Neuropsychological Trends

32
November 2022

Alexandrine Faye - François Osiurak - Mathieu Lesourd - Salem Hannoun François Cotton - Jérémy Besnard - Sophie Jacquin-Courtois
Numerical, spatial and material magnitude estimation in left and right brain-damaged patients 7

Zainab Khan - Muhammad Azharuddin - M. Ejaz Hussain Anam Aseem - Ashi Saif
Study on neuropsychological and neurophysiological functions: acute effect of aerobic exercise training in sleep disturbed collegiates 29

Michela Balconi - Laura Angioletti
Criticalities of Executive Functions (EFs) research in Gambling Disorder: between the behavioural and neurophysiological markers 55

Sudhanshu Kacker - Anshul Sharma - Sheshav Somani Shailesh K Kawale - Amit Tak
Rajyoga meditation: effects on visual evoked potentials in migraine patients 67

Katia Rovelli
Neurocognitive self-empowerment in occupational and managerial contexts: contribution of mindfulness-based neurofeedback protocols 85

Numerical, spatial and material magnitude estimation in left and right brain-damaged patients

Alexandrine Faye[1] - François Osiurak[1, 2] - Mathieu Lesourd[3] - Salem Hannoun[4] - François Cotton[5,6] - Jérémy Besnard[7] - Sophie Jacquin-Courtois[8,9]

[1]*Laboratoire d'Etude des Mécanismes Cognitifs (EA 3082), Université de Lyon, France*

[2]*Institut Universitaire de France, Paris, France*

[3]*Laboratoire de Psychologie, Université de Bourgogne Franche-Comté, Besançon, France*

[4]*American University of Beirut Medical Center (AUBMC), Beirut, Lebanon*

[5]*Service de Radiologie, Centre Hospitalier Lyon-Sud, Hospices Civils de Lyon, Pierre-Bénite, France*

[6]*CREATIS - CNRS UMR 5220 & INSERM U1044, Université de Lyon, France*

[7]*Laboratoire de Psychologie des Pays de la Loire (EA 4638), Université de Nantes et d'Angers, France*

[8]*Integrative, Multisensory, Perception, Action, & Cognition Team (INSERM-CNRS-UMR 5292), Université de Lyon, France*

[9]*Mouvement et Handicap, Hospices Civils de Lyon et Centre de Recherche en Neurosciences de Lyon, Hôpital Henry Gabrielle, Hospices Civils de Lyon, St Genis Laval, France*

DOI: https://dx.doi.org/10.7358/neur-2022-032-faye

francois.osiurak@univ-lyon2.fr

Abstract

In this study, we tested the main prediction derived from the "A Theory Of Magnitude" or ATOM, according to which discrete (e.g., numbers) and continuous (e.g., space, material) magnitudes are processed within the right hemisphere. To do so, we examined 11 right brain-damaged patients, 19 left brain-damaged patients, and 30 healthy subjects on different tasks assessing magnitude estimation: symbolic and non-symbolic numerical magnitude as well as spatial (i.e., length) and material (i.e., weight) magnitude. Contrary to the ATOM's predictions, we did not find significant correlations between all the magnitude estimation tasks in right brain-damaged patients. Correlations between numerical and length magnitudes were found in left brain-damaged patients and healthy subjects. Our results support the existence of a partial independence between the different forms of magnitude estimation processing.

Keywords: numerical cognition; numerical magnitude; material magnitude; right hemisphere

1. Introduction

Numerosity and numbers surround us in everyday life. All cultures possess a vocabulary to refer to quantities and compare sets of objects (e.g., Pica et al., 2004). Several studies have demonstrated that humans perform additions without a precise numerical system (e.g., Pica et al., 2004), or that infants (e.g., Izard et al., 2009) and some animals (Agrillo & Bisazza, 2018) could discriminate numerical quantities. Based on this propensity for numerosity manipulation, a complex learned achievement of the human brain has allowed the development of a symbolic system containing Arabic digits.

In this context, Dehaene and colleagues have developed the Triple Code Model theory (TCM), which posits the existence of three numerical representations (e.g., Dehaene & Cohen, 1995). Two codes are symbolic, verbal and culturally dependent. The auditory-verbal code gives a verbal label to the quantities (e.g., the word "three"), allowing the counting and retrieval of arithmetic facts via long-term memory. This code is lateralized in the left angular gyrus and perisylvian areas. The Arabic code corresponds to the visual form of quantities (e.g., Arabic digits) allowing parity judgments and resolution of multi-digit operations. This code is located within the occipito-temporal regions (Dehaene & Cohen, 1995). The third code is a pre-verbal and non-symbolic representation of quantities, allowing comparison, estimation and approximate calculation. In other words, this analogical code contains *the number sense* linking a symbol to a quantity (Dehaene, 1997). It is innate, automatic and common to all human beings and some animals. Two preverbal mechanisms underlie the analogical code. Subitizing is defined as the perception of small quantities without counting (Mandler & Shebo, 1982). Beyond four elements, the Approximate Number System (ANS) takes over (Dehaene, 1997; Piazza, 2010; Pica et al., 2004; Verguts & Fias, 2004). This system supports the numerical quantity representation in an approximate and compressed manner, so that two sets can be discriminated only if they differ in a given numerical ratio, according to the Weber law (Piazza, 2010). The data collected by Dehaene and Cohen (1995) allowed them to implement the analogical code in both intraparietal sulci (IPS; see also Faye et al., 2019).

