

## Automatic numerical-spatial association in synaesthesia: An fMRI investigation



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### ABSTRACT

A horizontal mental number line (MNL) is used to describe how quantities are represented across space. In humans, the neural correlates associated with such a representation are found in different areas of the posterior parietal cortex, especially, the intraparietal sulcus (IPS). In a phenomenon known as number-space synaesthesia, individuals visualise numbers in specific spatial locations. The experience of a MNL for number-space synaesthetes is explicit, idiosyncratic, and highly stable over time. It remains an open question whether the mechanisms underlying numerical-spatial association are shared by synaesthetes and nonsynaesthetes. We address the neural correlates of number-space association by examining the brain response in a number-space synaesthete (MkM) whose MNL differs dramatically in its ordinality and direction from that of a control group. MkM and 15 nonsynaesthetes compared the physical size of two numbers, while ignoring their numerical value, during an event-related functional magnetic resonance imaging session (fMRI). Two factors were analysed: the numerical distance effect (NDE; e.g., 2–4 small distance vs. 1–6 large distance), and the size congruity effect (e.g., 2–8 congruent vs. 2–8 incongruent). Only for MkM, the NDE elicited significant activity in the left and right IPS, supramarginal gyrus (bilateral), and in the left angular gyrus. These results strongly support the role of the parietal cortex in the automatic coding of space and quantity in number-space synaesthesia, even when numerical values are task-irrelevant.

### 1. Automatic numerical-spatial association in synaesthesia: an fMRI investigation

In both human and nonhuman primates, numbers have been shown to be strongly associated with space (Dehaene et al., 1993; Drucker and Brannon, 2014). In the normal population this association is implicit; however, in a phenomenon known as number-space synaesthesia (NSS), this association is explicit, idiosyncratic, automatic, and highly stable over time (Arend et al., 2013; Gertner et al., 2013b; Jarick et al., 2009, 2011; Piazza et al., 2006). Graphic examples of NSS have been documented in the literature (Galton, 1880; Gertner et al., 2009; Piazza et al., 2006). NSS has also been shown to frequently co-occur with other types of synaesthesia such as grapheme-colour (Sagiv et al., 2006).

NSS constitutes a window into the cognitive and neural mechanisms of numerical-spatial association. Does the processing of numerical information in synaesthetes recruit a distinct or overlapping neural circuitry relative to nonsynaesthetes? One hypothesis addressing the origins of number-space synaesthesia postulates that the number-space

association arises from the overlapping neural structures responsible for coding space and quantities (Hubbard et al., 2005). The suggestion is that parietal areas that are responsible for processing numbers and space in nonsynaesthetes would also be activated in the case of overlearned sequences in synaesthetes. That is, numerical processing would be quantitatively – not qualitatively – different in synaesthetes relative to nonsynaesthetes. For example, the intraparietal sulcus (IPS) has been shown to code different aspects of number processing such as symbolic and nonsymbolic dimensions (Dehaene et al., 2003) and the semantic distance between quantities in number comparison tasks (Piazza et al., 2004; Pineda et al., 2001). Although attractive, this hypothesis has not yet received support from brain imaging protocols. Previous studies addressing the neural mechanisms of synaesthesia have mainly focused on grapheme-colour synaesthesia (Cohen Kadosh et al., 2007; Rich et al., 2006; Rouw and Scholte, 2007; Sperling et al., 2006); therefore, the neural correlates of number processing in synaesthesia have not yet been systematically explored.

Tang et al. (2008) were the first to use a functional magnetic resonance imaging (fMRI) protocol to address the neural basis of

