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Numbers and time doubly dissociate

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ABSTRACT

The magnitude dimensions of number, time and space have been suggested to share some common magnitude processing, which may imply symmetric interaction among dimensions.

Here we challenge these suggestions by presenting a double dissociation between two neuropsychological patients with left (JT) and right (CB) parietal lesions and selective impairment of number and time processing respectively. Both patients showed an influence of task-irrelevant number stimuli on time but not space processing. In JT otherwise preserved time processing was severely impaired in the mere presence of task-irrelevant numbers, which themselves could not be processed accurately. In CB, impaired temporal estimation was influenced by preserved number processing: small numbers made (already grossly underestimated) time intervals appear even shorter relative to large numbers. However, numerical estimation was not influenced by time in healthy controls and in both patients. This new double dissociation between number and time processing and the asymmetric interaction of number on time: (1) provides further support to the hypothesis of a partly shared magnitude system among dimensions, instead of the proposal of a single, fully shared system or of independent magnitude systems which would not explain dissociations or interactions among dimensions; (2) may be explained in terms of a stable hierarchy of dimensions, with numbers being the strongest.

1. Introduction

Adults, infants and animals are all capable of discriminating number, space and time. For instance, they can approximate the number of items in a set, the length or the area covered by objects and the duration of events, and they use these approximate quantifications to guide behaviour (Dehaene & Brannon, 2010; Gallistel, 1990; Walsh, 2003).

1.1. *Shared magnitude representation or format across different dimensions*

Number, time and space have traditionally been thought to be processed via distinct, magnitude-specific systems (see Fig. 1a, Murphy, 1996, 1997; mentioned in Moyer & Landauer, 1967 and in Walsh, 2003). This hypothesis states that magnitude information is analysed separately for time, numbers and space and compared according to metrics unique to each comparison. Two predictions follow from this view. First, dissociations between magnitude dimensions are possible as they are thought to be independent. Second, no interactions should occur between magnitude dimensions as magnitude information is processed independently.

The hypothesis of distinct magnitude dimensions has subsequently been challenged by the idea that these dimensions are all represented by a single mechanism, or that they all share decision procedures in the form of comparison processes. This single device is the essence of Meck and Church (1983) mode-control model, consisting of a single 'internal accumulator' mechanism representing either the duration or the numerosity of events/objects at one given time (Boysen & Capaldi, 1993; Breukelar & Dalrymple-Alford, 1998; Meck & Church, 1983; Roberts & Church, 1978; see Fig. 1b). The idea of a single representational mechanism supporting magnitude processing has been recently extended within a new theory termed ATOM (A Theory of Magnitude, Walsh, 2003), which suggests a single representational mechanism that is only partly shared among time, quantity and also space (Walsh, 2003, Fig. 1b). These proposals of a common representation or decision processes are based on the observation that tasks requiring to estimate numerosity, time and space result in similar patterns of performance (Meck, 2005; Meck & Church, 1983) or similar rates of development (e.g. Brannon, Lutz, & Cordes, 2006; Brannon, Suanda, & Libertus, 2007; vanMarle & Wynn, 2006), they involve similar brain areas (e.g. Cohen Kadosh, Lammertyn, & Izard, 2008), and they can be equally impaired (e.g. Basso, Nichelli, Frassinetti, & di Pellegrino, 1996; Zorzi, Priftis, & Umiltà, 2002). Two predictions can be made based on the single

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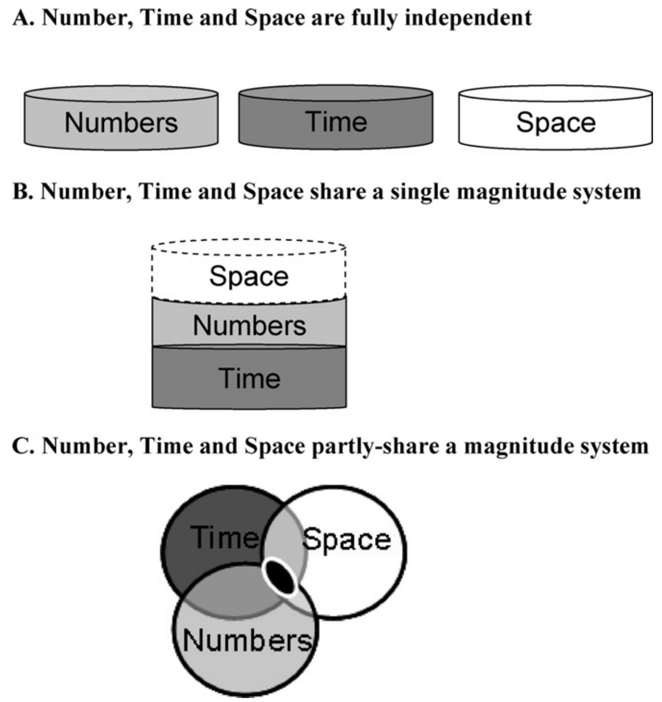


Fig. 1. Possible links between number, time and space. (A) Number, Time and Space are fully independent, such that magnitude information is analysed according to metrics unique to each dimension and therefore dissociations but no interactions may be expected between dimensions (e.g. Murphy, 1996, 1997). (B) Number and Time fully share a single magnitude system (that could be extended to Space, here shown with dotted lines), initially hypothesized as an 'internal accumulator' representing information about either the numerosity or the duration of events/objects at one given time (e.g. Meck & Church, 1983); a single magnitude system would predict no dissociations between number and time and symmetrical interactions between them. (C) Number, Time and Space partly share a magnitude system and are also implemented by dimension-specific processes, such that interactions are possible as well as dissociation among dimensions if the dimension-specific processes are selectively impaired (ATOM, Walsh, 2003; Cantlon et al., 2009; Cappelletti et al., 2009).

magnitude mechanism. First, no neuropsychological dissociations should be expected between time and numbers as impairments to the single device should equally affect both dimensions. Second, a logical implication of a shared mechanism is that dimensions of magnitude should interact symmetrically unless further assumptions are made such as that the mechanism is limited to process one dimension at a time (e.g. Meck & Church, 1983).

Conflicting evidence, however, suggests that different dimensions may not rely on a fully shared magnitude representation. For instance, although the psychophysical functions of number, time and space overlap at values of low intensity suggesting that they may indeed merge into a common representation, they nevertheless diverge at higher intensity (e.g. Feigenson, 2007). Moreover, some early developmental studies suggest that infants may be more sensitive to the numerical attribute of discrete arrays than to summary statistics such as cumulative area (e.g. Brannon, Abbott, & Lutz, 2004a; Brannon, Wolfe, Meck, & Woldorff, 2004b). This preference may also depend on the features of the experimental set, as infants attend preferentially to area over number when presented with small numerosities of homogeneous elements, but to number over area when elements are heterogeneous (Feigenson, 2005), again questioning the idea that different dimensions all equally rely on a common device. Recently, the proposal of a common mechanism across dimensions has been further challenged by showing that number, time and space can dissociate, with time being selectively impaired following a right hemisphere lesion (Cappelletti, Freeman, & Cipolotti, 2009).

1.2. Interactions between magnitude dimensions

A prediction of the proposal that different magnitude dimensions are all represented by a single device is that these dimensions may interact symmetrically. This prediction was initially based on the argument that the quantitative equivalence between numbers and time shown in animals' performance (such that for instance a count and 200 ms would be equivalent, Meck & Church, 1983) implies that magnitude representations formed by timing could be used in subsequent number discriminations and vice-versa (Meck & Church, 1983). Indeed, equivalence between magnitude dimensions has been shown in infants where expectations about one magnitude dimension can influence expectations about others; for instance, 9-month olds learn that if black/striped objects are larger in size, they may also be more numerous and last longer, suggesting an early, pre-linguistic origin of abstract magnitude (Laurenco & Longo, 2010). Likewise, in monkeys numerosity judgments are facilitated when the overall duration of the stimuli or the area they cover are correlated (Beran, 2007).

However, asymmetrical interactions across dimensions are common in many other studies. For instance, when asked to compare either the numerosity of two stimulus sets or their durations (i.e. 'Which set has more items or lasted longer?') or the length of two lines, participants frequently report longer durations in the presence of larger sets or longer lines, but duration has little or no influence on numerosity and length judgements (e.g. Bottini & Casasanto, 2010; Casasanto & Boroditsky, 2008; Casasanto, Fotakopoulou, & Boroditsky, 2010; Dormal, Seron, & Pesenti, 2006; Droit-Volet, Clément, & Wearden, 2001; Droit-Volet, Clement, & Fayol, 2003; Roitman, Brannon, Andrews, & Platt, 2007; Xuan, Zhang, He, & Chen, 2007). These asymmetries have sometimes been explained in terms of paradigm-dependent effects, whereby number, time and space would be differentially influenced by factors related to the task or the stimuli used (Droit-Volet et al., 2003; Droit-Volet, Clément, & Fayol, 2008; Roitman et al., 2007). For instance, temporal but not numerical discrimination is sensitive to experimental factors such as stimulus presentation order (e.g. blocked vs. randomised trials) and allocation of attention (e.g. explicit instructions vs. no instructions, e.g. Roitman et al., 2007). Asymmetric interactions may also be due to some magnitude dimensions being more salient or automatically accessed than others, for instance in the case of numbers relative to time (e.g. Dormal et al., 2006).

1.3. This study

This study aimed to clarify the relation between number, time and space in two ways. First, we present neuropsychological evidence for a double dissociation among magnitude dimensions in two patients. This allows us to verify the extent to which different dimensions share a common magnitude representation. Second, we further explored the nature of the relation between dimensions by investigating their interactions. Specifically, we tested whether asymmetries are due to intrinsic differences between dimensions, for instance with numbers being more salient or automatically accessed relative to time and space, and time being weaker, or whether differences are mere artefacts related to experimental factors. We reasoned that if differences are due to paradigm-related factors, then different paradigms may result in different patterns of asymmetry. In contrast, if different paradigms result in similar patterns of asymmetry across dimensions, then such interactions are more likely to be accounted for by stable differences between dimensions.

We used two experimental paradigms in 24 healthy control participants and two patients with lesions involving the left (JT) and right (CB) parietal regions. We have previously described CB's

Table 1
Results of neuropsychological background tests.