More recently, Walsh (2003, 2013) have documented a series of studies, in which the presence of mutual interference between different types of magnitudes (i.e., space, time, number) have been reported. He has proposed that the ANS is not specific to the numerical magnitude but part of a generalized magnitude system. This hypothesis is part of ATOM (A Theory of Magnitude; Walsh, 2003, 2013) according to which all the prothetic magnitudes, namely the dimensions described according to "more than-less than" relationships, are represented and processed in the similar way. The ATOM includes all dimensions that require an estimation of quantities, whether discrete or continuous. The generalized magnitude system might be useful to produce a rapid judgment about the physical world around us and would be located in the right IPS (Walsh, 2003, 2013; Bueti & Walsh, 2009). In other words, there would not be a number sense but *a sense of magnitude* (Leibovich et al., 2017). However, the literature has mainly focused on the relationships between magnitudes represented spatially (e.g., number, size, length). An unresolved issue is whether this sense of magnitude could be extended to the material magnitudes (e.g., weight) or whether this sense only concerns spatial magnitudes (e.g., length).

The goal of this article is to tackle this issue. To do so, we tested two patient groups with left or right brain damage (LBD, RBD) and a control group on (1) a battery of classical tasks assessing symbolic (Exact Addition, Approximate Addition, Number Comparison) and non-symbolic (Dot addition, Dot comparison) numerical skills and (2) two experimental tasks of length and weight estimation. According to the ATOM, we expected significant correlations between all the tasks involving magnitude processing (i.e., Number comparison, Dot comparison, Length estimation, Weight estimation), particularly in the RBD patients. These predictions diverge from those derived from the TCM concerning the ANS, according to which associations should be found only between the Approximate Addition, Number Comparison, Dot Addition and Dot Comparison tasks.

2. Methods

2.1 Participants

Nineteen right-handed LBD and eleven right-handed RBD patients were recruited from the rehabilitation unit of the Henry Gabrielle Hospital, Saint-Genis-Laval, France (see Table 1). The patients were hospitalized following a cerebrovascular accident. Twenty-four were returned home and 6 were hospitalized. Patients were included only if (1) they had unilateral brain damage (2) they passed visual perception tests (e.g., PEGV, OTA; see Table 1) in order to exclude visual deficit (e.g., agnosia) or spatial neglect, and (3) they could understand the instructions. Patients used their ipsilesional hand to control for the potential impact of sensorimotor deficits (e.g., hemiparesia). Thirty right-handed healthy subjects without psychiatric and neurological history were matched to the patients with respect to gender, age and educational level (see Table 1). They were recruited through advertisements published in pamphlets and posted on social media websites. Half of the control subjects used their right hand. The other half used their left hand. Written informed consent was obtained from all participants prior to the study. The study was conducted in accordance with the Declaration of Helsinki, seventh revision.

Table 1. Demographic and clinical data

	LBD (n = 19)	RBD (n = 11)	CONT (n = 30)	LBD versus RBD	LBD versus CONT	RBD versus CONT
Gender (n): F/M	9/10	3/8	15/15	ns	ns	ns
Age (years)	50.90(9.2)	55.13(19.12)	50.79(13)	ns	ns	ns
Education (years)	13.92(3.41)	12.67(3.68)	14.77(2.27)	ns	ns	ns
Laterality (n): right/left/ambidextrous	17/0/2	10/0/1	26/1/3	ns	ns	ns
Type of lesions: Ischemic /hemorrhagic	16/3	10/1	-	ns	-	-
Post-injury delay (months)	19.47(25)	6.09 (5.22)	-	s	-	-
Hemiparesis (n)	4	5	-		-	-
Hemiplegia (n)	1	0	-		-	-
Hemianopia (n)	2	1	-	ns	-	-
Visual perception (PEGV)*						
Similar Figures	9.84	9.23	-	ns	-	-
Overlapping Figures	35.73	34.15	-	ns	-	-
Bell test$^{\Phi}$	1.74	2.9	-	ns	-	-
OTA test$^{\beta}$						
Oblivion	0.3	1.5	-	s	-	-
Circled	0.1	0	-	ns	-	-
Line bisection test (percentage of deviation)$^{\Delta}$	2.2	2.3	-	ns	-	-

Legend: LBD, left brain-damaged patients; RBD, right brain-damaged patients; CONT, control subjects; n, number of participants; F, Female; M, Male; CVA, Cerebrovascular accident; ns, non-significant (p > .05); s, significant (p < .05). Intergroup comparisons were performed with the x^2 test for gender, laterality, and type of lesions, and with the Mann-Whitney test for the other variables. Standard deviations are given in brackets and italics. *Protocole Montréal-Toulouse d'Evaluation des Gnosies Visuelles (PEGV). In the Similar Figures subtest, the participant had to choose the picture similar to the target item (pathological score < 8). In the Overlapping Figures subtest, the participant had to choose the three pictures that compose the target item (as in the Poppelreuter test; pathological score < 30). $^{\Phi}$Bell test. The participants had to circle 36 bells scattered on an A4 sheet among distractors (pathological score > 6 forgotten bells). $^{\beta}$OTA test. The participant had to circle the full circles and to cross the open circles arranged on an A3 sheet, displayed horizontally. The pathological score corresponded to three or more oblivions. $^{\Delta}$Line bisection test. The participant had to mark the center of 10 lines, presented horizontally, one after the other (pathological score > 10% of deviation).