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number-space synaesthesia. They examined whether number-space associations represent the cardinality (e.g., three buses) or the ordinality (e.g., the third bus) of numbers. The idea was inspired by the fact that sequences in NSS are consistent with an ordinal representation of objects, such as the order of numbers or the order of letters, weekdays, and months. In the cardinal task used by Tang and colleagues, subjects needed to decide whether the numerical value matched that of the number of Xs in a string (e.g., xx3x or xx2x for compatible and incompatible stimuli, respectively), and in the ordinal task, subjects needed to decide whether the number was in the correct position within the string (e.g., x2xx and xxx2 for compatible and incompatible pairs, respectively). Brain imaging results showed that only the ordinal task elicited significant bilateral IPS activity for the synaesthete group but not for the control group, suggesting that a mental number line in synaesthesia is ordinal in nature. We believe this conclusion is rather premature. It is important to note that the synaesthete group only showed effects of ordinality in parietal areas when the stimuli were judged from left-to-right, and such a left-to-right arrangement was consistent with the synaesthetic representation. It is possible that reading habits (left-to-right scanning) may have elicited more parietal activity, considering that the parietal cortex responds to saccadic eye movements. This possibility is highlighted by the fact that all synaesthetes presented with a left-to-right association; therefore, their numerical-spatial representation could not be studied in isolation from reading (scanning) habits. Reading habits might have contributed to the effect in parietal areas, especially for synaesthetes. In addition, number-space synaesthetes report that the visualization they experience for a specific number and its corresponding spatial location occurs when a single number is presented, strengthening the argument that quantity information, and not ordinality, is an important aspect of number-space association in synaesthesia. To summarize, it is possible that the effects reported by Tang and colleagues (2008) may be derived by the ordinality of numbers imposed by the task requirements. However, we disagree with the authors' main claim that the mental number line in synaesthesia is ordinal in nature.

## 2. The present study

We addressed the neural basis of NSS by examining the neural correlates of number-space association in a rare case: a number-space synaesthete, MkM, who vividly experiences even and odd numbers in the left and right sides of space (see Fig. 1). This single case study constitutes a unique opportunity to examine the neural signature of quantity representation in synaesthesia when the synaesthetic MNL differs dramatically from that of a nonsynaesthete. MkM's representation offers a great opportunity to examine the following questions: 1) whether the automatic processing of number-space association will recruit number-relevant areas such as the IPS, the angular gyrus, and the supramarginal gyrus; and 2) whether the ordinal nature of the synaesthetic mental number line is what triggers IPS activity. The idea of ordinal representation implies that numbers (or any other concept such as letters or weekdays) are represented along a horizontal vector in which small numbers “come first” and large numbers “come later.” Because MkM's number representation consists of splitting even and odd numbers across the left and right sides of space, small and large numbers are not arranged in terms of their ordinality along a horizontal line.

To study whether the synaesthetic number-space association elicits activity in number-related areas for MkM under conditions of autonomous processing, we used a physical-size comparison task (“Report which stimulus is physically larger”; Henik and Tzelgov, 1982). In this type of task, two numbers are presented in different physical sizes. In congruent trials, the size and the value of the number match (e.g., 2 4), and in incongruent trials, the size and the value of the numbers are mismatched (e.g., 2 4). The size congruity effect (SiCE) is derived by the difference in response times for congruent relative to incongruent

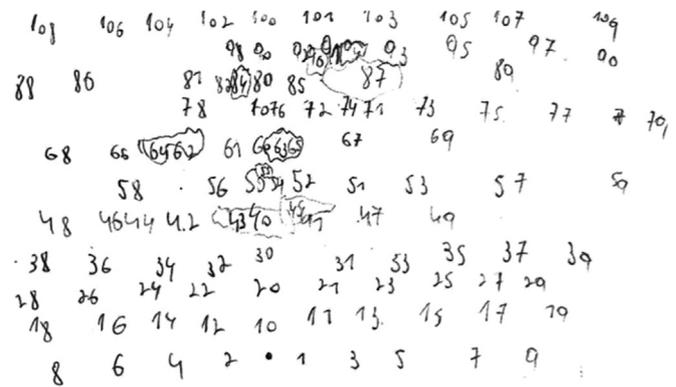


Fig. 1. Hand drawing of the synaesthete's numerical-spatial association.

trials. Our number pairs were selected to analyse the numerical distance effect (NDE).

### 2.1. The numerical distance effect

In humans, one of the classical ways to examine the behavioural manifestation of the MNL is by analysing the semantic distance of numbers through the so-called numerical distance effect (NDE; Moyer and Landauer, 1967). The NDE shows that, when deciding which number is the numerically larger, response times to large numerical distances (e.g., pair 1 6) are faster relative to response times to small numerical distances (e.g., pair 2 4). The NDE has been consistently observed even when the numbers are task irrelevant. Henik and Tzelgov (1982) used a physical comparison task to address the automatic processing of numbers. As expected, responses for congruent pairs were faster than for incongruent pairs. The NDE affected the SiCE such that the SiCE was found to be larger for large relative to small numerical distances, illustrating the automatic processing of numerical-spatial information.

