Check for updates

Commonalities for Numerical and Continuous Quantity Skills at Temporo-parietal Junction

Marinella Cappelletti[1,3], Rebecca Chamberlain[1], Elliot D. Freeman[2], Ryota Kanai[1], Brian Butterworth[1], Cathy J. Price[1], and Geraint Rees[1]

Abstract

■ How do our abilities to process number and other continuous quantities such as time and space relate to each other? Recent evidence suggests that these abilities share common magnitude processing and neural resources, although other findings also highlight the role of dimension-specific processes. To further characterize the relation between number, time, and space, we first examined them in a population with a developmental numerical dysfunction (developmental dyscalculia) and then assessed the extent to which these abilities correlated both behaviorally and anatomically in numerically normal participants. We found that (1) participants with dyscalculia showed preserved continuous quantity processing and (2) in numerically normal adults, numerical and continuous quantity abilities were at least partially dissociated both behaviorally and anatomically. Specifically, gray matter volume correlated with both measures of numerical and continuous quantity processing in the right TPJ; in contrast, individual differences in number proficiency were associated with gray matter volume in number-specific cortical regions in the right parietal lobe. Together, our new converging evidence of selective numerical impairment and of number-specific brain areas at least partially distinct from common magnitude areas suggests that the human brain is equipped with different ways of quantifying the outside world. ■

INTRODUCTION

Philosophers, neurologists, educators, and psychologists have long pondered the relation between number and continuous quantities, such as space and time (see Dehaene & Brannon, 2011): Are these dimensions built on one common system for quantification, or do they stand independently from each other? The first hypothesis derives from the popular idea that number, time, and space all depend on shared magnitude processing (Bueti & Walsh, 2009; Cantlon, Platt, & Brannon, 2009; Walsh, 2003). However, evidence for this common processing is mixed. For example, supporting data come from the similarity of performance in number, time, or space processing (e.g., Brannon, Suanda, & Libertus, 2007; Zorzi, Priftis, & Umiltà, 2002), but the opposite possibility—that number, time, and space may each be fully independent—is supported by TMS and lesion studies showing dissociations among these dimensions (e.g., Aiello et al., 2012; Dormal, Seron, & Pesenti, 2006; Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005). A third, intermediate, possibility is that number, time, and space are only partly independent (e.g., Walsh, 2003). This is suggested by interactions between dimensions: For instance, large numbers can be perceived as longer than veridical in physical size or duration (e.g., Dormal et al., 2006), even when number or time are selectively impaired by brain lesions (Cappelletti, Freeman, & Cipolotti, 2009, 2011).

Previous studies investigated the relationship between number, time, and space by examining performance either averaged across groups or in single cases, but here we complemented this approach by focusing on individual differences in task performance and in brain anatomy. Individual differences were assessed within the normal and abnormal spectrum of numerical skills, the latter consisting of participants whose numerical abilities are developmentally impaired, that is, dyscalculia (Butterworth, 2003). Our reasoning for including participants with dyscalculia was that they offer a unique perspective on the relation between number, time, and space and in particular, because number skills are by diagnosis impaired in dyscalculia, on possible associations or dissociations between number, time, and space.

The above three hypotheses on the link between number, time, and space predict different patterns of results. The proposal of a common magnitude system predicts that numerical proficiency will be associated with performance in continuous quantity discrimination in numerically normal and in participants with dyscalculia and also a possible correlation of number, time, and space measures with the volume of common brain regions. In contrast, the second hypothesis of fully independent magnitude dimensions predicts dissociation between behavioral measures and independent correlations of each measure with the

---

[1]University College London, [2]City University London, [3]Goldsmiths College, University of London

© 2014 Massachusetts Institute of Technology Published under a Creative Commons Attribution 3.0 Unported (CC BY 3.0) license

doi:10.1162/jocn_a_00546

Downloaded [illegible] 17 May 2021

volume of distinct brain regions. Dyscalculics' performance may provide converging evidence of independent rather than shared processes among dimensions if number processing dissociate from maintained continuous quantity processing. The third hypothesis of partial independence of number and continuous quantity processing predicts a partial correlation between behavioral measures, which may be associated with both common and distinct brain regions.

We first tested whether continuous quantity processing was maintained in participants with dyscalculia; having found a dissociation between impaired numerical abilities and preserved continuous quantity skills in dyscalculia, we then measured correlations between individual differences in number, time, and space performance in another non-dyscalculic sample for whom numeracy skills varied within the normal range. In the same sample, we used voxel-based morphometry (VBM; Ashburner & Friston, 2000), optimized for neurologically normal brains, to test whether our behavioral measures each correlated with anatomical differences in common and/or distinct brain areas.

METHODS

For all participants, we administered a series of carefully selected numerical and arithmetical tasks, as well as psychophysical tasks measuring continuous quantity discrimination in space and time. Our choice of tasks and stimuli was motivated by the aim of measuring numerical/arithmetical and continuous quantity skills as independently as possible. This independence was essential to obtain an unbiased measure of how these cognitive abilities correlate with each other. We reasoned that if experimental paradigms that are different but more suited to test each individual magnitude dimension result in similar behavioral and anatomical responses in processing number, time, and space, then such similarities are more likely to be accounted for by a common magnitude system or other processes shared between number and continuous quantity. We used symbolic numbers (1–9), typically employed to test numerical proficiency (Butterworth, 2010) independently from nonsymbolic continua (horizontal lines changing in length or duration), such that numbers were never manipulated along continuous dimensions and nonsymbolic continua were never presented with symbolic numbers.

Participants

Ninety-three right-handed, neurologically normal adults with normal or corrected-to-normal vision gave written informed consent to take part in the study. The main sample consisted of 16 participants (mean age = 34.7 years, range = 22–38 years, 15 women, 1 man) who had been diagnosed with dyscalculia (see below) and 37 participants who were age- and gender-matched to the previous group (Control Group 1: mean age = 23 years, range = 19–35, 23 women) but with numerical abilities within the normal range. All participants performed the numerical and continuous quantity tasks, and we obtained brain scans from 37 nondyscalculic participants only. Two additional groups of numerically normal participants performed two supplementary control tasks (Supplementary Task 1 in Control Group 2: $n = 18$, mean age = 26.1 years, range = 20–35 years, 8 women; Supplementary Task 2 in Control Group 3: $n = 22$, mean age = 24.6 years, range = 20–34 years, 13 women). The study was approved by the local research ethics committee.

Participants with Dyscalculia

Dyscalculia was diagnosed before participants were invited to take part in the study. The diagnosis was based on (1) the Dyscalculia Screener (Butterworth, 2003); (2) a standardized arithmetical task, that is, the Graded Difficulty Arithmetic Task (Jackson & Warrington, 1986); (3) the arithmetic subtest of WAIS-R (Wechsler, 1986); and (4) a task consisting of discriminating the numerosity of clouds of dots, which allows the calculation of the Weber fraction, an index of accuracy sensitive to dyscalculia (Mazzocco, Feingenson, & Halberda, 2011; Piazza et al., 2010; Halberda, Mazzocco, & Feigenson, 2008). General intelligence was also assessed (Wechsler, 1986).

In the Dyscalculia Screener, all 16 participants with dyscalculia obtained a score below the cutoff point in either the capacity or the achievement scale, thereby fulfilling the criteria for dyscalculia. They were also impaired in the other numerical or arithmetical tasks consistent with their diagnosis. IQ was average or high average, suggesting preserved intellectual functioning (see Table 1).

Experimental Tasks

There were two sets of experimental tasks, one testing continuous quantity discrimination and the other testing numerical competence. Stimulus presentation and data collection were controlled using the Cogent Graphics toolbox (www.vislab.ucl.ac.uk/Cogent/) and MATLAB 7.3 software on a Sony S2VP laptop computer with video mode of 640 × 480 pixels, screen dimensions of 20.8° horizontal by 15.83° vertical and 60 Hz refresh rate. Participants placed their head on a chin rest positioned 50 cm from the screen.