2.2 Assessments

2.2.1 Numerical cognition

For all the tasks presented in this section:

(1) The presentation order of items was random. Participants were prompted to respond as quickly and accurately as possible;

(2) The symbolic tasks contained Arabic digits in black Calibri on a white background. The non-symbolic tasks consisted of sets of dots;

(3) The stimuli were presented using the OpenSesame software. The participant sat approximately 30 cm from the monitor. The response keypad was on the left or right side of the computer, depending on the hand used. The participant had to press the right or the left key to respond. This did not concern the task of non-symbolic addition (see below);

(4) The scores corresponded to the total of correct responses. They were converted into percentages.

Symbolic tasks

Exact and Approximate Addition. We used the task created by Stanescu-Cosson et al. (2000). Twenty additions in Arabic notation were presented in two tasks. Problems with the same digits (e.g., 2 + 2) were excluded. In the Exact Addition task (i.e., arithmetic facts), one response was the correct result, and the other was a false result differing by no more than two units (Figure 1). In the Approximate Addition task, the correct response corresponded to the exact result with plus or minus one unit of difference, while the incorrect response deviated by three to eight units from the exact result (Figure 1). The stimuli appeared for 200 ms and the responses for 1000 ms. There was a fixation point of 1400 ms between the additions and the responses and between the responses and the subsequent additions. The test phase was preceded by four examples. One point was given if the response was correct and 0 point if the response was incorrect (max = 20 points per task).
Number Comparison. This task was based on the tasks developed by Nuerk and colleagues (e.g., Nuerk et al, 2004). Forty pairs of two-digit numbers, ranging from 21 to 99, were presented in Arabic notation (Figure 1). Three parameters were controlled: (1) the distance between the units (small: 1-3 *versus* large: 4-8), (2) the distance between the tens (small: 1-3 *versus* large: 4-8), (3) the congruence between the two pairs. A pair was congruent when the unit of the smaller number was also smaller than the unit of the largest digit (e.g., congruent: 21-57 *vs.* incongruent: 29-51). Tens, numbers too close and numbers divisible by each other were excluded. The ratio between the numbers of each pair was not controlled but the ratio was different for most of the pairs presented. The ratio between pairs was balanced and

ranged from 0.2 to 0.4, 0.4 to 0.6, 0.6 to 0.7, and 0.7 to 0.9. The stimuli were presented for 1000 ms and were separated by a fixation point of 1400 ms. The test phase was preceded by four examples. One point was given if the response was correct and 0 point if the response was incorrect (max = 40 points per task).

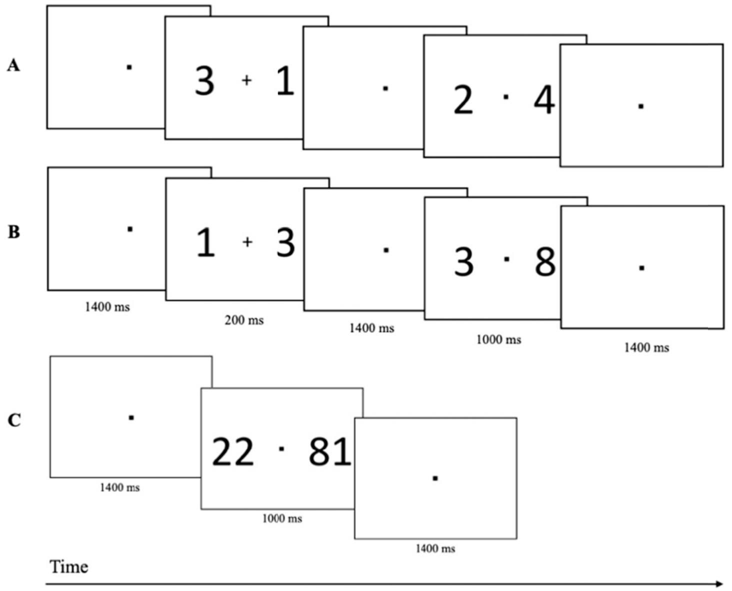

Figure 1. Symbolic tasks. A and B show the course of the Exact Addition task (A) and the Approximate Addition (B) task. The participant had to choose either the exact result (A) or the result closest to the exact result (B) of the addition presented. C illustrates the course of the Number Comparison task

Non-symbolic tasks

Dot Addition. This task was inspired by the work of Barth et al. (2006). Participants were presented with 40 non-symbolic additions. The operands contained 9 to 30 dots while the result included 12 to 98 dots (Figure 2). The ratios between the sum of the first two sets of dots and the third set were plus or minus 0.6 and 0.8. In other words, we divided and multiplied the correct result of the addition by 0.6 and 0.8 to obtain the third set of dots. The size of the dots was constant, and their position was randomized. They were presented in black on a gray background. The first and second sets of dots appeared for 800 ms, they were separated by the "+" operator for 1000 ms. Then a "RESPONSE" slide was presented for 1400 ms in order to prepare the participant to give their response. Finally, the third set of dots appeared for 1500 ms. The stimuli were separated by a fixation point of 1400 ms. The task was to choose whether the third set of dots was smaller than or greater than the sum of the two sets previously seen. The participant responded using a keyboard by clicking on "-" for the "smaller" response and "+" for the "greater" response. The test phase was preceded by eight examples. One point was given if the response was correct and 0 point if the response was incorrect (max = 40 points per task).