Tasks performed	Patient JT	Patient CB
General intellectual functioning		
NART I.Q.	97	NP
WAIS-R verbal I.Q.	80	113
WAIS-R performance I.Q.	85	91
Memory		
Recognition memory test – words (*N* = 50)	47 (>75th ‰)	46 (>75th ‰)
Digit span	11 (50–75th ‰)	11 (50–75th ‰)
Word retrieval		
Graded difficulty naming test (*N* = 30)	23 (1–5th ‰)	27 (>75th ‰)
Word fluency (letter ‘S’)	10 (>10th ‰)	13 (>20th ‰)
Executive functions		
WCST_No. categories (*N* = 6)	2[a]	5
Attention		
Elevator counting with distractors (*N* = 10)	8 (>75‰)	9 (>75‰)
Perception		
Incomplete letters Warrington & James, 1991 (*N* = 20)	20 (>5% cut-off)	20 (>5% cut-off)
Position discrimination (*N* = 20)	20 (>5% cut-off)	20 (>5% cut-off)
Neglect		
Balloon	Lat. Inat. Index: normal[b]	Lat. Inat. Index: normal[b]
Star cancellation	Three omissions	15 right; 17 left

NART = National adult reading test; WAIS-R (Wechsler, 1981) NP = not performed; ‰ = percentile; WCST = Wisconsin card sorting test; (Jackson & Warrington, 1986).

[a] Denotes impaired performance.

[b] Lateralized inattention index >50%.

selective impairment in time perception in the context of spared number and space (Cappelletti et al., 2009). Here we report the complementary dissociation in patient JT, namely a selective number impairment, as well as an additional and in-depth investigation of time processing in patient CB.

2. Participants

Both patients were referred to the Neuropsychology Department of the National Hospital for Neurology and Neurosurgery in London for evaluation of their cognitive impairments. Results of the neuropsychological assessment are reported in Table 1.

Background data as well as CB’s pattern of performance on tests assessing number, time and space processing are described in detail in an earlier publication (Cappelletti et al., 2009). However, in the current study CB was tested with a new set of magnitude tasks to further investigate the relation between number, time and space processing. Reference to previous results will be made where relevant for the present study.

2.1. Patient JT

JT is a 44-year-old right-handed native English-speaking woman with 14 years of education. In 2009 she sustained a left middle cerebral artery territory infarct.

An MRI-scan showed a lesion affecting the left parietal lobe extending slightly to the temporal regions. The left medial, lateral and superior parietal lobe, as well as the intraparietal sulcus (IPS) were damaged (see Fig. 2, top panel).

JT’s verbal and non-verbal intellectual functions showed a moderate decline relative to pre-morbid estimates. Visual and verbal memory functions, attention and perceptual functions were normal whereas nominal functions were in the borderline range. Frontal executive functions were impaired (see Table 1 and Appendix B for full-details of the neuropsychological background tests). JT reported difficulties in everyday life related to processing numbers, for instance she complained of no longer being able to calculate efficiently (e.g. to check the change in a shop) and to remember numbers. We therefore conducted a specific examination to evaluate JT’s numeracy skills, and we administered a series of temporal and spatial tasks since difficulties in processing numbers may be related to temporal or spatial impairments.

2.2. Patient CB

CB is a 62-year-old right-handed native English-speaking man with 17 years of education. In 2004 he sustained a right middle cerebral artery territory infarct.

An MRI-scan showed an extensive right hemisphere lesion involving the right inferior parietal regions extending to the right superior temporal lobe. Damage was also shown in the right inferior frontal and lateral prefrontal areas around the Silvian fissure extending deeply into the insula and the right basal ganglia. The IPS was intact and the cerebellum was normal (see Fig. 2, bottom panel).

CB’s performance on the WAIS-R suggested a mild degree of intellectual under-functioning only on tests with a non-verbal component. Visual and verbal memory functions as well as nominal, frontal executive functions and attention were normal (See Table 1 and Appendix B). CB was initially investigated as he reported difficulties in everyday life related to processing time, for instance he complained of not being able to decide when it was the right time to leave home to be on time for an appointment, or the amount of time needed for everyday activities (see Cappelletti et al., 2009).

2.3. Control subjects

Overall 24 right-handed neurologically healthy control subjects with normal or corrected-to-normal vision participated in the study. Twelve of these participants were age-matched to JT (5 males and 7 females, mean age: 43.4 years, range 40–49), and 12 to CB (6 males and 6 females, mean age: 62.8 years, range 60–68). Patients JT and CB were each compared to control participants that were aged-matched to them (see Table 3). Some of these control sub-

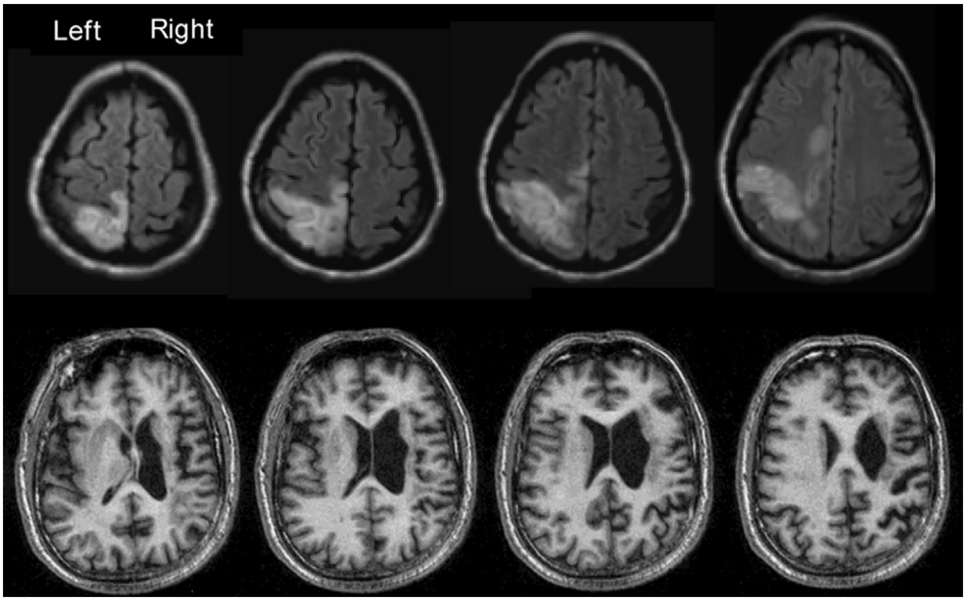


Fig. 2. Patients JT and CB's brain lesions. Patients JT's (top) and CB's (bottom) brain lesions displayed in the axial plane.

jects had already participated in a previous study (see Cappelletti et al., 2009). The patients and all control subjects gave informed written consent to participate in the study and were paid for their participation. The study was approved by the local research Ethics Committee.

2.4. *Preliminary investigation: number, time and space processing*

The patients' number, time and space processing were initially assessed with a set of paper-and-pencil and computerized tasks requiring participants to estimate the number of objects or event and their duration, to perform calculation as well as more basic operations like reading numbers aloud, comparing Arabic numbers or matching numbers to dots. Participants' space processing was tested by asking them to judge whether the left and right sections of a series of horizontal lines were of the same length (see Appendix B for more details). Although some of these tasks might be based on encyclopaedic knowledge, others required quantity-processing to be solved.

Relative to control subjects, JT's numerical processing was generally impaired on a range of standard measures. For instance, she was impaired at estimating numbers, calculating, and she failed to show a distance effect (Moyer & Landauer, 1967) in the number comparisons task which is taken as evidence that automatic number processing is impaired (see Appendix B for detailed investigations). In contrast, CB's numeracy processing was well preserved in both the number estimation, in number comparison tasks and in calculation. JT was accurate at estimating temporal durations, whereas CB was impaired in this task. Both JT and CB were accurate at bisecting lines. Control subjects performed well in all preliminary tasks assessing number, time and space skills (see Table 2).

The results of the preliminary investigation on number, time and space processing suggest that JT was specifically impaired in numerical processing, whereas her ability to process time and space were intact. In contrast, CB was specifically impaired in time processing whereas his number and space processing were spared. In order to provide a more specific account of these selective impairments of number and time processing and to further explore the relation between number, time and space, we conducted a more detailed experimental investigation.

3. Experimental investigation

There were nine experiments. Some of the paradigms used have been previously validated in both control participants and neurological patients and are known to engage numerical, temporal and spatial processing (for more details see Cappelletti et al., 2009).

Experiments 1–4 tested the estimation of the numerosity of events (Experiments 1 and 2) and their duration (Experiments 3 and 4) in the presence of non-numerical and numerical stimuli. Time discrimination was tested in the presence of primes which could be numbers (Experiment 5), a non-numerical symbol (Experiment 6), or letters of the alphabet (Experiment 7). Space discrimination was tested with primes that could be a non-numerical symbol (Experiment 8) or numbers (Experiment 9).

4. Methods

In all nine experiments stimulus presentation and data collection were controlled using the Cogent Graphics toolbox (http://www.vislab.ucl.ac.uk/Cogent) and Matlab7.0 software on a Sony S2VP laptop computer. The dimensions of the display, as rendered on the built-in liquid-crystal screen, were 23.5 cm horizontal × 18 cm vertical. The display had a resolution of 640 × 480 pixels and was refreshed at a frequency of 60 Hz. A chin-rest was used to stabilize head position of the participants and the viewing distance from the monitor was about 50 cm. When a task required oral responses, these were recorded and scored by the experimenter. As we were interested in the participants' response accuracy rather than their speed, un-timed oral answers were required and reaction times were not recorded in these tasks. See Table 3 for a summary of the experiments performed.

4.1. *Stimuli*

In Experiments 1 and 3, stimuli consisted of circles subtending a visual angle of 1.72°. Circles appeared in one of eight pre-selected colours (white, pink, red, green, yellow, orange, brown and blue) on a mid-grey background of luminance 44 cd/m^2. In Experiments 2 and 4, the stimuli consisted of Arabic numbers ranging from 1 to 9 (except 5) and presented in two separate sets in different blocks: small numbers (1–4) and large numbers (6–9). Arabic numbers subtended 0.87° vertically and between 0.25° and 0.65° horizontally from a viewing distance of 50 cm and appeared in white on a black background (see Figs. 3 and 4 left-most panels; for more details see Cappelletti et al., 2009).