Continuous Quantity Tasks

Two tasks were used, which have been extensively employed in neurologically normal and brain-lesioned participants (Cappelletti, Freeman, & Butterworth, 2011; Cappelletti, Freeman, & Cipolotti, 2011; Cappelletti et al., 2009). The two tasks required comparing visual stimuli along the dimension of length or the orthogonal dimension of time.

Downloaded from http://direct.mit.edu/jocn/article-pdf/26/5/986/1947336/jocn_a_00546.pdf by guest on 17 May 2021

Table 1. Performance of Numerically Normal Participants and of Participants with Dyscalculia in IQ and in Number Tasks (Stanine Score, Percentile, or Weber Fraction and Standard Deviation in Brackets)

Tasks Performed	*Numerically Normal Participants*	*Participants with Dyscalculia (n = 16)*
IQ[a]		112.7 (14.06)
Number tasks		
Dyscalculia Screener[b]		**2.36** (0.56)
Capacity subscale		**2.5** (0.8)
Dot–number matching	≥3	**2.69** (0.7)
Number Stroop	≥3	**2.0** (0.97)
Achievement subscale		**2.38** (0.7)
Addition	≥3	**2.56** (0.8)
Multiplication	≥3	**2.03** (0.94)
Graded Difficulty Arithmetic Test[c]	25–75[d]	**18**[d] (17.5)
Arithmetic subtest of WAIS-R	25–75[d]	**15**[d] (16.1)
Number discrimination (*wf*)[e]	0.27 (0.04)	**0.47** (0.16)

Impaired performance is shown in **bold**. Independent sample *t* tests were used to analyze performance of the group with dyscalculia relative to numerically normal age-matched participants (*n* = 50, 33 women, mean age = 35.6 years, *SD* = 9.43) who took part in a previous study (Cappelletti et al., in press); performance of individual dyscalculic was analysed with Crawford et al. (1998) *t* test.

[a] WAIS-3 (Wechsler, 1986). Full IQ calculated disregarding performance in the arithmetic subtask.

[b] Dyscalculia Screener expressing performance as stanine score ranging from 1 to 9 where ≤3 indicate an impairment (see Butterworth, 2003).

[c] Jackson and Warrington (1986).

[d] Percentile.

[e] Performance expressed as Weber fraction (*wf*, Halberda et al., 2008), an index sensitive to dyscalculia (e.g., Mazzocco et al., 2011; Piazza et al., 2010). Participants with dyscalculia were significantly impaired relative to a sample of numerically normal participants who took part in previous studies [$t(64) = 5.3, p < .001$].

Stimuli. These consisted of two horizontal white lines (thickness = 0.17°) centered on the vertical meridian on a black background and presented sequentially in a two-interval discrimination paradigm, one line 5.07° above the horizontal meridian and the other 5.07° below in random order.

Design. The first line stimulus (the Reference) was fixed (length of 10.29° and duration of 600 msec), whereas the second line (the Test) could vary according to the method of constant stimuli either in length or duration, depending on the dimension to be judged (the irrelevant dimension always matched the Reference). For each dimension, the ratio between the smaller and the larger stimulus could vary unpredictably over five levels: 1.06, 1.13, 1.2, 1.26, and 1.33 for time and 1.025, 1.05, 1.075, 1.10, and 1.25 for length, selected from previous studies (Cappelletti, Freeman, & Cipolotti, 2011; Cappelletti et al., 2009). Test stimulus values were randomly sampled without replacement from a set of five equally spaced values for each dimension (steps of 0.257° for length and 40 msec for time) with equal frequency. There were five blocks of 40 observations for each level of the test stimulus (total 200 observations for each task). The time and space discrimination tasks were run independently from each other in counterbalanced order across participants to avoid order effects.

Procedure. Each trial began with a centrally displayed fixation point (diameter = 0.17°), which remained visible until a key-press from the participant. The reference line was then immediately displayed followed by the test line and an interstimulus interval of 100 msec. The screen then remained blank with a fixation cross in the middle until a response from the participant. The next trial immediately followed the response (see Figure 1, bottom). In each task, participants made unspeeded responses by pressing either the "up" or "down" cursor arrow keys of the computer keyboard if either the upper or the lower line appeared the longest, either in duration or in spatial extent. Correct answers were equally assigned to the "up" or "down" keys in each task. For each task, before the first experimental block participants had at least 20 practice trials, which were not included in analysis.

Number Tasks

To test numerical and arithmetical competence, three tasks were devised (see Figure 1, top), for which participants were instructed to make speeded answers;

Downloaded ... 17 May 2021

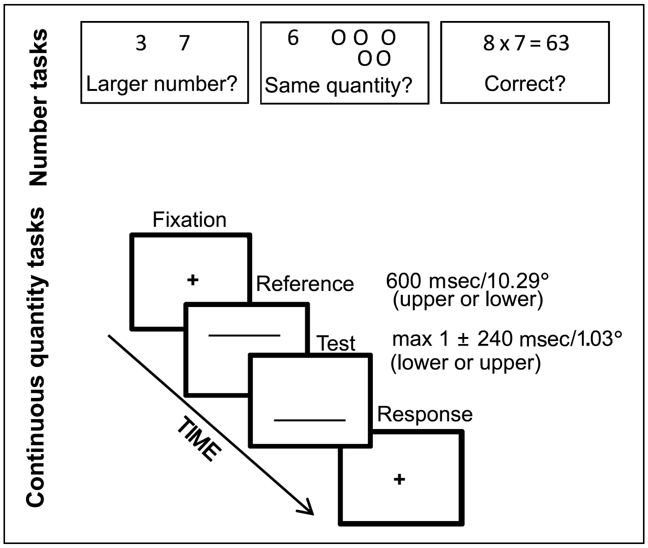

Figure 1. Experimental tasks. Schematic depiction of the number/arithmetic and the continuous quantity discrimination tasks. In the number tasks, participants had to decide (from left: the larger among two numbers; whether a number and a set of dots indicated the same quantity; whether the result of arithmetical operations was correct). In the continuous quantity tasks, participants indicated whether the upper or the lower line was longer in either duration or length, in different blocks.

accuracy and RTs were collected. These tasks were similar but not identical to those used to diagnose dyscalculia: For instance, the Screener uses a “Number Stroop” task where numbers change in value as well as physical size (e.g., 1 vs. 3) because this task is sensitive to dyscalculia (e.g., Rubinsten & Henik, 2005); moreover, the Screener is based on addition and multiplication problems only. In contrast, our experimental tasks used a number comparison task where the numbers changed only in value but not physical size; our tasks also included subtraction problems besides addition and multiplication to better capture the cognitive processes underlying different arithmetical operations because subtractions are thought to rely on quantity-based processes, whereas multiplications and additions on verbal memory processes (Dehaene, Piazza, Pinel, & Cohen, 2003).

Arithmetical verification. This task required participants to indicate as fast as possible using predefined response keys whether an arithmetic problem displayed the correct or incorrect answer. Twenty single-digit problems for each type of operation (addition, subtraction, and multiplication) were presented in separate blocks.

STIMULI AND DESIGN. Single-digit and two-digit Arabic numbers were presented as operands or as possible results of the arithmetical operations. For instance, participants were presented with problems such as “9 + 6 = 13,” “7 − 2 = 3,” or “6 × 3 = 16.” When results were incorrect, these were either 1 or 2 units apart from the correct result for addition and subtraction problems (e.g., “9 + 6 = 13” or “7 − 2 = 3”) or 2 units apart for multiplication problems (e.g., “6 × 3 = 16”).

PROCEDURE. Following a 500-msec central fixation cross, each operation was presented for up to 7 sec during which participants could provide an answer.

Number comparison. This asked participants to indicate as fast as possible the larger of two Arabic numbers.