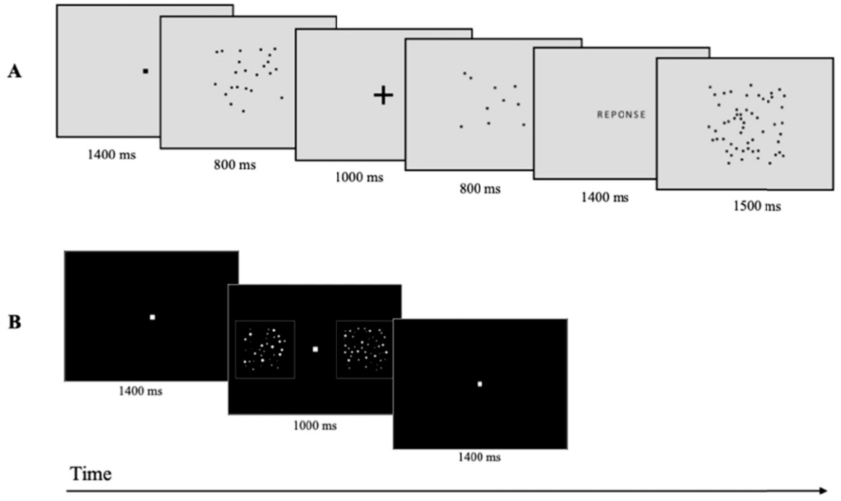

Figure 2. Non-symbolic tasks. A illustrates the Dot Addition task. The participant had to choose if the last set of dots was greater or lower than the sum of the two sets of dots previously seen. B illustrates the Dot Comparison task

Dot Comparison. We presented the same pairs as in the Number Comparison task. Two sets of dots were displayed. The area occupied by the dots was the same for both sets (Figure 2). The size of the dots was defined randomly through the software Processing. The stimuli were displayed in white on a black background. They were presented for 1000 ms and were separated by a fixation point of 1400 ms. The test phase was preceded by four examples. One point was given if the response was correct and 0 point if the response was incorrect (max = 40 points per task).

2.2.2 Estimation of physical properties

Length Estimation task. Nine sticks of three different lengths were presented (i.e., 3 cm, 6 cm and 9 cm). These sticks were presented vertically on the side of the assessed hand. A box was displayed in front of the participant, inside which a cube was placed at 9 cm, 15 cm, 21 cm or 27 cm from the right side of the box (Figure 3), creating four different items, each presented four times (i.e., 16 items, Table 2). The participant had to select three sticks to make a tool and to drop the cube by inserting the tool made through the hole located on the right side of the box, without exceeding the platform. So, for each distance, a best combination of three sticks was expected (Table 2). A demonstration and two examples were presented before the testing trials. The score corresponded to the margin of error, namely, the difference in absolute value between the actual distance of the cube and the participant's tool made (e.g., the cube was placed at 21 cm and the participant assembled two 3-cm sticks and one 9-cm stick to make a 15-cm tool; the margin of error is 21 cm – 15 cm = |6 cm|). Then, the absolute error margins of each item were summed (i.e., maximum = 240 cm). This score was converted into percentage values. The higher the percentage value, the lower the performance.

Table 2. Best combinations for each item of the Length Estimation task

Items	Best combination in cm
1: 9 cm	3 + 3 + 3
2: 15 cm	3 + 6 + 6
	3 + 3 + 9
3: 21 cm	6 + 6 + 9
	3 + 9 + 9
4: 27 cm	9 + 9 + 9

Weight Estimation task. Nine cubes of three different weights were presented (i.e., 15 g, 30 g and 45 g). These cubes were presented on the side of the assessed hand. A scale was displayed in front of the participant. A container was hanged at the end of the left arm. At the end of the right arm, the examiner hanged a target-weight of 23 g, 38 g, 53 g or 68 g (Figure 3), creating four different items, each presented four times (i.e., Table 3). The target-weight was attached to the scale. Participants had to choose three cubes, which could raise the item-weight up to the rod attached on the foot of the scale. Participants were allowed to weigh up a weight identical to the item-weight as well as cubes, but one by one and only with the evaluated hand (Figure 3). So, for each item-weight, a best combination of three cubes was expected (Table 3). The task was preceded by a demonstration and two examples. Here, the margin of error corresponded to the difference in absolute value between the expected weight (i.e., the weight of the three cubes that raised the item-weight up to the rod) and the participant's response (e.g., the item-weight was 53 g and the participant proposed two 15-g cubes and one 45-g cube; the margin of error is 53 g – 75 g = $|22\text{ g}|$). As for the Length Estimation task, absolute error margins were added (maximum = 1200 g) and converted into percentage values.