To this day, the NDE is a valuable tool used for investigating the cognitive aspects of number-space association in synaesthesia. In number-space synaesthetes, the NDE is found to be larger when the arrangement of the stimulus matches that of the synaesthetic representation (Gertner et al., 2009). That is, the NDE for synaesthetes representing numbers from left-to-right, will be larger when the display contains number pairs from left-to-right (e.g., 2 – 4) than from right-to-left (e.g., 4 – 2). The NDE of number-space synaesthetes also reflects the automatic coding of numerical quantities that occurs across different mental number line representations (Piazza et al., 2006). To the best of our knowledge, this is the first time that an fMRI protocol has been used to access task-irrelevant NDE in nonsynaesthetes. Previous studies have examined the NDE when number was a task-relevant dimension (Pinel et al., 2001, 2004; Kaufmann et al., 2005). A few studies used passive viewing of single digits or non-symbolic quantities (array of dots) to address quantity coding in the parietal cortex (Ansari et al., 2006; Cohen Kadosh et al., 2007; Piazza et al., 2004). These studies are in agreement with the idea that quantities are represented in the parietal cortex in the absence of an explicit task.

## 3. Method

### 3.1. Participants

MkM is a 28-year-old right-handed man, with normal visual acuity who presents with number-space synaesthesia. He became aware of his sequence-space synaesthesia when he was describing his experience to one of his friends three years before testing. He reports that he was surprised to discover that not everyone experienced numbers in the way that he does. Fig. 1 shows MkM's hand-drawn number-space representation. He reports having a strong “feeling” that, for example,

the number 5 is on the right-hand side. He reports visualizing the arrangement of numbers with his mind's eye. MkM has no history of traumatic brain injury. He was a university student during the time of testing. His synaesthetic experience was evaluated after one year, and both his drawings and his self-report were highly consistent between the first and the second evaluation session.

Fifteen age-matched controls (10 males, age  $M = 27$  years,  $SD = 3$  years) were also tested. All were right-handed with no history of neurological or psychiatric disorder, had normal visual acuity, and were not colour blind. All participants received financial compensation for taking part in the study. The control participants did not present with any with type of synaesthesia, and all were university students at the time of testing.

### 3.2. Stimuli and procedure

Stimuli consisted of white numbers printed against a black background. Each of the numbers had the following sizes: Arial font size 55: height 2.86°, width 1.91°; Arial font size 64: height 3.24°, width 2.10°; and Arial font size 73: height 3.81°, width 2.48°. The two numbers were separated by approximately five degrees of visual angle from centre to centre. To study the automatic activation of MkM's numerical arrangement in space, we selected large and small numerical distances. Small distances: distance 2 and 3 (number pairs 2 4; 7 9; 6 9; 1 4); large distance: distance 4 and 5 (number pairs 2 6; 3 7; 3 8; 4 9).

The trials began with the presentation of a fixation cross for 1000 ms, followed by a delay interval of 300 ms. Following the delay, two digits were presented for a period of 1500 ms or until the participant's response. A new trial began after an inter-trial-interval (ITI) that ranged from 1000 to 8000 ms. Participants were required to use their left and right index fingers to indicate the location of the larger stimuli. Participants were asked to respond as fast and accurately as possible. Each participant completed two runs of 64 trials each. Each run lasted 6.7 min. At the end of the experiment, participants were debriefed.

#### 3.2.1. fMRI acquisition

Whole brain functional data was acquired using a 3-Tesla Philips Ingenia MRI scanner using a gradient echo planar imaging (EPI) sequence (TR (repetition time) = 2 s; TE (echo time) = 60 s; flip angle = 90°). The order of imaging acquisition was ascending – interleaved, covering the entire brain of the participants. For each functional volume, 33 slices (3 mm thickness, FOV (field of view) = 192 mm × 192 mm, matrix = 64 × 64) were collected, resulting in a spatial resolution of 3 mm isotropic voxels. The acquisition resulted in 227 volumes per run. Each scanning session included the acquisition of a T1-weighted three-dimensional volume (voxel dimension = 1 mm × 1 mm × 1 mm) for co-registration and anatomical location of functional data.