In Experiments 5–9, stimuli were two horizontal white lines (thickness 0.17°) centred on the vertical meridian on a black background. The lines were 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 (see Fig. 5A). The first line stimulus in the two-interval sequence, termed the 'Reference', always had a length of 10.29° and duration of 600 ms. The second line, termed the 'Test', could vary according to a Method of Constant Stimuli,

Table 2
Performance in preliminary tasks of numeracy, time and space processing (percent correct).

Tasks performed	Patient JT		Patient CB	Control participants ($N = 16$)[a]			
				Matched to JT		Matched to CB	
	Accuracy	RTs	Accuracy	Accuracy[b]	RTs[b]	Accuracy[b]	RTs[b]
A. Numeracy processing							
Number estimation ($N = 30$)	18[c]	NR	90[d]	95.4 (2.5)	NR	93.2 (4.9)	NR
Number comparison							
Small distance ($N = 68$)	100	1140.78[c]	100	98.3 (2.3)	542.4 (76.3)	96.8 (2.9)	564.5 (65.1)
Large distance ($N = 68$)	96	1134[c]	100	99.1 (1.8)	509. 2 (62.1)	97.6 (2.8)	528. 3(43.2)
GDA ($N = 24$)	3 (defective)		10 (average)				
Reading 1–4 Arabic numbers ($N = 40$)	100	NR	97.5	99 (0.3)	NR	100 (0)	NR
Dot-number matching ($N = 36$)	85	2686.07[c]	NT	100 (0)	1031.7 (64.8)	100 (0)	1236.5 (48.3)
Arithmetical operations							
Additions ($N = 20$)	75[c]	3024.6[c]	NT	99 (0.5)	943.1 (129.4)	98.3 (2.1)	1108.3 (189.4)
Subtractions ($N = 20$)	85[c]	2413.41[c]		95.4 (1.8)	1167.5 (298.5)	93.4 (2.8)	1187.7 (204.6)
Multiplications ($N = 20$)	85[c]	1848.1[c]		94.3 (2.9)	1034.6 (320.2)	94.3 (3.2)	1115.3 (255.3)
B. Time processing							
Time estimation ($N = 30$)	86.7	NR	40[c]	97.6 (3.9)	NR	93.1 (3.5)	NR
Knowledge of exact temporal facts ($N = 20$)	NT		95	96.5 (1.8)		97.2 (1.9)	
Time comparison ($N = 15$)	NT		93.3	97.4 (1.5)		98.5 (3.1)	
C. Space processing							
Line bisection ($N = 12$)	100	NR	100	100 (0)	NR	100 (0)	NR

GDA = Graded difficulty arithmetic test Jackson & Warrington, 1986, NR = not recorded, NT = not tested.

[a] These controls are different from those that participated in the experimental tasks and are part of a larger sample collected at the National Hospital for Neurology and Neurosurgery in London (matched to JT: mean age = 43.8; range: 40–50; matched to CB: mean age = 61.2; range: 55–65).

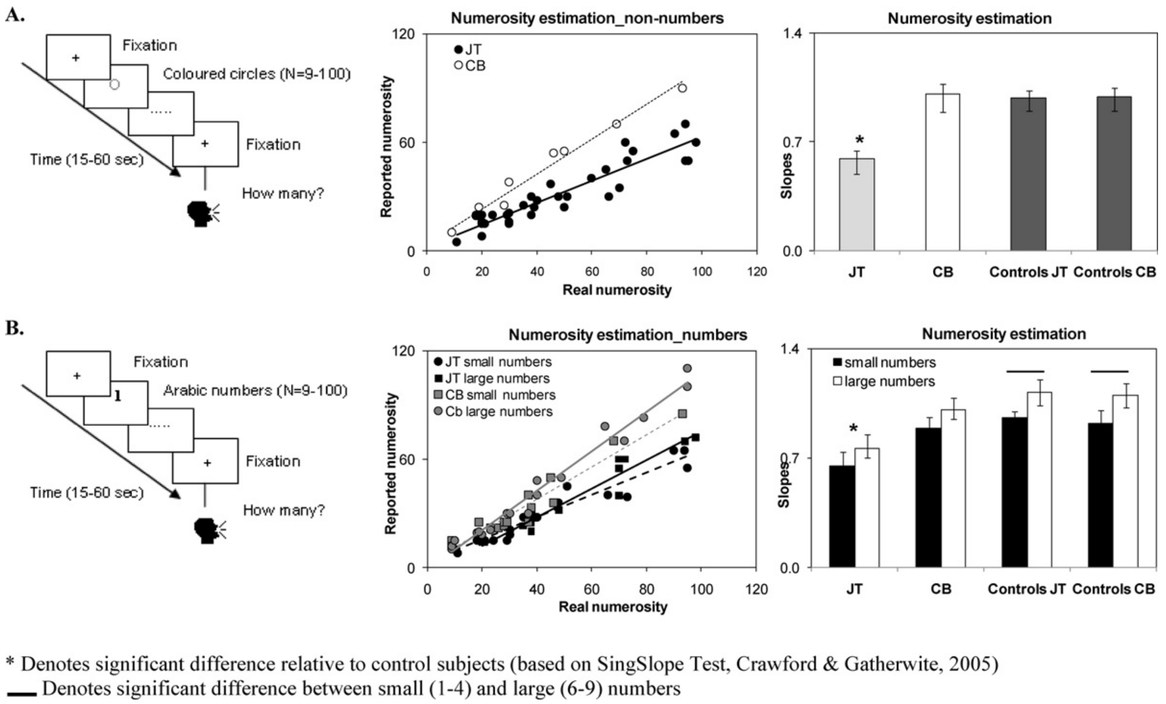
[b] Standard deviation in brackets.

[c] Denotes impaired performance.

[d] Indicates answers within 1 standard deviation from controls.

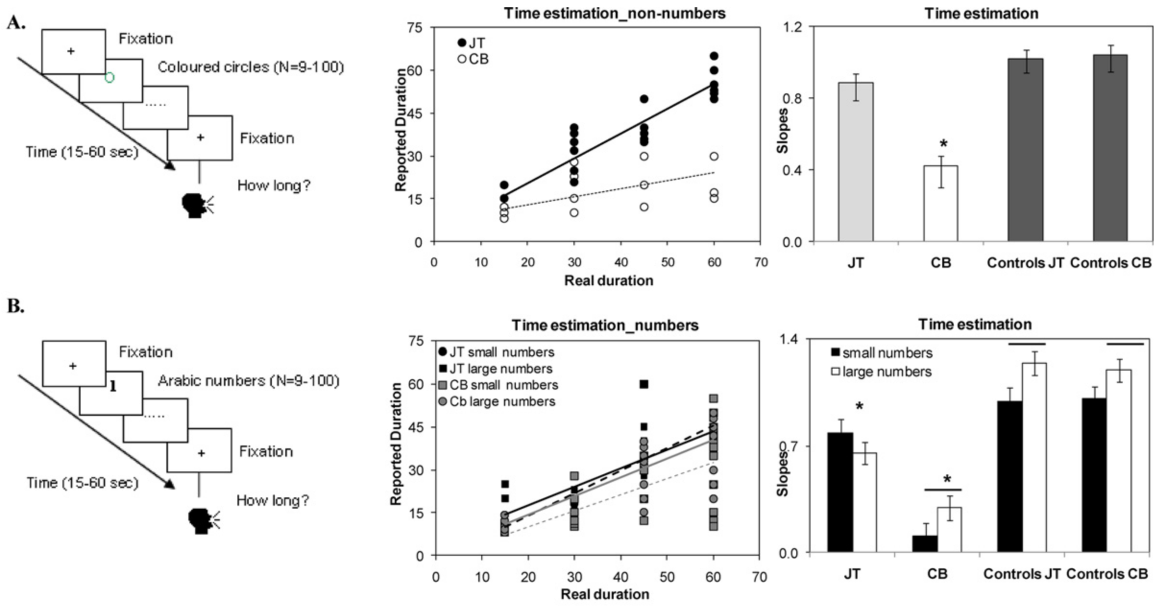
either in duration or length, depending respectively on whether the task was time or length discrimination (see below). In the time discrimination experiments (Experiments 5, 6, 7), Test line durations spanned a range of −240 to 240 ms relative to the Reference duration (i.e. from 360 to 840 ms in steps of 60 ms, including the Reference duration of 600 ms), while the Test line length was 10.29°. In the length discrimination experiments (Experiments 8 and 9), Test lines varied in length by ±1.03° relative to the Reference, over five equal steps of 0.257° including the Reference length, while the Test line duration was 600 ms.

Three types of prime were used. In the 'number' prime condition (Experiments 5 and 8), primes were two Arabic numbers, a small number, i.e. '1', and a large number, i.e. '9'. In the 'non-number' prime condition (Experiments 6 and 9) the prime was the symbol '#'. In the 'letter' prime condition (Experiment 7), primes were two letters of the alphabet, 'A' and 'Z'. All prime types subtended 0.87° vertically and between



* Denotes significant difference relative to control subjects (based on SingSlope Test, Crawford & Gatherwite, 2005)
▬ Denotes significant difference between small (1-4) and large (6-9) numbers