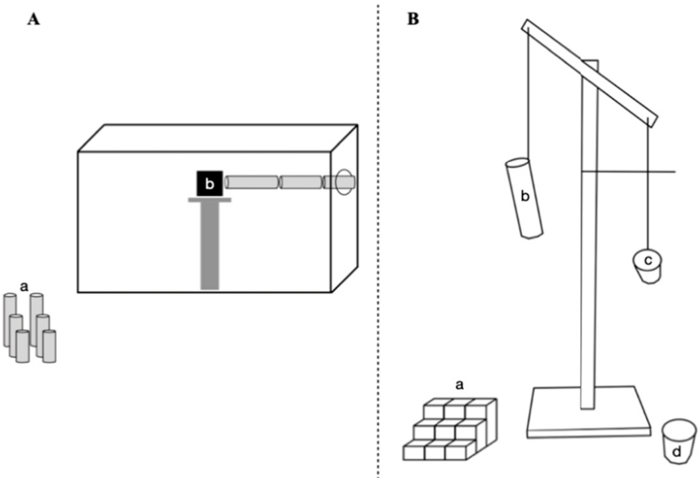

Figure 3. Physical properties estimation tasks. A displays the Length Estimation task. The participant had to choose three sticks (a) to drop the cube (b), without the assembled sticks exceeded the platform on which the cube was placed. B illustrates the Weight Estimation task, in which the participant had to choose 3 cubes (a) that must be put into the container (b) to raise the item-weight (c) to the rod. The participant could weigh up a weight identical (d) to the item-weight (c)

Table 3. Best combinations for each item of the Length Estimation task

Items	Best combination in g
1: 23 g	15 + 15 + 15
2: 38 g	15 + 30 + 30
	15 + 15 + 45
3: 53 g	30 + 30 + 45
	15 + 45 + 45
4: 68 g	45 + 45 + 45

2.3 Statistical analysis

Nonparametric statistics were preferred due to the non-normal distribution of some variables and the small sample sizes. Between-group comparisons were performed with pairwise Mann-Whitney tests and correlations were assessed with Spearman rank-order correlations. Statistical significance was set at $p < .05$.

3. Results

3.1 Between group comparisons

Results are shown in Figure 4 and Table 4. Mann-Whitney tests indicated that LBD patients had significantly lower scores ($M = 81.32$) than control subjects ($M = 93.00$) on the Exact Addition task ($W = 408.5$; $p = .004$). RBD patients scored significantly lower ($M = 69.09$) than control subjects ($M = 85.00$; $W = 79.5$; $p = .006$) and LBD patients ($M = 84.21$; $W = 52.5$, $p = 0.026$) on the Number Comparison task. RBD patients also scored significantly lower than control subjects on the Approximate Addition task ($M_{RBD} = 73.18$; $M_{Cont} = 83.83$; $W = 108.5$; $p = .048$), the Dot Addition task ($M_{RBD} = 57.95$; $M_{Cont} = 71.92$; $W = 100.5$; $p = .029$) and the Dot Comparison task ($M_{RBD} = 64.32$; $M_{Cont} = 77.17$; $W = 103.5$; $p = .036$), and produced more errors than control subjects on the Length Estimation task ($M_{RBD} = 8.86$; $M_{Cont} = 6.29$; $W = 228.5$; $p = .031$). No other comparison was statistically significant.

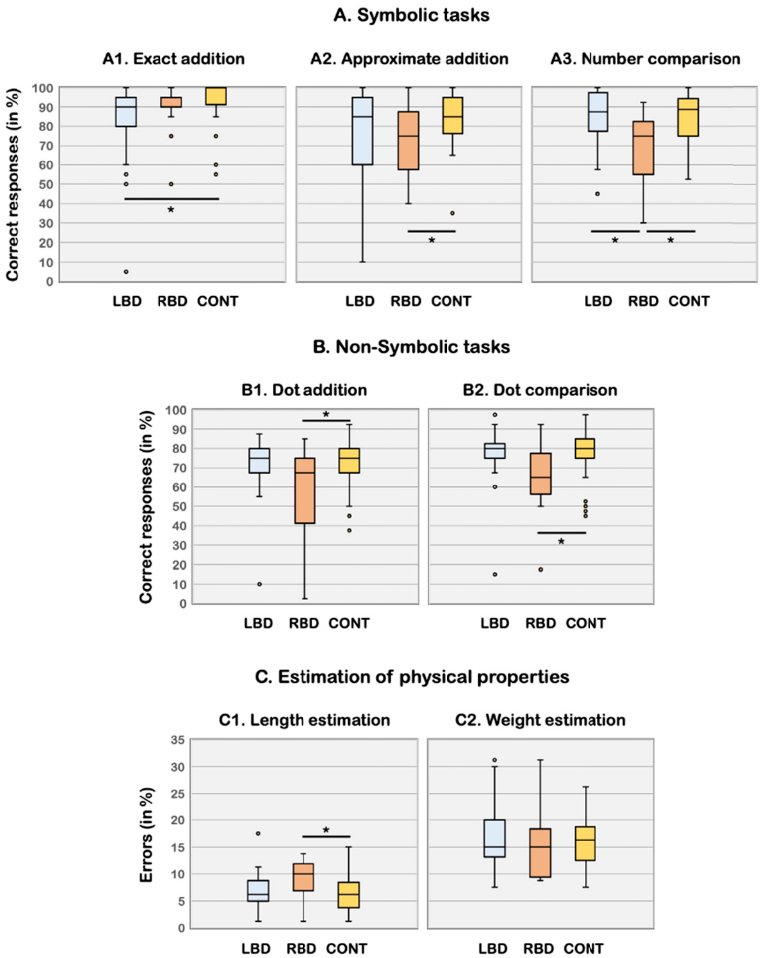

Figure 4. LBD patients', RBD patient's and control subjects' performance on the numerical cognition tasks and the physical properties estimation tasks. A represents the percentage of correct response in the Symbolic tasks, B in the Non-Symbolic tasks, and C the percentage of errors in the physical properties estimation tasks. The boxplots represent the median value for each group, the interquartile range, and the minimum and the maximum. Participants whose performance was lower or upper of the edge of the box at 0.5 were classified as outliers

Table 4. LBD patients', RBD patient's and control subjects' performance on the numerical cognition tasks and the physical properties estimation tasks.