#### 3.2.2. fMRI analysis

Data preprocessing and analyses were performed using SPM 12 (Wellcome Department of Imaging Neuroscience; [www.fil.ion.ucl.ac.uk/spm](http://www.fil.ion.ucl.ac.uk/spm)) implemented in MATLAB. Individuals' EPI images were first slicetime-corrected, realigned, and co-registered with the T1 anatomical image. The T1 anatomical image was subsequently segmented to obtain the deformation field for the normalization to the MNI space with reference to the ICBM brain template. The deformation field was then applied to the EPI images for spatial normalization (resampled to 2 mm isotropic voxels) and spatially smoothed by an 8 mm full-width half-maximum Gaussian kernel. Event-related activity for each condition was modelled by convolving the stimulus onset with a canonical hemodynamic response function. Also included as confounds in the model were six movement parameters estimated in the realignment stage (de Lange et al., 2005). Statistical parametric maps were generated for each subject using the General Linear Model (GLM).

**Table 1**  
Mean RTs for Controls and MkM as a Function of Experimental Condition.

Condition	Controls	MkM	<i>t</i> Crawford	<i>p</i>
Distance Main Effect				
Large	564 (85)	801	.69	.250
Small	578 (97)	814		
Congruity Main Effect				
Congruent	555 (83)	713	3.33	.004
Incongruent	600 (98)	903		
Distance * Congruity				
Congruent Large	523 (78)	717	8.05	.001
Incongruent Large	606 (94)	912		
Congruent Small	568 (95)	709	3.64	.001
Incongruent Small	589 (101)	893		

Note. *p* values are based on normalized data. Values in parentheses represent standard deviations. RTs in milliseconds. *t* Crawford = one-tailed *t*-test.

## 4. Results

### 4.1. Behavioural results

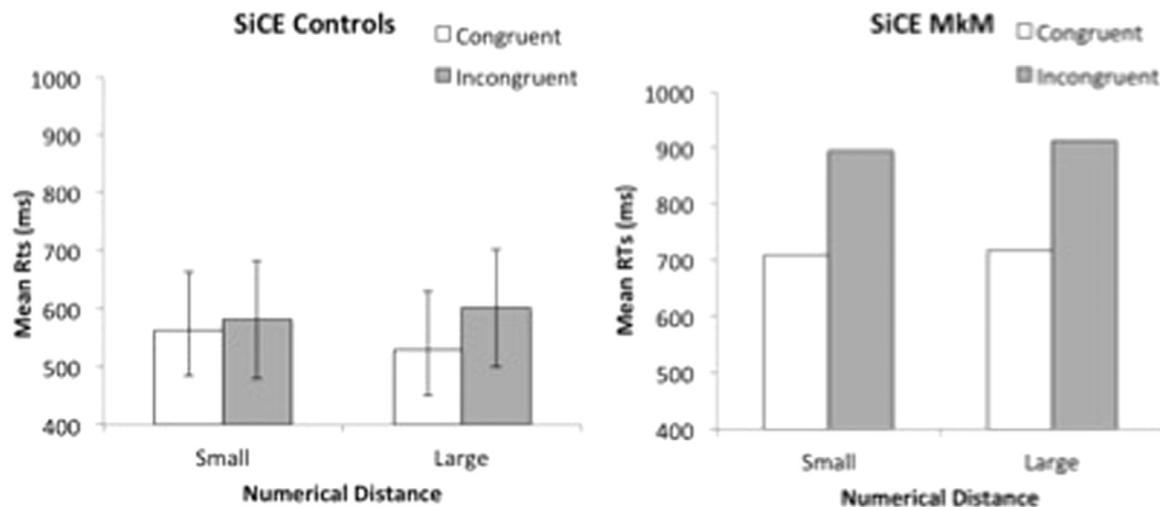
Errors constituted less than 1% of trials, therefore, they were not analysed further. We compared both the behavioural and the brain activation results of MkM with those of the controls by applying the procedure developed by Crawford and Garthwaite (2005) to compare single cases with a control population. This method was previously applied in a single case study that used a brain imaging protocol to examine the neural correlates of grapheme-colour synaesthesia (Cohen Kadosh et al., 2007).

Table 1 shows mean reaction times (RT) for MkM and for the control sample for each experimental condition. Significant results are displayed in bold font. Mean RTs were normalized in order to reduce overall differences between MkM and controls. Therefore, statistical (Crawford) tests were conducted on normalized RT data. The same pattern of results was observed for non-normalized RTs. Of main relevance for the present report is the pattern of the NDE. MkM was overall faster for large as opposed to small numerical distances (801 ms vs. 814 ms, respectively), as were controls (564 ms vs. 578 ms, respectively). MkM and controls did not differ in the NDE ( $t = .69$ ).