STIMULI AND DESIGN. Thirty-six pairs of single-digit Arabic numbers (1–9) were individually presented. Using a design similar to previous studies (e.g., Cappelletti, Didino, Stoianov, & Zorzi, in press), the following numerical distances were used: 1 (e.g., 7 vs. 6 or 4 vs. 5; eight trials), 2 (e.g., 3 vs. 1 or 7 vs. 9; eight trials), 3 (e.g., 5 vs. 8 or 4 vs. 1; eight trials), 4 (e.g., 6 vs. 2 or 3 vs. 7; eight trials), 5 (e.g., 9 vs. 4 or 1 vs. 6; four trials). Within each numerical distance, there was an equal number of trials where the smaller digit was displayed on the left or on the right of fixation.

PROCEDURE. Stimulus pairs were centered along the horizontal line of the computer screen and each displayed for 500 msec to the left or the right of the fixation cross. Stimuli were then replaced by a black screen for a maximum of 4 sec during which participants made an answer. After this, the following trial started immediately. Participants were required to make speeded answer by pressing one of two predefined keys.

Dot–number matching. This required participants to indicate as fast as possible with a finger press whether or not an Arabic number presented in one hemifield matched the number of dots presented in the other hemifield.

STIMULI AND DESIGN. Thirty-six pairs of stimuli ranging from 1 to 9 were used. When the stimuli did not match, they could differ by 1, 2, 3 or 4 units, for instance, 6 dots presented with the Arabic number 5, or 7 dots with number 8, or 5 dots with number 2.

PROCEDURE. Each pair of stimuli was presented for 500 msec with hemifield assignment of the dot and number stimuli counterbalanced between trials.

Control Tasks

Two control tasks were designed to match either the behavioral measures (accuracy and speeded RTs) or the experimental paradigm (line stimuli presented above and below fixation) of the number and continuous quantity tasks, respectively. However, these control tasks did not measure number, time, or space processing and as such allowed us to distinguish effects reflecting number and continuous quantity processing from other effects reflecting generic aspects of performance such as comparing stimuli or stimulus and response selection processes.

Downloaded from http://direct.mit.edu/jocn/article-pdf/26/5/986/1947832/jocn_a_00546.pdf by University of ... user on 17 May 2021

Location discrimination. This control task consisted of 40 trials each displaying a dot for 200 msec in random locations on the left or right of a computer monitor and following an ISI randomly selected between 500 msec and 2 sec. Similar to the number tasks, participants were instructed to make speeded responses identifying the location of each stimulus (left or right of fixation) by pressing one of two predefined keys. Accuracy and RTs were recorded similarly to the number tasks.

Luminance discrimination. In this second control task, participants made unspeeded responses indicating which of two horizontal lines was brighter by pressing either the "up" or "down" arrow key. The same design, procedure, and number of trials as the other continuous quantity tasks were used, except that the line stimuli varied along the dimension of luminance, whereas time and space were both kept constant (600 msec and 10.29°). The first line stimulus remained constant in luminance (40 cd m^{-2}, 50% of maximum display luminance), whereas the second line could have one of five linearly spaced input values, from 50% to 58% of maximum luminance, resulting in minimum and maximum luminances of 40 and 55.5 cd m^{-2}, respectively (i.e., a max increase of 38.75%).

Supplementary Control Tasks

There were two sets of supplementary control tasks: the first set aimed to control for the possible impact of variables that were unmatched between the continuous quantity and the number/arithmetic tasks, for instance, task instructions. Participants (Control Group 2) performed the same time and space discrimination tasks twice in randomized order, once following the identical instructions as previous participants and once under time pressure, similar to the number and arithmetic tasks. To make the number/arithmetic and the continuous quantity tasks as similar as possible, we also increased the amount of trials of the number/arithmetical tasks (from 132 to 324 trials) to equate it to the continuous quantity task (400 trials).

A second supplementary control task tested whether nonsymbolic discrete quantity may be linked to continuous quantity or number/arithmetic. We compared performance in the number/arithmetic and continuous quantity tasks with performance in another nonsymbolic task (i.e., numerosity discrimination), using the same design and procedure of an established paradigm (Halberda et al., 2008; Cappelletti et al., 2013) in a new group of numerically normal participants (Control Group 3).

MRI Imaging and Data Preprocessing

High-resolution anatomical images were acquired using a T1-weighted 3-D Modified Driven Equilibrium Fourier Transform (MDEFT) sequence (repetition time = 12.24 msec, echo time = 3.56 msec, field of view = 256 × 256 mm, voxel size = 1 × 1 × 1 mm) on a 1.5-T Siemens Sonata MRI scanner (Siemens Medical Systems, Erlangen, Germany). Analyses used SPM8 (Wellcome Trust Centre for Neuroimaging, www.fil.ion.ucl.ac.uk/spm) running under MATLAB 7.3 (MathWorks, Natick, MA). The images were spatially normalized to Montreal Neurological Institute space (MNI) and segmented into gray and white matter using the unified segmentation algorithm (Ashburner & Friston, 2005). Subsequently, a Diffeomorphic Anatomical Registration through Exponentiated Lie Algebra was performed for intersubject registration of the gray matter images. To ensure that the total gray matter volume was retained before and after spatial transformation, the image intensity was modulated by the Jacobian determinants of the deformation fields. The registered images were then smoothed with a Gaussian kernel (FWHM = 8 mm) and were then affine transformed to MNI stereotactic space using affine and nonlinear spatial normalization for multiple regression analysis.

Data Analysis

Behavioral Data

Performance in the continuous quantity discrimination tasks was expressed as the difference in duration or length that could be discriminated at 75% accuracy (Just Noticeable Difference, JND). The JND was calculated by plotting the percentage of "Test longer" (or "Test brighter") responses to the actual Test magnitude for each participant and each continuous quantity task. These percentages (typically from floor to ceiling performance, i.e., near 50% to near 100%) were then interpolated by a logistic function using a maximum-likelihood algorithm implemented by PSIGNIFIT toolbox for MATLAB (Wichmann & Hill, 2001). The JND was read off from the interpolated psychometric function as the line length, duration, or luminance at which 75% of the responses were "Test longer." For the number and arithmetical tasks, an efficiency score was calculated, that is, accuracy divided by mean RT for the correct answers for each task (Machizawa & Driver, 2011). JNDs and efficiency scores were normalized to produce z scores so that performance could be compared across tasks in planned two-tailed t tests.

Behavioral data were also included in a principal component analysis (PCA) based on the normalized efficiency scores and JNDs. Four components with eigenvalues higher than 1 were extracted and then Varimax rotated (Wood, Tataryn, & Gorsuch, 1996), and these values were used as a behavioral index for the VBM analysis. Correlation analysis was used to test the relation between performance in numerical/arithmetical and continuous quantity tasks.

MRI Data

VBM analyses of structural MRI images were performed in SPM8 on each voxel in the spatially normalized gray

Downloaded from http://direct.mit.edu/jocn/article-pdf/26/5/986/1946373/jocn_a_00546.pdf by guest on 17 May 2021

matter images (see above) using behavioral measures as the independent variable and the gray matter volume in each voxel as the dependent variable. Global signal intensity differences were removed using proportional scaling. For these analyses, we report regions that showed significant effects at a threshold $p < .05$, corrected for multiple comparisons (using family-wise error correction) across the whole brain. We used cluster level statistics with a nonstationary correction, which is essential to adjust cluster sizes according to local "roughness" (Hayasaka, Phan, Liberzon, Worsley, & Nichols, 2004). Three analyses were performed: Two were based on examination of the whole-brain volume and one on predefined ROIs in accordance with our prior hypotheses (see below).

Analysis 1: Gray matter volumes associated with performance on both number and continuous quantity tasks. This analysis introduced the two PCA rotated values corresponding to numerical/arithmetical and continuous quantity performance as behavioral regressors in the VBM analysis, controlling for age, sex, and intracranial volume, following an approach used successfully in previous VBM studies (e.g., Garrido et al., 2009). Statistical contrasts identified brain areas where there was a correlation between gray matter increase and (1) the main effect of each PC component, (2) any common effect between the first and second principle component (PC1 and PC2), and (3) any effect that was higher for one component over the other, that is, an interaction.