	Symbolic			Non-Symbolic		Physical properties estimation	
	EA	AA	NC	DA	DC	Length	Weight
LBD	81.32 (23.80)	73.68 (29.05)	84.21 (16.18)	70.00 (17.22)	76.32 (16.94)	6.91 (3.62)	17.37 (6.92)
RBD	89.09 (14.80)	73.18 (19.01)	69.09 (20.59)	57.95 (24.92)	64.32 (20.86)	8.86 (4.27)	15.38 (7.07)
CONT	93.00 (11.64)	83.83 (14.30)	85.00 (11.73)	71.92 (12.59)	77.17 (13.61)	6.29 (3.32)	16.13 (4.72)
LBD vs CONT	p=.004*	p=.29	p=.66	p=.45	p=.49	p=.32	p=.41
RBD vs CONT	p= .07	p=.048*	p=.006*	p=.029*	p=.036*	p=.031*	p=.77
LBD vs RBD	p=.30	p=.59	p=.026*	p=.13	p=.08	p=.13	p=.46

Legend: LBD, left LBD, left brain-damaged patients; RBD, right brain-damaged patients; CONT, control subjects; EA, Exact Addition; AA, Approximate Addition; NC, Number Comparison; DA, Dot Addition; DC, Dot Comparison; Length, Length Estimation; Weight, Weight Estimation. Standard deviations are given in brackets and italics. *, statistically significant

3.2 Correlations

Results of correlational analyses are given in Table 5. To correctly interpret the presence of negative or positive significant correlations between our tasks, it is noteworthy to remind that the scores of the Length Estimation task and the Weight Estimation task reflected a percentage of errors, whereas the scores on the other tests reflected a percentage of correct responses. In LBD patients, the performance of the Length Estimation task correlated positively with that of the Weight Estimation task (rho = 0.59, p = .007), and negatively with the Approximate Addition task (rho = -0.47, p = .041) and the Dot Comparison task (rho = -0.47, p = .039), the two latter being positively correlated (rho = 0.62, p = .004). A positive significant correlation was also found between the Dot Comparison task and the Number Comparison task (rho = 0.54, p = .017). We also found in RBD patients a positive correlation between the Length Estimation task and the Weight Estimation task (rho = 0.62, p = .043). The Length Estimation task was also significantly and negatively correlated to the Exact Addition task (rho = -0.64, p = .035). Significant positive correlations were also reported between the Number Comparison task and the Dot Addition task (rho = 0.68, p = .022), the Number Comparison task and the Dot Comparison task (rho = 0.94, p < .001), and the Dot Addition task and the Dot Comparison task (rho = 0.65, p = .029). Finally, in control subjects, a significant positive correlation was obtained between the Length Estimation task and the Dot Comparison task (rho = 0.40, p = .027), the Exact Addition task and the Approximate Addition task (rho = 0.60, p < .001), the Number Comparison task and the Dot Comparison task (rho = 0.51, p = .004), and the Number Comparison task and the Dot Comparison task (rho = 0.47, p = .009). No other correlation was statistically significant.

Table 5. Correlations between performance of numerical cognition and physical properties estimation tasks in LBD patients, RBD patients, and control subjects

LBD	Weight	EA	AA	NC	DA	DC
Length	0.59**	-0.11	-0.47*	-0.13	-0.36	-0.48*
Weight	—	-0.20	-0.28	0.18	-0.34	-0.19
EA		—	0.41	0.29	0.45	0.16
AA			—	0.41	0.16	0.62**
NC				—	0.07	0.54*
DA					—	-0.06
RBD	Weight	EA	AA	NC	DA	DC
Length	0.62*	-0.64*	0.09	-0.35	-0.42	-0.45
Weight	—	-0.57	-0.23	-0.05	0.08	-0.17
EA		—	0.51	0.49	0.38	0.58
AA			—	0.23	0.23	0.29
NC				—	0.68*	0.94***
DA					—	0.65*
CONT	Weight	EA	AA	NC	DA	DC
Length	0.11	0.09	-0.21	-0.12	-0.22	0.40*
Weight	—	0.14	0.04	0.05	-0.07	-0.17
EA		—	0.60***	0.04	0.14	0.02
AA			—	0.22	0.26	0.01
NC				—	0.51**	0.47**
DA					—	0.13

Legend: LBD, left brain-damaged patients; RBD, right brain-damaged patients; CONT, control subjects; EA, Exact Addition; AA, Approximate Addition; NC, Number Comparison; DA, Dot Addition; DC, Dot Comparison; Length, Length Estimation; Weight, Weight Estimation. *, $p < .05$; **, $p < .01$; ***, $p < .001$

4. Discussion

Globally, our results indicate that RBD patients performed worse than controls on most of numerical tasks whereas LBD patients scored lower than controls only in the Exact Addition task. Moreover, concerning the Length and Weight Estimation tasks, RBD patients showed difficulties but only for the Length Estimation task. Finally, the Length and Weight estimation tasks correlated together in both brain-damaged patient groups, but only the Length Estimation task was associated with some numerical tasks. In the next sections, we discuss these results in light of the predictions derived from the ATOM and TCM.