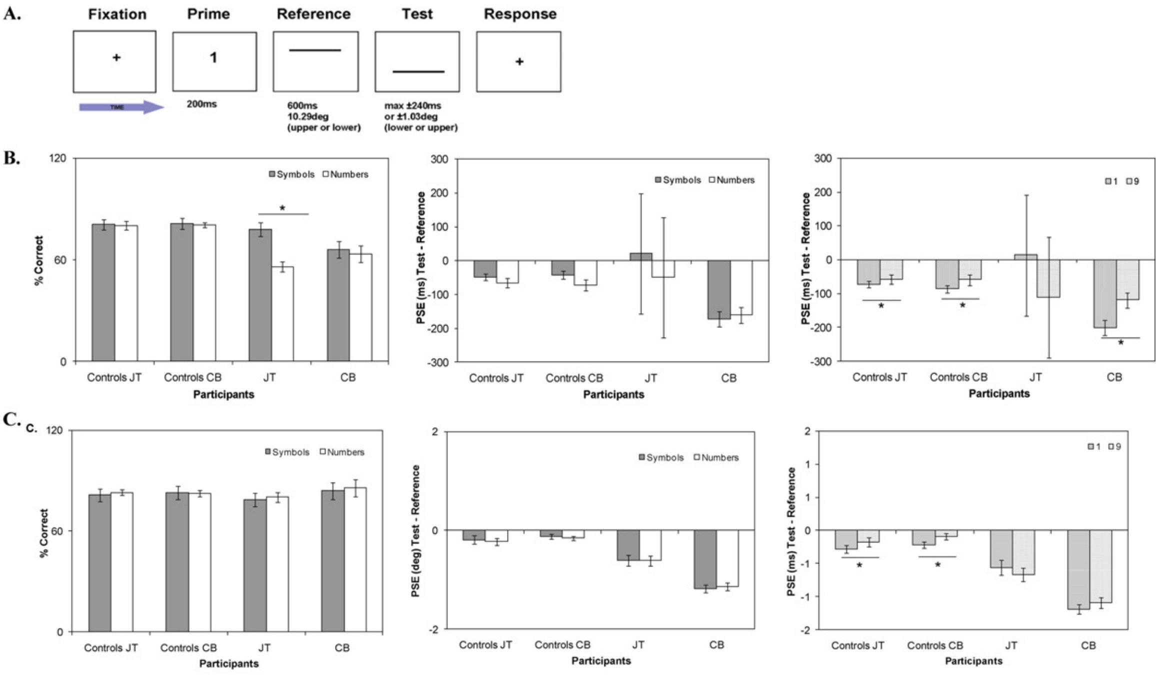
Fig. 3. Numerosity estimation with (A) non-number and (B) number stimuli (Experiments 1 and 2). Top left: in Experiment 1, participants estimated the numerosity of coloured circles (range 9–100) presented in each trial. Top right: Estimated numerosities (number of items) are expressed as a function of real numerosity and as slopes (right-most panel) with 95% confidence limits for patients JT and CB and for control subjects. Bottom left: in Experiment 2, participants estimated the numerosity of Arabic numbers (range 9–100) presented in each trial. Bottom right: numerosity estimation (number of items) of small (1–4) and large (6–9) numerical stimuli expressed as a function of real numerosity and as slopes (right-most panel) with 95% confidence limits for patients JT and CB and for control subjects.



* Denotes significant difference relative to control subjects (based on SingSlope Test, Crawford & Gatherwite, 2005)

▬ Denotes significant difference between small (1-4) and large (6-9) numbers

Fig. 4. Time estimation with (A) non-number and (B) number stimuli (Experiments 3 and 4). Top left: in Experiment 3, participants estimated the duration of each trial where coloured circles (range 9–100) were presented. Top right: Estimated durations (in seconds) are expressed as a function of real durations and as slopes (right-most panel) with 95% confidence limits for patients JT and CB and their matched control subjects. Bottom left: in Experiment 4, participants estimated the durations of each trial where Arabic numbers (range 9–100) were presented. Bottom right: Time estimation (in seconds) of small (1–4) and large (6–9) numerical stimuli expressed as a function of real duration and as slopes (right-most panel) with 95% confidence limits for patients JT and CB and their matched control subjects.



* Denotes significant difference between stimuli

Fig. 5. Time and length discrimination (Experiments 5–9). (A) Participants were asked to judge which of two horizontal lines either lasted longer (B) or was longer in length (C); the Reference line was preceded by a prime which could be a number (‘1’ or ‘9’ as in the example), a non-numerical symbol (‘#’), or a letter (‘a’ or ‘z’). Accuracy is reported for each task in patients JT and CB and in control subjects (left-most panels). Point of Subjective Equality (PSE) indicates the proportion of trials which were perceived as being of the same duration or length compared to the Reference and its estimated variability as calculated by bootstrapping (95% confidence intervals); PSEs for symbols and number primes (middle panels) as well as individual numerical primes (right-most panels) are reported for patients JT and CB and for control subjects.

Table 3
Summary of the experiments performed.

Experiment	How many items/how long?				Longer line?				
	1	2	3	4	5	6	7	8	9
Participants matched to	Numerosity (non-numbers)	Numerosity (numbers)	Time (non-numbers)	Time (numbers)	Time (numbers)	Time (non-numbers)	Time (letters)	Space (non-numbers)	Space (numbers)
JT ($N = 12$, 7F); 43.4(40–49)	6	6	6	6	12	12	8	12	12
CB ($N = 12$, 6F); 62.8(60–68)	6	6	6	6	12	12		12	12
No. of trials	16	16	16	16	720	360	720	360	720

F = females.

0.25° and 0.65° horizontally and were presented in the centre of the display (see Fig. 5A).

4.2. Design

In Experiments 1–4 each trial started with a central white cross that remained in the middle of the screen until subjects pressed the spacebar. Stimuli were then presented one at a time in the central position until the selected time interval was completed. The number of stimuli ranged from 9 to 100. The end of a trial was indicated by the presentation of another white cross in the middle of the screen (Figs. 3 and 4, left-most panel). The total duration of the sequence of stimuli was varied randomly over successive trials across four durations: 15, 30, 45 and 60 s. For data analysis, these sequence durations were grouped into two categories: short (15 and 30 s) and long (45 and 60 s). In different trials, individual stimulus presentation times were sampled randomly from rectangular distributions spanning one of two continuous ranges: fast (200–1100 ms) and slow (1101–2000 ms), with each stimulus immediately following the last (i.e. no inter-stimulus interval). This aimed to reduce the possibility that rhythmic presentation was used to make numerical and temporal judgments (e.g. Breukelar & Dalrymple-Alford, 1998). Each combination of stimulus duration (slow vs. fast) and trial duration (short vs. long) was sampled with equal frequency in two blocks of 16 trials each for each experiment. The order of the blocks was counterbalanced across subjects.

In Experiments 5–9, each trial began with a centrally displayed fixation point, which remained visible until a key-press from the participant. A prime was then immediately displayed centrally for 200 ms. A blank interval of 100 ms preceded the first line display (Reference Line), followed after an inter-stimulus interval of 100 ms by the second line display (Test line). The screen then remained blank with a fixation cross in the middle until a response from the subject. The next trial immediately followed the response (Fig. 5A). In both the duration and the length discrimination Experiments, test values were randomly sampled from a set of equally spaced values bracketing the Reference value, with equal frequency. Nine levels of duration were used in Experiments 5, 6, 7 and five levels in Experiments 8 and 9. The task-irrelevant dimension of the Test was always equal to the same dimension of the Reference. In each block of the experimental condition, number primes were randomly sampled from the two possible values with equal frequency. There were eight experimental blocks of 40 trials each; see Table 3 for the number of trials performed in each task.

4.3. Procedure

During all testing sessions participants sat in a quiet room with their head on a chinrest facing the computer screen under normal fluorescent room lighting.

In Experiment 1–4, participants were instructed to verbally report either how many items they had seen at the end of each trial, or how long the whole sequence of stimuli in each trial lasted for, whether the stimuli consisted of coloured circles (Experiments 1 and 3) or Arabic numbers (Experiments 2 and 4). In order to prevent sub-vocal counting and to avoid strategies used to keep track of elapsing seconds, participants were required to name aloud the colour of each circle or to read aloud each Arabic number, following a procedure used in previous studies (e.g. Cappelletti et al., 2009; Logie & Baddeley, 1987; Roitman et al., 2007). Moreover, the fast presentation of the stimuli (i.e. 200–1100 ms for half of the trials) was designed to further prevent any sub-vocal counting.

In Experiments 5–9, participants were instructed to press either the ‘up’ or ‘down’ cursor-arrow keys of the laptop keyboard to indicate the vertical position of the test line which appeared the longest either in duration (Experiments 5, 6 and 7) or in spatial extent (Experiments 8 and 9).

For each experiment, participants were given at least 20 practice trials prior to the first experimental block, although an additional practice block was run where necessary to ensure familiarity with the task. Practice trials were not included in analysis.

4.4. Data analysis

In Experiments 1–4, participants' accuracy for estimating numerosity and time was assessed in the following way. First, we used linear regression to estimate the slope relating veridical to estimate numerosity and time judgements. If estimates were veridical, the value of this slope should be unity (1), while over- or underestimations should result in values larger or smaller than unity respectively. Second, to assess whether the slopes obtained from the control subjects were significantly different from unity, we constructed within-subjects 95% confidence intervals (Cousineau, 2005) based on the standard deviation of the slope estimate. Confidence intervals that overlap the unity prediction line would indicate no significant deviation from the prediction of veridical estimation. This confidence interval was also used to assess whether the patients' performance lay within the normal range using the Bayesian inferential methods of Crawford and colleagues (Crawford, Howell, & Garthwaite, 1998; Crawford & Garthwaite, 2002, 2005; http://www.abdn.ac.uk/~psy086/dept/SingleCaseMethodsComputerPrograms). This method is based on the t-distribution rather than the standard normal distribution, which makes it more appropriate for evaluating single-case results against control groups. In Experiments 2 and 4 we also tested the possible interactions between time and numbers, i.e. any effect of the duration and of the size of the individual stimuli (only numerical stimuli for size) on estimates of duration and numerosity.

In Experiments 5–9, we first obtained a basic measure of accuracy by computing the proportion of all trials in which subjects correctly identified the longer line. Ideally for optimum psychometric function fitting, this accuracy should span a range from 100% to 50% correct for the largest and smallest test-reference differences respectively, without ceiling or floor effects (i.e. 50% chance) dominating excessively. When averaged over test-reference differences, this ideal scenario should result in scores close to 75%, with scores higher or lower than this criterion in cases where the discrimination was overall too easy or too hard, respectively. We could thus use these accuracy scores to check that our Method of Constant Stimuli was probing the optimal range, but also to check whether our duration and length discrimination experiments were equated in terms of their task difficulty.