Analysis 2: Gray matter volumes associated with performance on number/arithmetic and continuous quantity tasks relative to control tasks. This analysis included the normalized raw values corresponding to performance in the number/arithmetic, the continuous quantity, and the two control tasks (individual tasks for number/arithmetic and for continuous quantity averaged together). It tested whether any gray matter change in areas previously identified (Analysis 1) remained significant after controlling for any effect related to the control tasks.

Analysis 3: Predefined ROIs. This analysis was restricted to brain regions identified by a previous functional imaging study we conducted (Cappelletti, Lee, Freeman, & Price, 2010) and by meta-analyses of functional results based on behavioral tasks similar to those used here (Wiener, Turkeltaub, & Coslett, 2010; Cohen Kadosh, Lammertyn, & Izard, 2008; Dehaene et al., 2003). Specifically, it included the bilateral intraparietal sulcus (IPS), superior parietal lobe, and left angular gyrus for numbers and the left SMA, right inferior parietal lobe and supramarginal gyrus, and the left frontal gyrus for continuous quantity. For these areas, we used small spheres of 8-mm radius placed in the anatomical ROIs and reported effects at a threshold of $p < .05$ after correction.

RESULTS

Comparison of Behavioral Performance in Participants with Dyscalculia and in Numerically Normal Participants

In participants with dyscalculia, we found individual variability in performing number and arithmetic tasks, consistent with previous studies looking at dyscalculic performance (Cappelletti & Price, 2014; Rubinsten & Henik, 2009). For instance, accuracy across number tasks ranged from 50% (chance) to 68% correct, and the mean RT varied from about 760 msec to over 4 sec. We also found a large and not previously reported variability in performing the continuous quantity tasks such that, for example, accuracy for discriminating the smallest increment ranged from 50% (chance) to 90% correct for length discrimination from 50% to 73% correct for time.

Moreover, in adults with dyscalculia, performance in the number/arithmetic tasks correlated significantly with a measure of nonsymbolic numerosity discrimination [i.e., indicating the set with the larger number of items, see Halberda et al., 2008, $r = 0.56$, $F(1, 15) = 6.6$, $p = .02$] and consistent with previous reports (e.g., Mazzocco et al., 2011; Piazza et al., 2010). Performance in time and space discrimination tasks also correlated significantly [$r = 0.79$, $F(1, 15) = 21.3$, $p < .001$]. Critically, continuous quantity and number performance did not correlate significantly [time vs. mean number tasks: $r = 0.25$, $F(1, 15) = 0.8$, $p = .36$, *ns*; space vs. mean number tasks: $r = 0.29$, $F(1, 15) = 1.2$, $p = .29$, *ns*], similar to numerically normal participants (see below).

To examine the extent to which performance in participants with dyscalculia was outside the normal range, we compared them to our sample of numerically normal participants (Control Group 1). An ANOVA based on the normalized raw data of the number/arithmetic tasks and of the time and space discrimination tasks was used with Task (number/arithmetic vs. continuous quantity) as within factor and Group (dyscalculic vs. numerically normal participants) as between factor. The interaction of Task and Group was the only significant effect found [$F(1, 51) = 49.1$, $p < .001$], and post hoc tests indicated a significant numerical impairment in participants with dyscalculia relative to numerically normal participants [$t(51) = 20.9$, $p < .001$], but normal performance in the continuous quantity tasks [space: $t(51) = 1.8$, $p > .08$, *ns*; time: $t(51)$: 1.7, $p = .1$, *ns*; see Figure 2]. These effects were significant even when the dyscalculic sample was compared with a subsample of numerically normal participants more closely matched for sex and age within Control Group 1 [$n = 16$: 15 women, 1 man; mean age = 32.0 years, range = 22–37 years; $F(1, 30) = 5.7$, $p < .02$]. Post hoc comparisons based on this subsample confirmed that participants with dyscalculia were impaired in the number and arithmetic tasks [$t(30) = 11.3$, $p < .001$], but not the continuous quantity ones [space: $t(30) = 0.8$, $p < .09$, *ns*; time: $t(30)$: 2.3, $p = .2$, *ns*].

Downloaded from http://direct.mit.edu/jocn/article-pdf/26/5/986/1947326/jocn_a_00546.pdf by guest on 17 May 2021

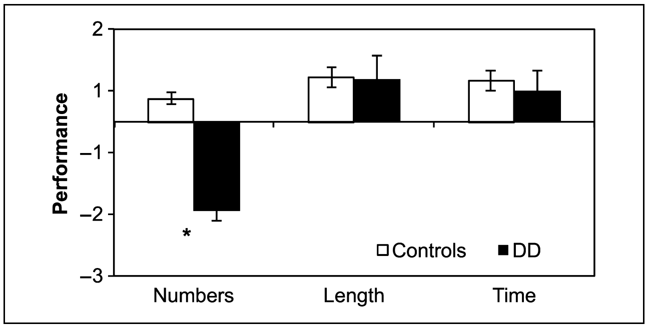

Figure 2. Behavioral results. Mean performance across participants with dyscalculia (DD, n = 16; black bars) versus numerically normal participants included in the VBM analysis (Control Group 1, n = 37; white bars). Dyscalculia show impaired performance on numerical tasks but preserved JNDs for time and space discrimination (normalized values). Asterisk indicates a significant in the two groups ($p < .001$).

The dissociation between number/arithmetic and continuous quantity performance in participants with dyscalculia as well as the lack of correlation between these tasks suggests that atypical number development leaves spared other types of quantity processing like time and space (see also Cappelletti, Freeman, & Butterworth, 2011; Rubinsten et al., 2005).

Behavioral Performance in Numerically Normal Participants

Given the dissociation between number/arithmetic and continuous quantity tasks in dyscalculics' performance, we examined whether or not there was a similar dissociation in numerically normal healthy adults or whether such dissociation may reflect peculiarities of the dyscalculic sample. In numerically normal participants (Control Group 1), we found remarkably large individual variability in performing number and arithmetic tasks, consistent with previous studies (Halberda et al., 2008). For instance, accuracy across these tasks ranged from about 70% correct to 100% and mean RT varied from about 300 msec to 1.9 sec. We also found a similar variability in the continuous quantity tasks, which has not previously been documented (see Figure 3). Hence, accuracy for discriminating the smallest increment ranged from 50% (chance) to 88% correct for space discrimination and from 50% to 78% correct for time; for both space and time, averaged JNDs ranged from 1.5% to 14% increments. JNDs for space and time correlated [Pearsons' $r = 0.48$, $F(1, 36) = 10.7$, $p = .002$] and similarly performance in number/arithmetic tasks expressed as efficiency score correlated (Table 2). Nonetheless, there was no significant correlation between performance in the continuous quantity and the number/arithmetic tasks neither when performance was compared on the basis of efficiency scores and JNDs (all $p > .1$, see Figure 3, Table 2) nor when compatible measures of accuracy were considered (JNDs and percent correct only; all ps $> .2$), or when JNDs in continuous quantity were compared with just RTs in the number tasks, which may be more sensitive than accuracy to quantify number performance (all $p > .3$).

In the control tasks, participants also showed large variability in performance: In the location discrimination task, RTs ranged from about 250 to 680 msec; in the luminance task, accuracy for discriminating the smallest increment ranged from chance to 84% correct, and JNDs ranged from 2.6% to 10.5%. Neither of the control tasks correlated with the number or continuous quantity tasks, with the exception of number comparison and the location discrimination task [$r = 0.6$, $F(1, 36) = 20.5$, $p < .001$; see Table 2]; this may be because these tasks were both defined in terms of speed of response rather than accuracy, which was at ceiling or close to ceiling in both cases.

