The range of numerosity chosen (i.e. 2–5) was within the canonical subitizing range, so that answers were likely to be based on processing discrete items, rather than continuous quantity, i.e. amount of colour [18]. However, since the discrete and continuous quantity correlated in the quantity task, it is not possible to identify the precise quantity strategy used by participants to perform the task. See Table 1 for example trials of each task.

The timeline of a single trial is illustrated in Fig. 1. Following a 400 msec fixation point, each stimulus was presented for