A psychometric function for individual subjects in each condition was then plotted for both the duration and length discrimination experiments. This function relates the probability of "Test longer" responses to the actual test line duration or length. Response probabilities (on Y-axis) should typically increase from 0% to 100% as a function of the Test magnitude in either duration or spatial extent (plotted on the X-axis), passing through 50%, where the Test is judged to be longer or shorter with equal probability (the Point of Subjective Equality, PSE). In a further analysis step, a logistic function was fitted to the data, using a maximum-likelihood algorithm (provided by the PSIGNIFIT toolbox for Matlab, Wichmann & Hill, 2001). From this function we could read off the PSE Test magnitude (duration or length) that was perceptually equivalent to the reference. The same software was used to derive 95% confidence intervals on the PSE estimate (and Just Noticeable Difference estimate, JND, see below), via a bootstrapping procedure. For individual patients, differences between priming conditions '1' and '9' were accepted as statistically significant ($p < 0.05$) where these 95% confidence intervals for the two conditions did not overlap. In cases of partial overlap of confidence intervals, statistical significance was assessed via Monte Carlo simulation (provided by the *pfcmp* function in the PSIGNIFIT toolbox) to test the null hypothesis that the difference between PSEs (and JNDs) is not different from zero.

For each participant, we also calculated the Just Noticeable Difference (JND), namely the minimal difference in duration or length between test and reference lines that can be discriminated with reliable accuracy. The JND was computed by reading off from the fitted psychometric function the line durations or lengths at which 25% and 75% of the responses were "test longer", then dividing the difference between these values by two (Coren, Ward, & Enns, 1999).

Finally, PSEs or JNDs of the individual patients for '1', '9' and '#' primes were compared with the control group using tests devised by Crawford and Garthwaite such as the Standardized Test (ST) which compares each patient's performance with the control sample, or the Revised Standardized Difference Test (RSDT) which compares each patient's discrepancy in two tasks with the control sample (Crawford & Garthwaite, 2002, 2005). All reported P values are 1-tailed, unless otherwise specified. Other standard non-parametric (e.g. Kruskal–Wallis) and parametric statistical tests (e.g. ANOVA, T-Test) were also used to analyze results from the patients and the control sample respectively.

5. Results

Results from Experiments 1 to 4 will be presented first followed by Experiments 5–9. For Experiments 1–4 we will focus on JT's performance and where appropriate CB's performance will be mentioned for comparison purposes (see also Cappelletti et al., 2009). Results of Experiments 5–9 will focus on both patients' performance. A summary of the main results is presented in Table 4.

5.1. Experiment 1: how many items have you seen? (coloured circles)

The first experiment aimed to test whether JT's numeracy impairment that emerged in the preliminary investigation extended to her ability to estimate the numerosity of the stimuli presented. Moreover, CB's previously tested ability to estimate numerosities (Cappelletti et al., 2009) will be reported here for comparison purposes.

5.1.1. Accuracy

JT underestimated the numerosity of circles presented; for instance, given 30 items she might report only 18 (regression coefficient 0.59, significantly different from 1, $p < 0.05$, see Table 4), and this significantly differed from control subjects' performance (SingSlope, Test a: $t = 5.59$, $p < 0.001$; see Fig. 3A). There was no modulation from the duration of the individual stimuli (no difference between slow vs. fast conditions, Kruskal–Wallis $\chi^2 = 0.13$, $p = 0.72$, *ns*).

For comparison, CB was accurate at estimating the numerosity of the stimuli presented, with no significant difference in performance from control participants (regression coefficient 1.01, SingSlope, Test a: $t = 0.76$, $p = 0.24$, *ns*; see Fig. 3A). Control subjects showed no impairment in numerosity estimation with non-numerical stimuli (age-matched to JT: slope = 0.98, SE = 0.05, and CB: slope = 0.99, SE = 0.02 not significantly different from 1, Fig. 2B).

5.2. Experiment 2: how many items have you seen? (Arabic numerals)

In the second experiment, a task identical to the previous one was used except that Arabic numbers rather than coloured circles were presented to participants. This experiment aimed to test whether despite her numeracy impairment, JT's estimate of numerosity could be still modulated by the quantity expressed by Arabic numbers.

5.2.1. Accuracy

JT underestimated the number of Arabic numerals presented; for instance, given 30 stimuli presented she might report only 21 (regression coefficient across small and large numbers 0.7, significantly different from 1, $p < 0.05$, see Table 4), which significantly differed from control subjects' performance (SingSlope, Test d: $t = 3.45$, $p < 0.001$, see Fig. 3B). There was no significant effect of the quantity indicated by numbers (no significant main effect of stimulus size, Kruskal–Wallis $\chi^2 = 2.7$, $p = 0.09$, *ns*), nor of the individual stimulus duration (Kruskal–Wallis $\chi^2 = 3.1$, $p = 0.08$, *ns*). There was no difference between JT's numerosity estimation of coloured circles and of Arabic numbers (Mann–Whitney U Test, $U = 611$, $Z = -0.12$, $p = 0.99$, *ns*), suggesting that JT's impaired number processing was stimulus-independent.

For comparison, CB was accurate at estimating how many Arabic numbers were presented (regression coefficient across small and large numbers 0.99, not significantly different from 1), with no difference relative to control subjects (SingSlope, Test b: $t = 0.35$, $p = 0.36$, *ns*). Moreover, CB's performance was modulated by the quantity expressed by numbers (main effect of stimuli size, Kruskal–Wallis $\chi^2 = 4.14$, $p < 0.01$; see Fig. 3B), such that small numbers resulted in the interval being reported as containing fewer stimuli and larger numbers in the interval being reported as containing more stimuli. In contrast, there was no significant effect of the individual stimulus duration (Kruskal–Wallis $\chi^2 = 1.02$, $p = 0.35$, *ns*).

Control subjects were accurate at numerosity estimation with Arabic numbers (age-matched to JT: slope = 1.05, SE = 0.08; to CB: slope = 1.02, SE = 0.07 not significantly different from 1, see Table 4). Separate regression analyses were performed for each control subject to derive individual slope estimates for smaller and larger numbers, which were then entered into an ANOVA. This showed that control subjects' numerosity estimation was influenced by the quantity expressed by numbers (matched to JT: $F(1, 5) = 11.91$, $p = 0.018$, and to CB: $F(1, 5) = 10.94$, $p = 0.02$, Fig. 3B). Therefore, larger numbers (i.e., 6–9) resulted in reporting a larger number of items (controls matched to JT: slope = 1.12, SE = 0.01, and to CB 1.1, SE = 0.08) relative to small numbers (i.e., 1–4; controls matched to JT: slope = 0.96, SE = 0.02, and to CB 0.92, SE = 0.06). The effect of stimulus duration on the perceived numerosity was not significant, such that stimuli lasting longer did not make the overall interval being perceived as containing more items (matched to JT: $F(1, 5) = 4.2$, $p = 0.09$, *ns*; and to CB: $F(1, 5) = 3.8$, $p = 0.1$, *ns*).

Table 4
Main results of Experiments 1–9 in patients JT and CB, and in control participants.

Experiment	JT	CB	Controls to JT	Controls to CB
1. Numerosity estimation_non-numbers				
Slopes (SE)	0.59 (0.04)[*,a]	1.01 (0.03)	0.98 (0.05)	0.99 (0.02)
2. Numerosity estimation_numbers				
Slopes (SE)	0.7 (0.075)[a,*]	0.99 (0.04)	1.05 (0.08)	1.02 (0.07)
Small numbers 1–4 (SE)	0.65 (0.08)[a,*]	0.89 (0.05)	0.96 (0.02)	0.92 (0.06)
Large numbers 6–9 (SE)	0.76 (0.07)[a,*]	1.09 (0.07)	1.12 (0.01)	1.1 (0.08)
3. Time estimation_non-numbers				
Slopes (SE)	0.89 (0.06)	0.42 (0.045)[a,*]	1.02 (0.05)	1.04 (0.09)
4. Time estimation_numbers				
Slopes (SE)	0.72 (0.06)[a,*]	0.21 (0.05)[a,*]	1.11 (0.06)	1.16 (0.02)
Small numbers, 1–4 (SE)	0.79 (0.05)[a,*]	0.11 (0.07)[*]	0.99 (0.02)	1.01 (0.04)
Large numbers, 6–9 (SE)	0.65 (0.07)[a,*]	0.29 (0.01)[*]	1.24 (0.08)	1.20 (0.08)
5. Time discrimination_number primes				
Accuracy	0.56[**,b]	0.63[**,b]	0.8 (2.5)	0.8 (1.5)
Accuracy ‘1’	0.55	0.66	0.81 (3.1)	0.8 (1.2)
‘9’	0.56	0.61	0.79 (1.1)	0.8 (1.7)
PSE ‘1’ (95% C.I.)[c]	613.04 (205.9)[**,b]	398.46 (2.36)[*,b]	526.6 (23.7)	513.9 (16.5)
‘9’ (95% C.I.)	488.03 (150.9)	480.08 (43.94)	541.1 (20.5)	540.37 (13)
JND ‘1’ (95% C.I.)	558.81 (679.28)[**,b]	95.78 (72.45)[*,b]	71.7 (7.2)	83.1 (10.1)
JND ‘9’ (95% C.I.)	582.98 (885.15)	56.57 (40.26)	77.0 (7.1)	88.7 (4.7)
6. Time discrimination_non-number prime				
Accuracy	0.78	0.66[*]	0.8 (4.1)	0.81 (2.2)
PSE[c] (95% C.I.)	621 (23.1)	427.98 (22.5)[**]	575 (26.1)	567 (18.9)
JND (95% C.I.)	95.3 (5.2)	72.35 (31.92)[*]	84.6 (5.8)	81.5 (3.9)
7. Time discrimination_letter primes				
Accuracy	0.77	NP	0.81 (2.1)	
PSE[c] (95% C.I.)	609.01 (19.94)		527.67 (15.5)	
JND (95% C.I.)	71.19 (24.4)		82.3 (15.3)	
8. Space discrimination_non-number prime				
Accuracy	0.79	0.84	0.81 (3.8)	0.82 (2.4)
PSE[d] (95% C.I.)	10.02 (0.11)	9.4 (0.8)	10.1 (0.09)	10.21 (0.5)
JND (95% C.I.)	0.24 (0.14)	0.21 (0.11)	0.27 (0.04)	0.25 (0.06)
9. Space discrimination_number primes				
Accuracy	0.80	0.835	0.83 (5.0)	0.825 (4.4)
Accuracy ‘1’	0.79	0.85	0.82 (4.7)	0.82 (5.2)
‘9’	0.82	0.82	0.84 (5.3)	0.83 (3.6)
PSE[d] ‘1’ (95% C.I.)	10.01 (0.11)	9.3 (0.7)	10.01 (0.6)	10.07 (0.6)
‘9’ (95% C.I.)	9.8 (0.10)	9.4 (0.8)	10.12 (0.7)	10.18 (0.6)
JND ‘1’ (95% C.I.)	0.28 (0.14)	0.24 (0.09)	0.35 (0.03)	0.33 (0.7)
JND ‘9’ (95% C.I.)	0.24 (0.13)	0.26 (0.11)	0.31 (0.03)	0.30 (0.4)

SE: standard error, C.I.: confidence interval, NP: not performed.