To establish potential overlap of function and to reduce the dimensionality of the behavioral data for further analyses, we performed a PCA on the data from the 37 numerically normal participants (Control Group 1; see Methods). Four orthogonal factors emerged, overall accounting for about 81% of the variance (40.8%, 16.2% 13.1%, and 10.6%, respectively; see Table 3). PC factor 1 was characterized by tasks that despite several methodological differences were all defined in terms of numerical/arithmetical processing (i.e., arithmetical verification, number comparison and dot-number matching). PC factor 2 contained just the space and time discrimination tasks, and PC factor 3 was associated with luminance discriminability, despite the time, space, and luminance tasks all employing similar stimuli and experimental paradigms. Hence, commonalities between space and time (PCA 2) are likely to be driven by the processing of some continuous quantity rather than similarities in the paradigm used. PC

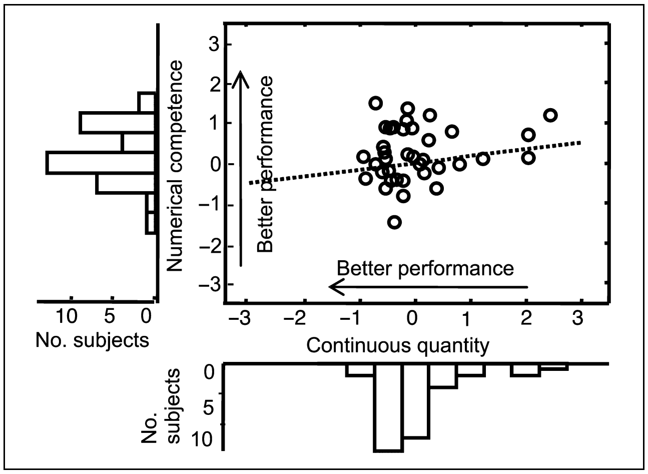

Figure 3. Behavioral results of numerically normal participants. Scatterplot (with marginal histograms), plotting normalized measures of efficiency in numerical tasks (y axis), and JND for continuous quantity discrimination (x axis) in the numerically normal participants (Control Group 1). Symbols represent results from individual participants, with superimposed line of best fit revealing no significant correlation.

Downloaded from [illegible] 17 May 2021

Table 2. Correlations between Tasks and between Behavior and Gray Matter Volume

	Brain Area									
Task	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Number^{a}										
1 D-N matching	–	.37*	.54**	*ns*	*ns*	*ns*	*ns*	.6**	.65**	*ns*
2 Number comparison		–	.31*	*ns*	*ns*	.57**	*ns*	.29*	.37*	.36*
3 Arithmetics			–	*ns*	*ns*	*ns*	*ns*	.5**	.59**	.46*
Continuous Quantity^{b}										
4 Space				–	.48**	*ns*	*ns*	*ns*	*ns*	.42*
5 Time					–	*ns*	*ns*	*ns*	*ns*	.48**
Control Tasks										
6 Location detection^{a}						–	*ns*	*ns*	*ns*	*ns*
7 Luminance^{b}							–	*ns*	*ns*	*ns*
8 IPS								–	.48**	*ns*
9 Cuneus									–	*ns*
10 TPJ										–

Significant correlations (indicated by asterisks) between performance in number/arithmetic, continuous quantity, control tasks (expressed as efficiency scores or JNDs), and gray matter volume in the IPS, cuneus, and TPJ regions.

D-N matching = dot–number matching; *ns* = not significant.

^{a}Efficiency score = accuracy/mean RT of correct answers only.

^{b}JNDs.

$^{*}p < .05$.

$^{**}p < .001$.

factor 4 was associated with the location discrimination task. In summary, the PCA (1) confirmed our initial hypothesis that our tasks probe distinct versus common resources and (2) allowed us to reduce the number of behavioral dimensions used in the VBM analyses, as done in previous studies (see Garrido et al., 2009).

Our behavioral data showed a dissociation between number/arithmetic and continuous quantity tasks in participants with dyscalculia and no evidence for a correlation between these tasks in numerically normal participants. This was also the case when we controlled for variables that were unmatched between the continuous quantity and the number/arithmetic tasks, for instance, task instructions (Supplementary Control Task 1). Indeed, when task instructions were similar, we found that performance in the time and space discrimination indexed by JNDs correlated irrespective of whether the tasks were performed under time pressure [$r(16) = .53$, $p < .04$] or with no time pressure [$r(16) = .72$, $p < .003$], consistent with our previous results. However, performance in time and space discrimination did not correlate with number and arithmetic proficiency whether this was measured in terms of accuracy ($p > .09$) or RTs ($p > .8$).

Moreover, proficiency in the numerosity task (measured in Supplementary Control Task 1) correlated with accuracy in arithmetic verification [$r = 0.45, p = .03$] and dot–number matching tasks [$r = 0.43, p = .04$], but not number comparison [$r = 0.3, p < .1$, *ns*]. Critically, performance in the numerosity discrimination task did not correlate with performance in either the time [$r = 0.33$, $p = .1$, *ns*] or the space discrimination tasks [$r = 0.26$, $p = .7$, *ns*].

VBM of Regional Gray Matter Volume

A dissociation and no correlation between number/arithmetic and continuous quantity tasks might indicate their independence or alternatively the presence of additional uncontrolled variables. To test such possible independence, we used VBM with the prediction that independence in our experimental tasks might result in different brain regions being associated with number/arithmetic and continuous quantity. In contrast, commonality in number/arithmetic and continuous quantity processing might be reflected in commonality in the brain regions associated with these processes.

Downloaded from http://direct.mit.edu/jocn/article-pdf/26/5/986/1947324/jocn_a_00546.pdf on 17 May 2021

Table 3. PCA for Numerically Normal Participants Revealing Four Independent Factors Accounting for Performance in Number/Arithmetic Tasks (Factor 1), Time and Space Discrimination (Factor 2), Luminosity Discrimination (Factor 3), and Location Discrimination (Factor 4), Respectively

	Factor			
Task	*1*	*2*	*3*	*4*
Number and Arithmetic				
Dot–number matching	**0.860**	0.230	0.037	−0.147
Number comparison	**0.843**	−0.106	0.007	0.264
Arithmetics	**0.824**	−0.047	0.091	0.165
Addition problems	**0.890**	−0.195	0.079	−0.108
Subtraction problems	**0.825**	−0.170	0.038	0.032
Multiplication problems	**0.822**	0.115	0.300	0.096
Continuous Quantity				
Space discrimination	0.190	**0.740**	−0.287	−0.209
Time discrimination	−0.151	**0.799**	0.235	0.107
Control Tasks				
Luminosity discrimination	0.114	−0.003	**0.940**	−0.061
Location discrimination	−0.360	−0.158	0.232	**0.823**

We first assessed whether normal individual differences in number/arithmetic competence and in continuous quantity discrimination correlated with individual differences in gray matter volume (for Control Group 1, see Methods). Using PCA Rotated Factors 1 and 2 as indices of behavior (see Table 3), we found significant relationships between gray matter volume and performance measures on both number/arithmetic and continuous quantity in the right TPJ [$r = 0.62, p < .001$; see Table 4]. Yet, there were significantly greater associations (i.e., significant interaction) between gray matter volume and number/arithmetic relative to continuous quantity

Table 4. Brain Areas of Increased Gray Matter Volume Associated with Performance in Number/Arithmetic and in Continuous Quantity Tasks (Space and Time)

		Coordinates			*Number*	*Continuous Quantity*[a]	*Interaction*	*Number–control Task*[b]	*Continuous Quantity–Control Task*[c]
Area	*H*	*x*	*y*	*z*	*Z Score (No. of Voxels)*				
Cuneus	L	3	−75	13	4.3 (596)	*ns*	4.1 (505)	3.3 (16)	
IPS[d]	R	27	−52	54	4.1 (56)	*ns*	3.2	2.8 (22)	
TPJ	R	56	−55	21	3.1 (33)	4.3 (1027)	*ns*	3.2 (10)[e]	3.6 (94)

Only areas significant ($p < .001$) after correcting for multiple comparisons are reported.

H = hemisphere; L = left; R = right; *ns* = not significant.

[a] Space and time.

[b] Location discrimination.

[c] Luminosity discrimination.

[d] ROI based on functional data obtained in similar number tasks (Cappelletti et al., 2010) and consistent with previous studies (Cohen Kadosh et al., 2008; Dehaene et al., 2003).

[e] Within 6-mm radius.