The link between the two physical properties estimation tasks reported in both patient groups is consistent with the ATOM, which suggests the existence of a generalized magnitude system involved in all prothetic magnitudes (Walsh, 2003, 2013). Support for the ATOM also comes from the associations found in LBD patients between the Length Estimation task and some numerical tasks. The conclusion of the existence of a generalized magnitude system is nevertheless to be tempered because of the absence of links (1) between the Weight Estimation task and the numerical tasks and (2) between the physical properties estimation tasks and the numerical magnitude tasks in RBD patients. The latter finding is all the more important because RBD patients met difficulties in both the Length Estimation task and the numerical magnitude tasks. Therefore, strong associations between all these tasks could be expected. Two explanations can be provided.

First, the generalized magnitude system would only include the magnitudes represented spatially, explaining the link between length estimation and numerical skills. The magnitudes concerning material properties (e.g., weight) would be handled through other processes, involving other brain areas than the right IPS. This first explanation remains viable even if it does not account for the correlation found between Length and Weight estimation tasks. A second explanation can be offered taking into consideration this discrepancy. We can suppose a fragmentation of the generalized magnitude system where the spatial and the material magnitudes would be processed by connected subsystems. At the cerebral level, Newman et al. (2005) showed that the lateral occipital complex was involved in the multi-sensory processing of spatial and material properties, the IPS being activated during the processing of spatial properties and the extra-striated area during the processing of material properties. Finally, these explanations support the hypothesis of partial independence (e.g., Cappelletti et al., 2014) according to which magnitudes share common but partially independent processes, suggesting interactions and dissociations between different dimensions.

The predictions of the TCM concerning the ANS were not fully confirmed by our findings in that we found a link between the estimation of length and some numerical skills. One potential explanation is that the ANS is a subsystem of the generalized magnitude system more specifically involved in space processing (e.g., mental number line; see just above for a somewhat similar interpretation). Another explanation is that some numerical skills such as approximate calculation (e.g., addition) were involved in our Length Estimation task. Nevertheless, in this context, we should also observe significant correlations between our Weight Estimation task and addition tasks, but we did not. Besides, our findings corroborated the TCM as only LBD patients had difficulties with arithmetic facts assessed with the Exact Addition task, thereby confirming the left hemisphere specialization for the auditory-verbal code.

The present study presented several limitations. Firstly, the size of samples limited us in the choice of statistical tests. It would have been interesting to perform ANCOVA to explore whether covariables had effects on our results (e.g., visuospatial tasks, post-injury period). Secondly, it has been shown that RBD patients may be deficient in processing spatial dimensions (Bonato et al., 2012; Calabria et al., 2011). Therefore, it would have been appropriate to recruit two groups of patients, one with and another without unilateral spatial neglect. Thirdly, the Length Estimation task certainly needed working memory and mental rotation skills. We did not explore this aspect in patients. Future research is needed to explore whether these potential confounds had an impact on patients' performance.

To conclude, we would like to stress the strength of the present study, which is the first one aiming to assess numerical and physical magnitude estimation skills in brain-damaged patients. Although we found some discrepancies, the fact that physical properties and numerical magnitude estimation seem to be preferentially impaired after right brain damage incites us to pursue the research to test the existence of a dependance or an independence between the different magnitude systems or subsystems. A potential promising avenue for future research is to adapt our physical properties estimation tasks to an experimental paradigm that is more inclined to investigate the sense of magnitude. Indeed, if humans possess a sense of magnitude that shares the same characteristics as the initial concept of the sense of number (i.e., ANS), then we should observe the same effects for non-numerical quantities as for numerical quantities. For instance, the well-known Spatial-Numerical Association of Response Codes (SNARC) effect reflects the orientation of a "mental number line" (i.e., small numbers are associated with faster left responses and large numbers with faster right responses in people raised in the context of left-to-right writing; Dehaene et al., 1993). If this effect is not specific to the sense of number but extends to other dimensions, then we could imagine reporting it also for physical quantities such as the spatial dimension or the material dimension. Some experimental evidence has confirmed the presence of SNARC-like effects for the temporal dimension (Ishihara et al., 2008) as well as for physical properties, such as size (Prpic et al., 2020; Sellaro et al., 2015). However, the outstanding question is whether such an effect can also be found for non-spatial physical properties such as weight. Exploring this aspect could help us better understand whether the sense of magnitude can extend to any material dimension.

Availability of data and material

The dataset is available from the corresponding author on reasonable request.

Funding

This work was supported by grants from ANR (Agence Nationale pour la Recherche; Project "Cognition et économie liée à l'outil/Cognition and tool-use economy" ECOTOOL; ANR-14-CE30-0015-01).

Competing interests

The authors declare that there are no competing interests regarding the publication of this paper.

Authors' contributions

A.F., F.O and S.J. designed the experiments and analyzed the data. A.F. drafted the manuscript. All the authors approved the final version of the manuscript.