[a] Significantly different from 1, i.e. impaired performance.

[b] Different from controls across priming conditions.

[c] In milliseconds.

[d] In degree.

[*] $p < 0.01$ based on Crawford and Gatherwide test (2005).

[**] $p < 0.001$ based on Crawford and Gatherwide test (2005).

5.3. *Summary of Experiments 1 and 2*

JT tended to underestimate the numerosity of the stimuli presented irrespective of the type of stimulus used, consistent with preliminary results suggesting a specific disorder in number processing. In contrast, patient CB was accurate at estimating the numerosity of the stimuli presented. Moreover, JT's estimation of numerosity was not modulated by the duration of the individual stimuli nor by the quantity expressed by the numbers. This contrasted with CB and controls for whom small numbers (i.e. 1–4) resulted in estimating an interval as containing fewer items and large numbers (i.e. 6–9) more items (see also Cappelletti et al., 2009).

5.4. *Experiment 3: how long was a trial? (coloured circles)*

The common magnitude hypothesis would predict that impairment of one magnitude dimension (e.g. numbers in JT) might correspond to impairment to other dimensions, for instance time and space processing. To test this hypothesis, Experiment 3 assessed JT's ability to estimate the duration of a sequence of non-numerical stimuli (see Experiments 8 and 9 for tests of space processing).

5.4.1. *Accuracy*

JT was accurate at estimating the duration of temporal intervals when coloured circles were presented (regression coefficient 0.9, not significantly different from 1, see Fig. 4A), with no difference from control subjects (SingSlope, Test c: $t = 1.45$, $p = 0.17$, *ns*).

In contrast, CB consistently underestimated the duration of temporal intervals displaying coloured circles (regression coefficient 0.42, significantly different from 1, $p < 0.05$), with a significant difference from controls (SingSlope, Test d: $t = 5.04$, $p < 0.001$, see Table 4 and Fig. 4A). Control subjects showed no impairment in time estimation with non-numerical stimuli (matched to JT: slope = 1.02, SE = 0.05, and to CB: slope = 1.04, SE = 0.09 not significantly different from 1, Fig. 4).

5.5. *Experiment 4: how long was a trial? (Arabic numerals)*

The results of Experiment 3 suggested that time processing was preserved in JT. We then aimed to test whether, despite JT's numerical impairment, her time estimation could nevertheless be influenced by numbers, similar to the effects previously observed in controls (see Cappelletti et al., 2009). A task equivalent to the previous one (Experiment 3) was used, the only difference being that Arabic numbers instead of coloured circles were presented to participants.

5.5.1. Accuracy

JT was impaired at estimating the duration of temporal intervals when Arabic numbers were displayed. For instance, given a duration of 30 s, she might report a duration of only 22 s (regression coefficient across small and large numbers 0.72, $p < 0.05$, see Table 4). Her temporal judgments showed no effect of number quantity (no difference between small vs. large numbers, Kruskal–Wallis $\chi^2 = 0.22$, $p = 0.63$, *ns*; see Fig. 4B). JT's performance differed significantly from controls (SingSlope, $t = 6.03$, $p < 0.001$). Critically, JT's temporal estimation differed depending on the stimulus used, such that only numerical stimuli but not coloured circles resulted in temporal impairment (Mann–Whitney *U* Test, $U = 257.5$, $Z = -4.2$, $p < 0.001$).

CB grossly underestimated the duration of temporal intervals when Arabic numbers were displayed (regression coefficient across small and large numbers 0.21, significantly different from 1, $p < 0.05$), with a significant difference from controls (SingSlope, test a: $t = 3.52$, $p < 0.001$). Furthermore, there was a significant modulation of number quantity, such that small numbers (i.e. 1–4) resulted in the interval being reported as lasting shorter (slope = 0.11), and large numbers (i.e., 6–9) in the interval being reported as lasting longer than the veridical duration (slope = 0.29, see Fig. 4B).

Control subjects were accurate at estimating temporal intervals when Arabic numbers were displayed (matched to JT: slope = 1.11, SE = 0.06, and to CB: slope = 1.16, SE = 0.02 not significantly different from 1, see Table 4). Separate regression analyses were performed for each control subject to derive individual slope estimates for small and large numbers, which were then entered into an ANOVA. This showed that control subjects' time estimation was influenced by the quantity expressed by numbers (matched to JT: $F(1, 5) = 10.55$, $p < 0.03$, and to CB: $F(1, 5) = 11.02$, $p = 0.015$, Fig. 4B). Therefore, larger numbers (i.e., 6–9) resulted in reporting longer durations (controls matched to JT: slope = 1.24, SE = 0.08 and to CB 1.20, SE = 0.08) relative to small numbers (i.e., 1–4, controls matched to JT: slope = 0.99, SE = 0.02 and to CB 1.01, SE = 0.04). The effect of the stimuli duration of the perceived overall duration of a trial was not significant, such that stimuli lasting longer did not make the overall interval being perceived as lasting longer (age-matched to JT: $F(1, 5) = 3.02$, $p = 0.13$, *ns*, and to CB: $F(1, 5) = 2.5$, $p = 0.2$, *ns*).

5.6. Summary of Experiments 3 and 4

JT was accurate at estimating temporal durations when non-numerical stimuli were used. In striking contrast, she significantly underestimated temporal durations when task-irrelevant numerical stimuli were displayed, suggesting that her numerical impairment affected temporal processing. JT's impaired temporal processing was not modulated by the size of the numerical stimuli used. This contrasted with CB and control subjects, for whom small and large numbers (i.e. 1–4 and 6–9) resulted in perceiving an interval as lasting shorter or longer than its veridical duration, respectively (also reported in Cappelletti et al., 2009).

Although in the previous experiments numerical stimuli were task-irrelevant, it is possible that they were too salient to be ignored. This may have distracted JT's performance in the temporal task, which was accurate when non-numerical stimuli were presented. We thus tested JT's time processing in the context of a more subtle manipulation of the number stimuli. To achieve this, numbers were briefly presented as primes before the experimental stimuli whose temporal duration had to be judged (see Section 4 above). Patient CB was also tested with this new set of experiments to further understand the relationship between numbers and time.

5.7. Experiment 5: which line lasted longer (with numerical primes)

5.7.1. Accuracy

JT performed near chance when asked to compare the duration of two stimuli preceded by a numerical prime, with a significant difference from controls across priming conditions (ST: $t = 9.22$, $p < 0.001$, see Table 4 and Fig. 5B).

CB was impaired when comparing the duration of two stimuli preceded by a numerical prime (ST: $t = 11.14$, $p < 0.001$, see Table 4 and Fig. 5B), with no difference between the two prime conditions relative to control participants (RSDT: $t(11) = 0.12$, $p = 0.45$, *ns*).

Control participants were equally accurate at comparing stimulus duration preceded by a small or a large prime, showing no significant difference between the prime conditions ($t(23) = 1.16$, $p < 0.28$, *ns*).

5.7.2. PSE

JT's PSEs showed no significant difference between the '1' and '9' prime conditions ($p > 0.05$, based on bootstrapped 95% confidence intervals and Monte Carlo simulation, see Section 4.4 above), namely there was no modulation of the numerical value of the prime on the temporal performance (relative to controls ST: $t = 0.1$, $p = 0.51$, *ns*).

CB's PSEs for the '1' and '9' prime conditions differed significantly, such that he tended to underestimate the duration of a line more in the presence of the prime '1' relative to '9' ($p < 0.05$, based on bootstrapped 95% confidence intervals and Monte Carlo simulation, see Fig. 5B). CB and controls differed significantly (across primes, ST: $t = 5.66$, $p < 0.001$), with CB showing a strong tendency to underestimate the duration of the Reference line. This is consistent with his performance in the previous time estimation experiments, where he also underestimated the duration of temporal intervals.

In control participants, mean PSEs differed significantly for the primes '1' and '9' ($t(23) = 2.52$, $p = 0.02$), with the mean PSEs for both primes significantly shorter in duration than the Reference of 600 ms ('1' prime: $t(23) = 5.67$, $p < 0.001$; '9' prime: $t(23) = 5.01$, $p < 0.001$). This suggests that the Reference duration was consistently underestimated, so that a shorter Test duration was necessary to achieve perceptual equivalence to the Reference. Moreover, it suggests that durations were further underestimated in the presence of lower vs. higher number primes.

5.7.3. JND

JNDs (across priming conditions) were significantly smaller for controls relative to both JT (ST: $t = 26.5$, $p < 0.001$) and CB (ST: $t = 1.9$, $p = 0.04$).

5.8. Experiment 6: which line lasted longer (with non-numerical prime '#')

The previous results suggested that JT was impaired at time discrimination when numbers were presented even as task-irrelevant stimuli. This is consistent with her poor performance at interval estimation in the presence of task-irrelevant numbers (Experiment 4) but is in contrast with JT's performance in Experiment 3 where she was accurate at estimating temporal intervals displaying coloured circles. However, it is unclear whether this difference is due to the stimuli used (task-irrelevant numbers vs. coloured circles) or the type of temporal task performed (estimation vs. discrimination). To test which of these variables may have influenced

JT's performance, we administered another task which was identical to Experiment 5 except that primes were no longer Arabic numbers but the non-numerical symbol '#'.