Downloaded from http://direct.mit.edu/jocn/article-pdf/26/5/988/1947526/jocn_a_00546.pdf by guest on 08 June 2024
Downloaded from http://mitprc.silverchair.com/jocn/article-pdf/26/5/988/1947526/jocn_a_00546.pdf by University of London user on 17 May 2021

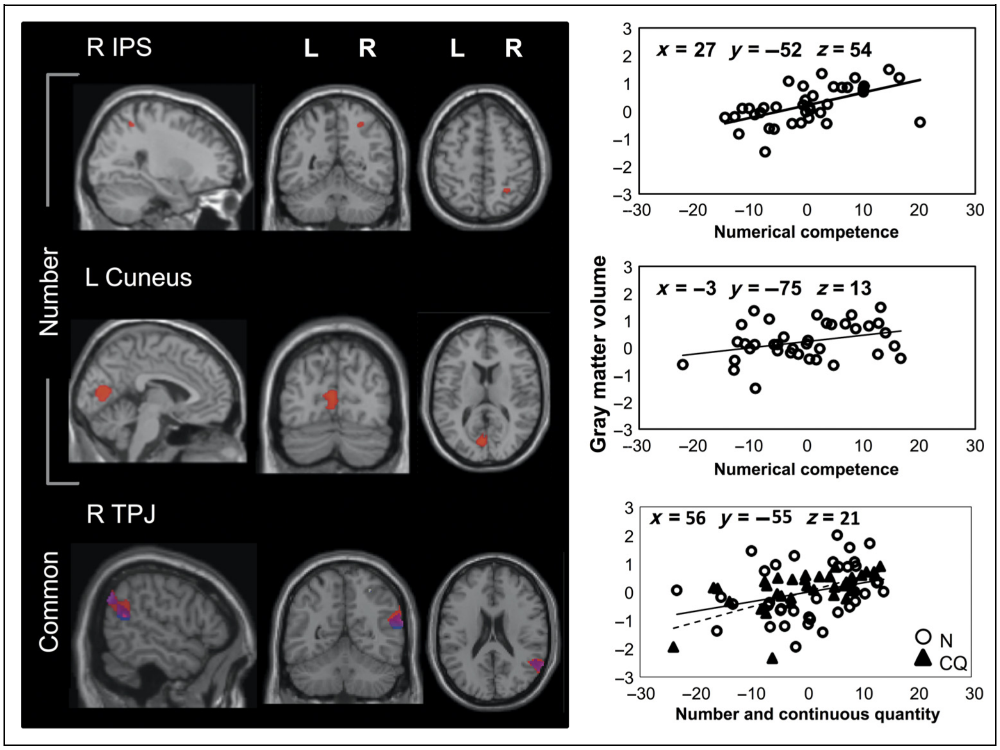

Figure 4. Neuroanatomical results. Left column shows structural MRI sections from a standard T1 template in MNI stereotactic space in sagittal, coronal, and axial view. Each row highlights a different cortical locus where correlation between gray matter volume and PCA-rotated behavioral measures was significant in numerically normal participants of Control Group 1 ($p < .05$ for multiple comparisons across the whole brain using family-wise error correction, see also Table 2; red = numerical competence, blue = continuous quantity). Each graph on the right plots normalized gray matter volume (y axes) sampled from the corresponding highlighted region on its left (with Talairach coordinates), against the behavioral measure with which it was found to correlate (x axes, in z scores). In the bottom graph, circle symbols (and continuous line of best fit) represent numerical/arithmetical competence (N), and triangles represent performance on continuous quantity tasks (CQ, with dotted line of best fit). Note that, for convenience of comparison with numerical competence, the continuous quantity JNDs have been sign-inverted (i.e., negative values transformed to positive and vice versa), so that higher values correspond on the graph to better rather than poorer performance.

performance in the right IPS [$r = 0.56$, $p < .001$] and in the left cuneus [$r = 0.19$, $p < .05$; see Table 4 and Figure 4].

One possibility is that gray matter volume in the regions identified simply reflected a correlation with any measure of RT or accuracy respectively. In this case, gray matter volume in the right IPS, cuneus, and TPJ regions should also correlate with the control tasks, which shared the same behavioral measures with the experimental tasks. However, we found that performance in neither the location discrimination nor in the luminance discrimination (expressed as efficiency scores or JNDs) correlated with gray matter volume in any of these brain regions (all ps > .18; see Table 2), therefore suggesting that the effect of number/arithmetic and continuous quantity did not simply reflect the type of behavioral measure used (RTs vs. accuracy). We also tested whether the link between gray matter volume and behavior was driven by any specific task grouped within each PCA factor. We therefore looked at correlations between gray matter volume and each individual task used (rather than the PCA factors). We used the estimates of gray matter volume extracted from the significant clusters identified in Analysis 1 and the normalized raw scores of the number/arithmetic and continuous quantity tasks. Besides correlating with the PCA factors, gray matter volume in the right IPS and cuneus correlated with all the number tasks (with the exception of a marginal correlation for the number comparison task, $p = .07$) and in TPJ regions with both continuous quantity tasks used, after correcting for multiple comparisons. This indicates that all the tasks included in the PCA factors contributed to the correlation between gray matter volume and behavior.

Finally, we examined whether there was any effect of number/arithmetic or continuous quantity in a set of predefined ROIs (see Methods). These ROI analyses indicated that our number/arithmetic-specific parietal effects corresponded to the same right IPS number area reported in previous functional imaging studies (Cappelletti et al., 2010; Wiener et al., 2010; Cohen Kadosh et al., 2008; Dehaene et al., 2003). No further brain regions reached significance.

DISCUSSION

Our study aimed to investigate the relation between numerical/arithmetical abilities and other continuous quantity abilities, such as those involved in time and space processing. Specifically, we used neuropsychology, psychophysics, and VBM to test whether the ability to process continuous quantities was maintained when numerical processes are developmentally impaired (i.e., in dyscalculia) and whether number and continuous quantity

Downloaded from http://direct.mit.edu/jocn/article-pdf/26/5/986/1947326/jocn_a_00546.pdf by guest on 17 May 2021

correlated behaviorally and anatomically in numerically normal participants. Our results indicate that proficiency in numerical and continuous quantity tasks dissociated in dyscalculia (i.e., impaired number but spared time and space processing). Moreover, performance in these tasks did not correlate in numerically normal participants, although individual differences in performing numerical and continuous quantity tasks both correlated with increased gray matter volume in the right TPJ. By using several control measures, we also established that these results did not just depend on generic aspects of our behavioral measures but appeared specific for numerical and continuous quantity tasks. In addition, gray matter in right IPS and left cuneus was more closely related to numerical/arithmetical than continuous quantity tasks.

Numerical Proficiency Dissociates from Time and Space Processing

Our two main findings of behavioral independence despite anatomical association of numerical and continuous quantity skills provide a deeper understanding of the relation between these skills. The independence of number and continuous quantity was supported by their dissociation in dyscalculia, the lack of behavioral correlation in numerically normal participants, and the number-specific anatomical correlations in right IPS and cuneus. This independence may reflect some intrinsic differences in processing number and continuous quantity. For instance, unlike continuous quantity, number has discrete referents and is based on enumeration and arithmetical principles rather than approximation as in time and space processing (Henik, Leibovich, Naparstek, Diesendruck, & Rubinsten, 2011; Castelli, Glaser, & Butterworth, 2006). Critically, the dissociation between numerical and continuous quantity skills in dyscalculia suggests that contrary to numerical skills, continuous quantity processing develops adequately and is adequately maintained in dyscalculia (see also Cappelletti, Freeman, & Butterworth, 2011). However, it is currently unknown whether in dyscalculia number processing is independent and dysfunctional from birth or whether numerical and continuous quantity skills correctly develop together with number skills deteriorating later.

Besides the IPS, increased gray matter volume associated with RTs but not accuracy in number tasks was shown in the cuneus, a brain area frequently reported in relation to working memory (Slotinick & Schacter, 2006), suggesting that this area may be sensitive to task difficulty in the context of number processing.