REFERENCES

Agrillo, C., & Bisazza, A. (2018). Understanding the origin of number sense: A review of fish studies. *Philosophical Transactions of the Royal Society B: Biological Sciences, 373*, 20160511. https://doi.org/10.1098/rstb.2016.0511

Barth, H., La Mont, K., Lipton, J., Dehaene, S., Kanwisher, N., & Spelke, E. (2006). Non-symbolic arithmetic in adults and young children. *Cognition, 98*, 199–222. https://doi.org/10.1016/j.cognition.2004.09.011

Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: Evidence for a mental time line. *Neuroscience & Biobehavioral Reviews, 36*, 2257–2273. https://doi.org/10.1016/j.neubiorev.2012.08.007

Bueti, D., & Walsh, V. (2009). The parietal cortex and the representation of time, space, number and other magnitudes. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*, 1831–1840. https://doi.org/10.1098/rstb.2009.0028

Calabria, M., Jacquin-Courtois, S., Miozzo, A., Rossetti, Y., Padovani, A., Cotelli, M., & Miniussi, C. (2011). Time perception in spatial neglect: A distorted representation? *Neuropsychology, 25*, 193–200. https://doi.org/10.1037/a0021304

Cappelletti, M., Chamberlain, R., Freeman, E. D., Kanai, R., Butterworth, B., Price, C. J., & Rees, G. (2014). Commonalities for numerical and continuous quantity skills at temporo-parietal junction. *Journal of Cognitive Neuroscience, 26*, 986–999. https://doi.org/10.1162/jocn_a_00546

Dehaene, S. (1997). *The number sense: How the mind creates mathematics.* Oxford University Press. https://global.oup.com/academic/product/the-number-sense-9780199753871?cc=fr&lang=en&

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122*, 371–396. https://psycnet.apa.org/doi/10.1037/0096-3445.122.3.371

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition, 1*, 83–120. https://www.scienceopen.com/document?vid=bd20f245-aea9-411d-b13f-f9ab186f497f

Faye, A., Jacquin-Courtois, S., Reynaud, E., Lesourd, M., Besnard, J., & Osiurak, F. (2019). Numerical cognition: A meta-analysis of neuroimaging, transcranial magnetic stimulation and brain-damaged patients studies. *NeuroImage: Clinical, 24*, 102053. https://doi.org/10.1016/j.nicl.2019.102053

Ishihara, M., Keller, P., Rossetti, Y., & Prinz, W. (2008). Horizontal spatial representations of time: Evidence for the STEARC effect. *Cortex, 44*, 454–461. https://doi.org/10.1016/j.cortex.2007.08.010

Izard, V., Sann, C., Spelke, E. S., & Streri, A. (2009). Newborn infants perceive abstract numbers. *Proceedings of the National Academy of Sciences of USA, 106*, 10382–10385. https://doi.org/10.1073/pnas.0812142106

Leibovich, T., Katzin, N., Harel, M., & Henik, A. (2017). From "sense of number" to "sense of magnitude": The role of continuous magnitudes in numerical cognition. *Behavioral and Brain Sciences, 40*, e164. https://doi.org/10.1017/s0140525x16000960

Mandler, G., & Shebo, B. J. (1982). Subitizing: An analysis of its component processes. *Journal of Experimental Psychology: General, 111*, 1–22. https://doi.org/10.1037//0096-3445.111.1.1

Newman, S. D., Klatzky, R. L., Lederman, S. J., & Just, M. A. (2005). Imagining material versus geometric properties of objects: An fMRI study. *Cognitive Brain Research, 23*, 235–246. https://doi.org/10.1016/j.cogbrainres.2004.10.020

Nuerk, H.-C., Kaufmann, L., Zoppoth, S., & Willmes, K. (2004). On the development of the mental number line: More, less, or never holistic with increasing age? *Developmental Psychology, 40*, 1199–1211. https://doi.org/10.1037/0012-1649.40.6.1199

Piazza, M. (2010). Neurocognitive start-up tools for symbolic number representations. *Trends in Cognitive Sciences, 14*, 542–551. https://doi.org/10.1016/j.tics.2010.09.008

Pica, P., Lemer, C., Izard, V., & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian Indigene group. *Science, 306*, 499–503. https://doi.org/10.1126/science.1102085

Prpic, V., Soranzo, A., Santoro, I., Fantoni, C., Galmonte, A., Agostini, T., & Murgia, M. (2020). SNARC-like compatibility effects for physical and phenomenal magnitudes: A study on visual illusions. *Psychological Research, 84*, 950–965. https://doi.org/10.1007/s00426-018-1125-1

Sellaro, R., Treccani, B., Job, R., & Cubelli, R. (2015). Spatial coding of object typical size: Evidence for a SNARC-like effect. *Psychological Research, 79*, 950–962. https://doi.org/10.1007/s00426-014-0636-7

Stanescu-Cosson, R., Pinel, P., van de Moortele, P.-F., Le Bihan, D., Cohen, L., &

Dehaene, S. (2000). Understanding dissociations in dyscalculia. *Brain, 123*, 2240–2255. https://doi.org/10.1093/brain/123.11.2240

Verguts, T., & Fias, W. (2004). Representation of number in animals and humans: A neural model. *Journal of Cognitive Neuroscience, 16*, 1493–1504. https://doi.org/10.1162/0898929042568497

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*, 483–488. https://doi.org/10.1016/j.tics.2003.09.002

Walsh, V. E. (2013). Magnitudes, metaphors, and modalities: A theory of magnitude revisited. In J. Simmer and E. M. Hubbard (Eds.), *The Oxford Handbook of Synesthesia* (p. 837–852). Oxford University Press. https://academic.oup.com/edited-volume/34492?login=false