5.8.1. Accuracy

In striking contrast with JT's performance in the same task with number primes (Experiment 5), here she showed normal accuracy when comparing the duration of two stimuli preceded by a non-numerical prime (significant difference between number primes and the symbol prime '#', RSDT, $t(11) = 11.12$, $p < 0.001$). There was no significant difference from controls (ST: $t = 0.47$, $p = 0.32$, *ns*, see Table 4 and Fig. 5B). In contrast, CB was impaired in temporal discrimination relative to controls (ST: $t = 3.4$, $p < 0.002$; see Table 4 and Fig. 5B), irrespective of whether the prime was a number or the symbol '#' (RSDT, $t(11) = 0.094$, $p = 0.46$). Control participants showed equally good accuracy in the context of the non-numerical prime '#' compared to either numerical primes (prime '1': $t(7) = 0.7$, *ns*; prime '9': $t(7) = 0.46$, *ns*; see Table 4).

5.8.2. PSE

JT's PSE for the '#' prime did not differ significantly from controls (ST: $t = 1.8$, $p = 0.1$, *ns*) but differed from JT's performance in the same task with the number primes (RSDT, $t(11) = 1.8$, $p = 0.04$). In contrast, CB's PSE for the '#' prime was significantly different from controls (ST: $t = 7.02$, $p < 0.001$), showing again a bias towards underestimating the duration of the reference stimulus.

In controls, mean PSE for the '#' prime was significantly shorter in duration than the Reference of 600 ms ($t(23) = 7.73$, $p < 0.001$), suggesting that the Reference duration was consistently underestimated, so that a shorter Test duration was necessary to achieve perceptual equivalence to the Reference.

5.8.3. JND

There was no significant difference in mean JNDs between controls and JT (ST: $t = 1.77$, $p = 0.1$, *ns*), although there was a difference relative to JT's performance in the same task with the number primes (RSDT, $t(11) = 38.8$, $p < 0.001$). JNDs differed between controls and CB (ST: $t = 2.5$, $p = 0.03$), indicating that CB was less sensitive to differences in duration.

6. Experiment 7: which line lasted longer (with letter primes)

Results of Experiment 6 suggested that JT could perform the time discrimination task when a non-numerical prime was displayed. This contrasted with JT's impaired time discrimination when the identical task was used in the context of numerical primes, suggesting that time discrimination was preserved except in the context of numbers.

It is possible, however, that JT's impaired performance was not due to the presence of numbers per se but rather to the fact that they may have acted as distractors. This may be because there were two primes appearing randomly across trials, which may have made it difficult for JT to concentrate on the temporal task. This was not the case for Experiment 6 where only one type of prime ('#') was used across all trials. To test whether JT's impaired temporal discrimination in the presence of numbers may have been caused by the numbers acting as distractors, we used an identical time discrimination task where the primes were two non-numerical stimuli, i.e. the two letters of the alphabet 'A' and 'Z', appearing randomly in exactly the same fashion as the number primes.

We predicted that if numbers only acted as distractors, then letters of the alphabet appearing randomly should also affect JT's temporal performance. Conversely, if JT's problem in time discrimination was related specifically to numbers, then time performance with letter primes should be better than with number primes. As only JT showed a discrepancy in the temporal discrimination task with numerical and non-numerical stimuli, the letter prime condition was only investigated in JT and not CB.

6.1.1. Accuracy

JT was accurate at comparing the duration of two stimuli preceded by letter primes (see Table 4), and did not differ from controls (ST: $t = 2.3$, $p = 0.12$, *ns*), but differed significantly from the same task performed with number primes (RSDT, $t(7) = 6.06$, $p < 0.001$).

6.1.2. PSE

JT's PSEs across the letter prime conditions did not differ significantly from controls (ST: $t = 1.69$, $p = 0.15$, *ns*), but differed from JT's performance in the same task with the number primes (RSDT, $t(8) = 19.3$, $p < 0.001$).

6.1.3. JND

There was no significant difference between controls and JT's mean JNDs (ST: $t = 0.43$, $p = 0.11$, *ns*), but differed from JT's performance in the same task with the number primes (RSDT, $t(11) = 35.9$, $p < 0.001$).

6.2. Summary of Experiments 5–7

Results of Experiments 5–7 showed that JT's time processing was impaired only when tested in the context of numbers, but that it was otherwise preserved. This suggests that numbers may have interfered with time processing in JT. To test whether numbers had a similar impact on space processing, we tested space judgments in the context of both numerical and non-numerical primes. If numbers have such disrupting effect on JT's spatial processing similar to time, a difference should be expected between conditions with numerical and non-numerical primes. In contrast, if numbers have no impact on space processing, the type of prime used should not change performance. Moreover, we aimed to test whether CB's performance in a spatial task could be modulated by numerical magnitude similar to the time tasks.

6.3. Experiment 8: which line was longer in length (with non-numerical prime '#')

To measure space processing in a 'neutral' condition, namely not involving numbers, we first tested it in the context of a non-numerical prime ('#') in both patients.

6.3.1. Accuracy

JT was accurate when comparing the length of two stimuli preceded by a non-numerical prime, with no significant difference from controls (ST: $t = 0.8$, $p = 0.22$, *ns*; see Table 4 and Fig. 5C). Similarly, CB was accurate in spatial discrimination relative to controls (ST: $t = 0.36$, $p = 0.3$, *ns*; see Table 4 and Fig. 5C). Control participants were accurate at comparing stimulus length, with no difference relative to the time comparison (no main effect of task, $F(1, 23) = 1.7$, $p = 0.2$, *ns*; see Table 4).

6.3.2. PSE

Controls' PSEs for the '#' prime did not differ significantly relative to either JT (ST: $t = -0.2$, $p = 0.5$, *ns*) or CB (ST: $t = -0.5$, $p = 0.3$, *ns*). In control participants, PSE's did not differ from veridical length (see Table 4 and Fig. 5C).

6.3.3. JND

There was no significant difference between mean JNDs for controls compared to both JT (ST: $t = 0.24$, $p = 0.49$, *ns*), and CB (ST: $t = 0.23$, $p = 0.49$, *ns*).

6.4. Experiment 9: which line was longer in length (with Arabic number primes)

Results of Experiment 8 suggested that both JT and CB were accurate at space discrimination when a non-numerical prime was displayed. We then explored whether number primes may interfere with spatial judgments in the same way they did on time judgments in JT. We therefore tested both patients and controls on a task identical to the previous one except that numerical primes ‘1’ and ‘9’ were used instead of the ‘#’ prime.

6.4.1. Accuracy

JT was accurate when comparing the length of two stimuli preceded by numerical primes, with no significant difference from controls (ST: $t = 0.5$, $p = 0.3$, *ns*). Similarly, CB was accurate in length discrimination relative to controls (ST: $t = 0.23$, $p = 0.1$, *ns*; see Table 4 and Fig. 5C).

In control participants, accuracy did not differ between priming conditions ($t(23) = 1.6$, $p = 0.1$, *ns*), nor between the non-numerical prime # and either numerical primes (prime ‘1’: $t(23) = 0.93$, $p = 0.12$, *ns*; prime ‘9’: $t(23) = 0.52$, $p = 0.6$, *ns*, see Table 4). In controls there was no overall difference between length and duration discrimination experiments (unrelated samples adjusted for unequal variances: $t(22) = 1.48$, $p = 0.1$, *ns*), thus suggesting no difference in difficulty between temporal and spatial tasks.

6.4.2. PSE

Both JT's and CB's PSEs showed no significant difference between the ‘1’ and ‘9’ prime conditions ($p > 0.05$, based on bootstrapped 95% confidence intervals and Monte Carlo simulation, see Section 4.4 above). JT and CB did not differ significantly from controls (ST: $t = 0.24$, $p = 0.4$, *ns* and ST: $t = 0.1$, $p = 0.45$, *ns* respectively, see Fig. 5C).

In control participants, mean PSEs differed significantly between the ‘1’ and ‘9’ primes ($t(23) = 4.03$, $p < 0.001$), consistent with the Reference length being perceived as approximately 0.12° shorter when preceded by a low-valued prime compared to a high-valued prime. Moreover, there was no significant difference between ‘#’ and either numerical primes (‘1’: $t(23) = 1.4$, *ns*; ‘9’: $t(23) = 0.28$, *ns*). As for Experiments 5 and 6, a shorter Test length was generally required to achieve perceptual equivalence to the Reference.

6.4.3. JND

Across priming conditions, there was no significant difference in mean JNDs between controls compared and both JT (ST: $t = 1.65$, $p = 0.07$, *ns*) and CB (ST: $t = 1.88$, $p = 0.1$, *ns*).

7. Discussion

In this study, we undertook a detailed investigation of number, time and space processing in two patients with a left and right hemisphere lesion and in 24 control participants.

7.1. A selective impairment in number and time processing

Our results indicated that JT with a left parietal lesion was selectively impaired in processing numbers as indicated by the lack of the classical distance effect when comparing Arabic numerals, by her poor performance in arithmetic tasks and in numerosity estimation. Time processing was entirely accurate unless it was tested in the context of numbers even if these were task-irrelevant. For instance, JT's underestimation of the duration of intervals displaying Arabic numbers could be up to 2/3 of their veridical duration (e.g. 40 s for a veridical 60 s interval). Strikingly, the same temporal interval was correctly judged as lasting approximately 1 min when coloured circles were displayed. Similarly, JT could correctly discriminate which of two line stimuli lasted longer in the presence of task-irrelevant symbols or letter primes, but she performed at chance when the identical stimuli were preceded by numerical primes. Such discrepant results between numerical and non-numerical conditions did not occur in an equivalent task testing space processing. Therefore, JT was equally accurate at discriminating the length of two line stimuli whether they were preceded by task-irrelevant numerical primes or by a non-numerical prime.

In contrast, CB with a right hemisphere lesion was selectively impaired in processing time whereas number and space processing were preserved. His time impairment affected the ability to estimate temporal intervals as well as the ability to discriminate between temporal durations. For instance, CB's underestimation of temporal intervals could be up to 1/3 of their veridical duration (e.g. 18 s for a veridical 60 s interval) and he was equally impaired irrespective of the stimuli displayed, i.e. coloured circles or Arabic numbers. Despite this impairment, CB's temporal estimation and discrimination were influenced by the magnitude of the numerical stimuli, similar to control participants: small numerical stimuli or small numerical primes resulted in a significantly more underestimation of temporal durations relative to larger numerical stimuli or larger numerical primes. Contrasting with his time impairment, CB's number and space processing were spared. He was accurate at estimating the numerosity of sets of stimuli, regardless as to whether these consisted of coloured circles or of numbers. Spatial processing was also entirely preserved, as CB was accurate at indicating the longer of two lines irrespective of the prime used. This double dissociation between time and number processing rules out the possibility that the single dissociation we previously reported for time processing in patient CB (Cappelletti et al., 2009) might have been enhanced by experimental factor affecting time more than space or number.