A recent study indicated a link between performing continuous quantity tasks (spatial extent), numerosity discrimination, and arithmetical abilities. Specifically, space and numerosity processing were shown to be linked and foundational to arithmetical proficiency (Lourenco, Bonny, Fernandez, & Rao, 2012). This is different to what we found, although a closer look at these recent data shows only an apparent discrepancy with ours: Indeed, the contribution of space processing to arithmetical abilities was actually only indirect, with a much stronger role in performing geometry rather than arithmetical tasks (Lourenco et al., 2012).

One or Multiple Quantity Systems?

Our second finding is of an association between number/arithmetical and continuous quantity tasks, which were both related to an increase in gray matter volume in TPJ. The anatomical association between these tasks could reflect magnitude processes (Cantlon et al., 2009; Walsh, 2003) or alternatively the cognitive resources needed to judge magnitude, which could include decision, stimulus, response selection, or attentional processes (Cappelletti et al., 2010; Cohen Kadosh et al., 2008). The contribution of attentional processes may be suggested by the involvement of the right TPJ region, a brain area part of a stimulus-driven attention system that detects relevant stimuli or changes in their status (Kincade, Abrams, Astafiev, Shulman, & Corbetta, 2005; Corbetta & Shulman, 2002) also on dimensions such as duration, location, and numerosity (Coull, Cheng, & Meck, 2011; Vetter, Butterworth, & Bahrami, 2011; Ansari, Lyons, van Eimeren, & Xu, 2007). Our data indicate that such processes can also be associated with symbolic numbers, in line with lesion data showing that right TPJ lesions affect attention-related processes. These processes, albeit not always in the context of TPJ lesions, are known to interfere with number (Vuilleumier, Ortigue, & Brugger, 2004) or with continuous quantity manipulation (Danckert et al., 2007).

Attentional processes associated with right TPJ may subserve different functions on which different tasks may rely. For instance, separate processes may be needed to maintain attention up to the end of the stimulus presentation (in the time task) to respond to a change in the stimuli (in both the time and space tasks) or to extract the meaning of symbols or retrieve the correct result of the arithmetical operations (in the arithmetic tasks). This hypothesis of multiple types of attention converging in the right TPJ may explain the apparent similarity of performance in number and continuous quantity tasks previously reported (Vetter et al., 2011; Brannon et al., 2007; Zorzi et al., 2002) and may be the reason why performance on number and continuous quantities tasks did not correlate in our study. Alternatively, the right TPJ might support the same function in all number and continuous quantity tasks, for instance, comparison processes may be a point of convergence between these tasks (Cantlon et al., 2009). More specifically, the number and the continuous quantity tasks imply the preparation and maintenance of a target-stimulus template to be compared with the actual

Downloaded from http://direct.mit.edu/jocn/article-pdf/26/5/[illegible] 17 May 2021

target, that is, a matching or mismatching process, which is linked to the left and right TPJ area (DiQuattro & Geng, 2011; Doricchi, Macci, Silvetti, & Macaluso, 2010; Kincade et al., 2005). This comparison or matching process may be different in the luminance task, possibly because information about luminance could be obtained directly from every local part of the stimulus line (Gilchrist & Radonjić, 2009). Therefore, participants did not need to build up and keep active the whole line stimulus template to perform the luminance comparison, as they would do for time and space. This may explain why discriminating luminance, arguably another quantity dimension (Pinel et al., 2004), did not correlate with gray matter volume in the right TPJ, which was linked to number, time, and space. Likewise, in the other control task used, location discrimination, there was no reference–template matching or mismatching a stimulus target, a process linked to the TPJ area (Doricchi et al., 2010; Kincade et al., 2005). Thus, although luminance discrimination and location detection tasks aimed respectively to control for response and stimulus selection processes in common with the time and space discrimination tasks and to match the behavioral measure used with the number tasks, they differed substantially in other underlying cognitive processes. This may explain the lack of anatomical overlap with the number, time, and space tasks.

It may be surprising that common resources were not detected in the IPS, a region previously hypothesized to host a shared magnitude representation (Walsh, 2003) and that functional imaging studies often report as involved in number processing (e.g., Cappelletti et al., 2010; Dehaene et al., 2003; Dormal et al., 2012; Fias et al., 2003). This may be because functional and structural imaging studies measure different things, and currently the relationship between function and structure is only poorly understood (however, see Song, Schwarzkopf, & Rees, 2013, for a study on the relation between brain function and structure in primary visual cortex). Functional imaging looks at neural responses averaged across individuals (i.e., activations common across many participants), and it measures current involvement in a task, with more activation for more involvement (less with practice and efficiency). In contrast, in structural imaging measures are derived from differences across individuals, and they reflect many different factors including a lifetime of responses and efficiency (more with practice and efficiency; Kanai & Rees, 2011). As many different activations can engage the same process (e.g., spatial attention), there may be no correlation with performance of a single task (e.g., numerical processing), but a correlation might arise with a measure that encompasses process rather than task.

In conclusion, we report novel evidence that characterizes the relation between number and continuous quantity processing. First, in a population with a developmental numerical dysfunction, that is, dyscalculia, continuous quantity processing was well maintained; second, in numerically normal people, numerical/arithmetical and continuous quantity skills were at least partially dissociated, both behaviorally and anatomically. Despite no correlation between behavioral measures, both number/arithmetic and continuous quantity correlated with structural changes in right TPJ, whereas the right IPS and the cuneus were distinguished by their correlation with the number/arithmetic tasks only. Together, our new evidence of a number-specific impairment and of number-specific brain areas distinct from common magnitude areas suggests that the human brain is equipped with different ways of quantifying the outside world.

Acknowledgments

This work was supported by the Wellcome Trust (G. R., C. J. P.); a Royal Society Dorothy Hodgkin Fellowship, Royal Society, and British Academy Research Grants (M. C.); and the Japan Society for the Promotion of Science and Japan Science and Technology Agency (R. K.). We would like to thank two anonymous reviewers for their helpful comments.

Reprint requests should be sent to Marinella Cappelletti, University College London, Institute of Cognitive Neuroscience, 17 Queen Square, London, WC1N 3AR, UK, or via e-mail: m.cappelletti@ucl.ac.uk.

REFERENCES

Aiello, M., Jacquin-Courtois, S., Merola, S., Ottaviani, T., Tomaiuolo, F., Bueti, D., et al. (2012). No inherent left and right side in human "mental number line": Evidence from right brain damage. *Brain, 135,* 2492–2505.

Ansari, D., Lyons, I. M., van Eimeren, L., & Xu, F. (2007). Linking visual attention and number processing in the brain: The role of the temporo-parietal junction in small and large symbolic and nonsymbolic number comparison. *Journal of Cognitive Neuroscience, 19,* 1845–1853.

Ashburner, J., & Friston, K. J. (2000). Voxel-based morphometry. The methods. *Neuroimage, 11,* 805–821.

Ashburner, J., & Friston, K. J. (2005). Unified segmentation. *Neuroimage, 26,* 839–851.

Brannon, E. M., Suanda, S., & Libertus, K. (2007). Temporal discrimination increases in precision over development and parallels the development of numerosity discrimination. *Developmental Science, 10,* 770–777.

Bueti, D., & Walsh, V. (2009). The parietal cortex and the representation of time, space, number and other magnitudes. *Phil Trans of Royal Society, Series B, Biological Science, 364,* 1831–1840.

Butterworth, B. (2003). *Dyscalculia screener*. London: Nelson Publishing Company Ltd.

Butterworth, B. (2010). Foundational numerical capacities and the origins of dyscalculia. *Trends in Cognitive Sciences, 14,* 534–541.

Cantlon, J. F., Platt, M. L., & Brannon, E. M. (2009). Beyond the number domain. *Trends in Cognitive Science, 13,* 83–91.

Cappelletti, M., Didino, D., Stoianov, I., & Zorzi, M. (in press). Number skills are maintained in healthy aging. *Cognitive Psychology*.