The selective numerical and temporal impairments in JT and CB suggest that these are unlikely to be due to task difficulty. If any task was disproportionately more difficult than the others, it is likely that both patients would have been impaired at it, which was not the case. Similarly, controls would have performed consistently different; however, we showed that in controls there was no difference in any measure of performance in the numerosity and temporal estimation tasks (Experiment 1–4) nor in the temporal and the spatial discrimination tasks (Experiment 5–9). Although we cannot completely exclude intrinsic differences in performing numerical, temporal or spatial tasks, within each experimental paradigm differences in the stimulus presentation or procedure were avoided by equating the tasks on as many parameters as possible. For instance, tasks assessing time and numerosity estimation (Experiments 1–4) were identical in terms of the experimental stimuli and procedure used, the only difference being in the instructions given to participants. Similarly, the temporal and spatial discrimination tasks with lines (Experiments 5–9) were closely comparable except for the instructions to participants. We also excluded the possibility that numerical primes in the temporal discrimination task (Experiment 5) acted as distractors relative to the non-numerical prime ‘#’ (Experiment 6), which might have explained JT's poor performance with number primes. Indeed we showed that non-numerical stimuli, i.e. letters of the alphabet (Experiment 7), presented as primes in the same random fashion as numbers, did not result in temporal impairment in JT. Moreover, number primes did not affect her performance in the length discrimination task, therefore ruling against the idea that they can simply act as distractors.

7.2. A partly shared magnitude system

Our results indicate that: (i) number processing was impaired in JT but not in CB; (ii) in JT time processing was preserved unless numbers were part of the experimental paradigm even as task-irrelevant stimuli; (iii) in CB selectively impaired time processing was nevertheless modulated by numerical value, similar to controls; and that (iv) space processing was preserved in both patients. These results are problematic for the proposal of a fully shared magnitude mechanism similar to Meck and Church's (1983) mode-control model (see Fig. 1B), which would predict equal impairment of different magnitude dimensions. However, we found selective impairments in number and time processing in JT and CB respectively. Our evidence of interactions between dimensions is also not compatible with the idea of magnitude dimensions being fully independent, as this would not predict any influence of a dimension on another (see Fig. 1A, e.g. Murphy, 1996, 1997). Instead, we suggest that our results are best explained by the proposal of a magnitude system partly shared among dimensions. This is the idea that besides sharing an approximate magnitude system number, time and space are also implemented by dimension-specific processes (e.g. Cantlon, Platt, & Brannon, 2009; Cappelletti et al., 2009; Walsh, 2003, see also Fig. 1C). A partly shared mechanism would account for interactions as well as dissociations among dimensions, which can be explained by dimension-specific processes being impaired rather than the common magnitude system. Moreover, the interactions between number, time and space allow us to further specify the nature of the connection between these dimensions.

7.3. An asymmetric relation between time, space and number processing

Our data suggest that the relation between dimensions is asymmetrical, with numbers appearing as the most dominant dimension and time the weakest. This is indicated by three findings: (1) numerical magnitude modulated temporal estimation but differences in temporal durations of individual stimuli did not modulate numerosity estimation in controls and patients CB and JT (Experiments 1–4); (2) impaired numbers disrupted time but not space processing in JT; (3) impaired time processing did not disrupt number processing in CB. These asymmetries between dimensions are not in line with the original proposals of a fully shared mechanism, which predicts that time and numbers would only interact symmetrically (Meck & Church, 1983; Walsh, 2003). However asymmetrical interactions could in principle be found within such a system if one dimension was more salient or automatically accessed than others. Our evidence of asymmetric interaction between time and numbers is consistent with previous studies reporting unidirectional interactions between numbers and time or stronger sensitivity for numbers relative to time, such that for example stimuli that are larger in numerical value (i.e. '6–9' vs. '1–4') or large numerosity (more vs. less dots) are judged as lasting longer whereas stimuli changing in duration do not modify the perceived numerosity accordingly and are not perceived larger than their veridical size (e.g. Cappelletti et al., 2009; Dormal et al., 2006; Droit-Volet et al., 2003, 2008; Oliveri et al., 2008; Roitman et al., 2007; Xuan et al., 2007). This suggests that both symbolic and non-symbolic number stimuli seem to modulate time processing.

The asymmetries between magnitude dimensions might in principle be due to number, time and space being differentially affected by paradigm-dependent variables. If this were the case, our two paradigms, which differed in terms of their task-requirements, stimuli, and attentional load should have resulted in different patterns of interaction among dimensions. However, we showed that the same interaction of number on time occurred in very different paradigms requiring temporal estimation and discrimination respectively. Moreover, paradigm-dependent variables do not readily account for JT's different performance in the same temporal tasks involving numerical vs. non-numerical stimuli (i.e. Experiments 3 vs. 4, and 5 vs. 6). Those tasks were identical in terms of stimuli presentation, procedures and instructions, the only exception being that either numerical or non-numerical stimuli were used. It seems therefore unlikely that a change in (task-irrelevant) stimuli alone can explain the dramatic difference in performing the two tasks.

Alternatively, asymmetries among magnitude dimensions have also been explained on the basis of theories of metaphoric mental representation (e.g. Lakoff & Johnson, 1999). These suggest that the representation of abstract concepts such as time and number depend asymmetrically on representations built through perceptuo-motor experience of more concrete concepts such as space (Garner, 1974; Talmy, 1988). However, consistent with several previous studies (e.g. Dormal et al., 2006), we have shown that the asymmetry in the interaction occurred between dimensions whose representation is considered abstract, namely numbers and time, rather than between 'abstract' and more 'concrete' concepts such as space. We have also shown that numbers interacted with space (Experiment 8), which would not be predicted by the metaphoric mental representation theories (e.g. Lakoff & Johnson, 1999).

Rather than artefacts or differences between experimental paradigms, we suggest that asymmetric relations between magnitude dimensions are due to intrinsic differences between these dimensions, with numbers thought to be a more salient dimension or more automatically accessed relative to time. Whether numbers are a more salient dimension also relative to space remains to be established as our paradigms only explored the effect of numerical magnitude on length but not the opposite. The hypothesis of intrinsic differences between dimensions has previously been proposed to explain differences in performing duration and numerosity tasks in adults and children (e.g. Dormal et al., 2006; Droit-Volet et al., 2003; Roitman et al., 2007; Xuan et al., 2007). Further support to this idea comes from the observation that time, but not number or space, is a vulnerable magnitude dimension which can be easily disrupted by several factors for instance the Treisman clicks (Treisman & Brogan, 1992), the presentation of 'filled' or 'empty' stimuli (Rammsayer & Lima, 1991), dual tasks (e.g. Casini & Macar, 1997), and manipulations of dopamine and acetylcholine (Meck, 1996). Intrinsic differences between dimensions account for the fact that in our controls time was modulated by numerical magnitude but not the opposite. Moreover, the automatic access or the saliency of numbers may explain why they still exerted an influence on impaired time in CB. Finally, the idea that time is a vulnerable dimension found support in JT's performance in temporal tasks showing that her temporal processing was destroyed by numerical stimuli even when they were task-irrelevant. Notably, such impairment did not emerge in case of space, again reinforcing the proposal that magnitude dimensions differ intrinsically, with time but not space or number being a weak dimension.

7.4. Time, space and numbers in the brain

The locus of the magnitude system shared among number, time and space processing has been originally proposed in the right inferior parietal cortex (e.g. Walsh, 2003). However, the selectively impaired numerical and temporal processing shown here, together with preserved space processing in both patients are difficult to accommodate within this proposal. Rather, these data allow us to make two suggestions. First, it is possible that besides the parietal areas, other brain regions are involved in processing codes that are dimension-specific, also consistent with a recent review of the ATOM (see Bueti & Walsh, 2009). This would explain why some of these codes can be impaired while others remain intact. Support for this hypothesis comes from studies showing that some parietal regions, and specifically the IPS, seems critical for numerical but not time processing (Dormal, Andres, & Pesenti, 2008), and would be consistent with CB's brain lesion that spared the IPS areas. Indeed, CB's lesion extended to the right inferior frontal and lateral prefrontal areas and deeply into the insula and the right basal ganglia. As these regions have been shown to be relevant for time processing (e.g. see Wiener, Turkeltaub, & Coslett, 2010 for a review), it is possible that besides the parietal areas, damage to these additional regions may account for CB's time impairment. Secondly, it is possible that the neuronal correlates of different magnitude codes may recover in different ways following a brain lesion, revealing alternative neuronal and cognitive mechanisms for performing the tasks, i.e. degenerate systems (Price & Friston, 2002), or that perilesioned areas are still sufficient for processing some of these dimensions but not others (e.g. Price & Friston, 2002). Although our data do not allow us further speculations, we note that degeneracy and recovery may account for inconsistencies between dissociations and associations between magnitude dimensions (e.g. Basso et al., 1996; Zorzi et al., 2002). Likewise, different ways of recovering may accommodate evidence that the parietal regions are critical for number, time and space processing (e.g. Maquet et al., 1996; Pouthas et al., 2000), with our results showing that some of these dimensions can be maintained despite parietal lobe lesions.

8. Conclusions

In conclusion, the present study provides evidence that number and time processing can doubly dissociate following lesions involving the left or right parietal lobe. Space processing was spared in our two patients. However, parietal lesions can often result in space impairment (see Rorden et al., 2006), therefore more cases need to be examined before reaching firm conclusions on the role of the parietal lobes in space processing. Moreover, we documented a striking asymmetrical interaction between numbers and time processing, such that time can either be modulated by numerical magnitude in control participants and in patient CB, or it can be dramatically impaired by the mere presentation of numerical stimuli in JT. Our data can be explained by the hypothesis of a partly shared magnitude system between magnitude dimensions, and endorse the proposal that asymmetries between number, time and space may relate to intrinsic, paradigm-free differences between these dimensions, with number being the strongest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuropsychologia.2011.07.014.

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