Cappelletti, M., Freeman, E., & Butterworth, B. (2011). Time perception in dyscalculia. *Frontiers in Cognitive Science, 2,* 364.

Downloaded from http://direct.mit.edu/jocn/article-pdf/26/5/986/1947324/jocn_a_00546.pdf by guest on 17 May 2021

Cappelletti, M., Freeman, E. D., & Cipolotti, L. (2009). Dissociations and interactions between time, numerosity and space processing. *Neuropsychologia, 47,* 2732–2748.

Cappelletti, M., Freeman, E. D., & Cipolotti, L. (2011). Numbers and time doubly dissociate. *Neuropsychologia, 49,* 3078–3092.

Cappelletti, M., Gessaroll, E., Hithersay, R., Mitolo, M., Didino, D., Kanai, R., et al. (2013). Neuroenhancement: Greatest, long-term and transferable quantity judgement induced by brain stimulation combined with cognitive training. *The Journal of Neuroscience, 33,* 14899–17907.

Cappelletti, M., Lee, H. L., Freeman, E. D., & Price, C. J. (2010). Dissociating number selectivity and response-times in the parietal lobes. *Journal of Cognitive Neuroscience, 22,* 331–346.

Cappelletti, M., & Price, C. J. (2014). Residual number skills in adults with dyscalculia. *Neuroimage Clinical, 4,* 18–28.

Castelli, F., Glaser, D. E., & Butterworth, B. (2006). Discrete and analogue quantity processing in the parietal lobe: A functional MRI study. *Proceedings of the National Academy of Sciences, U.S.A., 103,* 4693–4698.

Cohen Kadosh, R., Lammertyn, J., & Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology, 84,* 132–147.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Review Neuroscience, 3,* 215–229.

Coull, J. T., Cheng, R., & Meck, W. H. (2011). Neuroanatomical and neurochemical substrates of timing. *Neuropsychopharmacology, 36,* 3–25.

Crawford, J. R., Howell, D. C., & Garthwaite, P. H. (1998). Payne and Jones revisited: Estimating the abnormality of test score differences using a modified paired samples *t* test. *Journal of Clinical and Experimental Neuropsychology, 20,* 898–905.

Danckert, J., Ferber, S., Pun, C., Broderick, C., Striemer, C., Rock, S., et al. (2007). Neglected time: Impaired temporal perception of multisecond intervals in unilateral neglect. *Journal of Cognitive Neuroscience, 19,* 1706–1720.

Dehaene, S., & Brannon, E. M. (2011). *Space, time and number in the brain: Searching for evolutionary foundations of mathematical thought*. London: Elsevier.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20,* 487–506.

DiQuattro, N. E., & Geng, J. J. (2011). Contextual knowledge configures attentional control networks. *Journal of Neuroscience, 31,* 18026–18035.

Doricchi, F., Guariglia, P., Gasparini, M., & Tomaiuolo, F. (2005). Dissociation between physical and mental number line bisection in right hemisphere brain damage. *Nature Neuroscience, 12,* 1663–1665.

Doricchi, F., Macci, E., Silvetti, M., & Macaluso, E. (2010). Neural correlates of the spatial and expectancy components of endogenous and stimulus-driven orienting of attention in the Posner task. *Cerebral Cortex, 20,* 1574–1585.

Dormal, V., Dormal, G., Joassin, F., & Pesenti, M. (2012). A common right fronto-parietal network for numerosity and duration processing: An fMRI study. *Human Brain Mapping, 33,* 1490–1501.

Dormal, V., Seron, X., & Pesenti, M. (2006). Numerosity-duration interference: A Stroop experiment. *Acta Psychologica (Amsterdam), 121,* 109–124.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., & Orban, G. A. (2003). Parietal representation of symbolic and nonsymbolic magnitude. *Journal of Cognitive Neuroscience, 15,* 47–56.

Garrido, L., Furl, N., Draganski, B., Weiskopf, N., Stevens, J., Tan, G. C., et al. (2009). VBM reveals reduced gray matter volume in the temporal cortex of developmental prosopagnosics. *Brain, 132,* 3443–3455.

Gilchrist, A. L., & Radonjić, A. (2009). Anchoring of lightness values by relative luminance and relative area. *Journal of Vision, 9,* 1–10.

Halberda, J., Mazzocco, M. M. M., & Feigenson, L. (2008). Individual differences in nonverbal number acuity predict maths achievement. *Nature, 455,* 665–668.

Hayasaka, S., Phan, K. L., Liberzon, I., Worsley, K. J., & Nichols, T. E. (2004). Non-stationary cluster-size inference with random field and permutation methods. *Neuroimage, 22,* 676–687.

Henik, A., Leibovich, T., Naparstek, S., Diesendruck, L., & Rubinsten, O. (2011). Quantities, amounts, and the numerical core system. *Frontiers in Human Neuroscience, 5,* 186.

Jackson, M., & Warrington, E. K. (1986). Arithmetic skills in patients with unilateral cerebral lesions. *Cortex, 22,* 611–620.

Kanai, R., & Rees, G. (2011). The structural basis of inter-individual differences in human behaviour and cognition. *Nature Reviews Neuroscience, 12,* 231–242.

Kincade, J. M., Abrams, R. A., Astafiev, S. V., Shulman, G. L., & Corbetta, M. (2005). An event-related functional magnetic resonance imaging study of voluntary and stimulus-driven orienting of attention. *Journal of Neuroscience, 25,* 4593–4604.

Lourenco, S., Bonny, J., Fernandez, E., & Rao, S. (2012). Nonsymbolic number and cumulative area representations contribute shared and unique variance to symbolic math competence. *Proceedings of the National Academy of Science, 109,* 18737–18742.

Machizawa, M., & Driver, J. (2011). Principal component analysis of behavioural individual differences suggests that particular aspects of visual working memory may relate to specific aspects of attention. *Neuropsychologia, 49,* 1518–1526.

Mazzocco, M., Feingenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child Development, 82,* 1224–1237.

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., et al. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition, 116,* 33–41.

Pinel, P., Piazza, M., LeBihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number size and luminance during comparative judgements. *Neuron, 41,* 983–993.

Rubinsten, O., & Henik, A. (2005). Automatic activation of internal magnitudes: A study of developmental dyscalculia. *Neuropsychology, 19,* 641–648.

Rubinsten, O., & Henik, A. (2009). Developmental dyscalculia: Heterogeneity may not mean different mechanisms. *Trends in Cognitive Science, 13,* 92–99.

Slotinick, S., & Schacter, D. (2006). The nature of memory related activity in early visual areas. *Neuropsychologia, 44,* 2874–2886.

Song, C., Schwarzkopf, D. S., & Rees, G. (2013). Variability in visual cortex size reflects tradeoff between local orientation sensitivity and global orientation modulation. *Nature Communications, 4,* 2201.

Downloaded [illegible] 17 May 2021

Vetter, P., Butterworth, B., & Bahrami, B. (2011). A candidate for the attentional bottleneck: Set-size specific modulation of right TPJ during attentive enumeration. *Journal of Cognitive Neuroscience, 23,* 728–736.

Vuilleumier, P., Ortigue, S., & Brugger, P. (2004). The number space and neglect. *Cortex, 40,* 399–410.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7,* 483–488.

Wechsler, D. (1986). *Wechsler Adult Intelligence Scale-Revised*. New York: The Psychological Corporation.

Wichmann, F. A., & Hill, N. J. (2001). The psychometric function: I. Fitting, sampling and goodness-of-fit. *Perception and Psychophysics, 63,* 1293–1313.

Wiener, M., Turkeltaub, P., & Coslett, H. B. (2010). The image of time: A voxel-wise meta-analysis. *Neuroimage, 49,* 1728–1740.

Wood, D. J., Tataryn, R., & Gorsuch, L. (1996). Effects of under and overextraction on principal axis factor analysis with varimax rotation. *Psychological Methods, 14,* 354–365.

Zorzi, M., Priftis, C., & Umiltà, C. (2002). Neglect disrupts the mental number line. *Nature, 417,* 138.

Downloaded [illegible] 17 May 2021