With respect to the congruity effect, MkM showed faster responses for congruent trials as opposed to incongruent trials (713 ms vs. 903 ms, respectively), and this difference was significantly different from the control group (555 ms vs. 582 ms, respectively) (one-tailed probability,  $t = 3.33$ ,  $p = .004$ ). That is, the congruity effect for MkM was significantly larger than that observed for the control sample, illustrating the greater impact of irrelevant numerical values for MkM relative to the control group.

For the control sample, the congruity effect was also modulated by the NDE. As illustrated in Fig. 2, the NDE was larger for congruent as opposed to incongruent trials. For the control sample, this pattern was confirmed by a repeated-measures analysis of variance (ANOVA) taking congruity (congruent vs. incongruent) × numerical distance (small vs. large) as factors on mean RTs. There was a significant main effect of congruity,  $F(1, 14) = 40.80$ ,  $p < .0001$ ,  $\eta^2 = .75$ , but not a significant main effect of numerical distance,  $F(1, 14) = 2.38$ ,  $p = .15$ ,  $\eta^2 = .15$ . The interaction between the two factors was significant,  $F(1, 14) = 17.37$ ,  $p = .001$ ,  $\eta^2 = .55$ . Planned comparisons revealed that the congruity effect was larger for the large numerical distances (83 ms;  $t(14) = 7.43$ ,  $p < .0001$ ) as opposed to small numerical distances (21 ms;  $t(14) = 1.9$ ,  $p = .07$ ).

MkM's congruity effect for large distances (195 ms) was significantly different from that of controls (one-tailed probability,  $t = 8.05$ ,  $p = .001$ ). Likewise, MkM's congruity effect for small distances (184 ms) was also significantly different from that of controls (one-tailed



**Fig. 2.** Mean response times for the control sample and the synaesthete (MkM) as a function of numerical distance (small vs. large) and congruity (congruent vs. incongruent). Error bars for the control sample represent standard error of the mean.

probability,  $t=3.64$ ,  $p=.001$ ). Both the results of MkM and the control sample nicely illustrate the frequently observed pattern of larger congruity effects for large numerical distances relative to small numerical distances when numbers are task-irrelevant (Henik and Tzelgov, 1982; Tzelgov et al., 1992).

The behavioural results can be summarized as follows: 1) both MkM and the control group showed the NDE; 2) both MkM and controls showed faster RTs for congruent than for incongruent trials; 3) the distance effect modulates the congruity effect: large numerical distances produced a larger congruity effect relative to small distances for both groups.

#### 4.2. fMRI results

Under autonomous number processing, large numerical distances have a greater impact than small numerical distances on the congruity effect, thus our contrast of interest consisted of large > small distances (e.g., pair 2 6 vs. 2 4). The reverse contrast, small > large distance, was also applied. For MkM, the contrast large > small revealed enhanced activation in the left postcentral gyrus, left angular gyrus extending to the lateral occipital complex (LOC), right premotor cortex, right inferior parietal lobule, specifically the horizontal segment of the IPS (anterior hIP2 and hIP1), extending to the posterior supramarginal gyrus (see Fig. 3 and Table 2). The effect in each one of these regions was modulated by the enhanced activity for large relative to small distance, and for all regions the activations for MkM were different from those of the control group (see Table 2). No activation was found when the contrast was reversed (small > large distance).

For the control group, neither large > small contrast nor small > large contrast elicited significant activations using the same threshold ( $p < .05$  with FWE correction). However, when a more liberal threshold ( $p < .05$  uncorrected) was applied to the small > large contrast, a cluster of voxels was found in the right superior parietal lobule (SPL)/IPS ( $x=-22$ ,  $y=-72$ ,  $z=52$ ; 970 voxels, anterior hIP3). Importantly, we further examined brain activations associated to numbers for the control sample by conducting a one-way sample test, taking number trials against rest. Results of this analysis revealed a number of cortical areas (see Table 3) that have been found to be associated to the processing of numerical information such as parietal sites (e.g., angular gyrus and bilateral IPS), and also task-related areas (e.g., anterior cingulate and post central gyrus) (Kaufmann et al., 2005).<sup>1</sup>

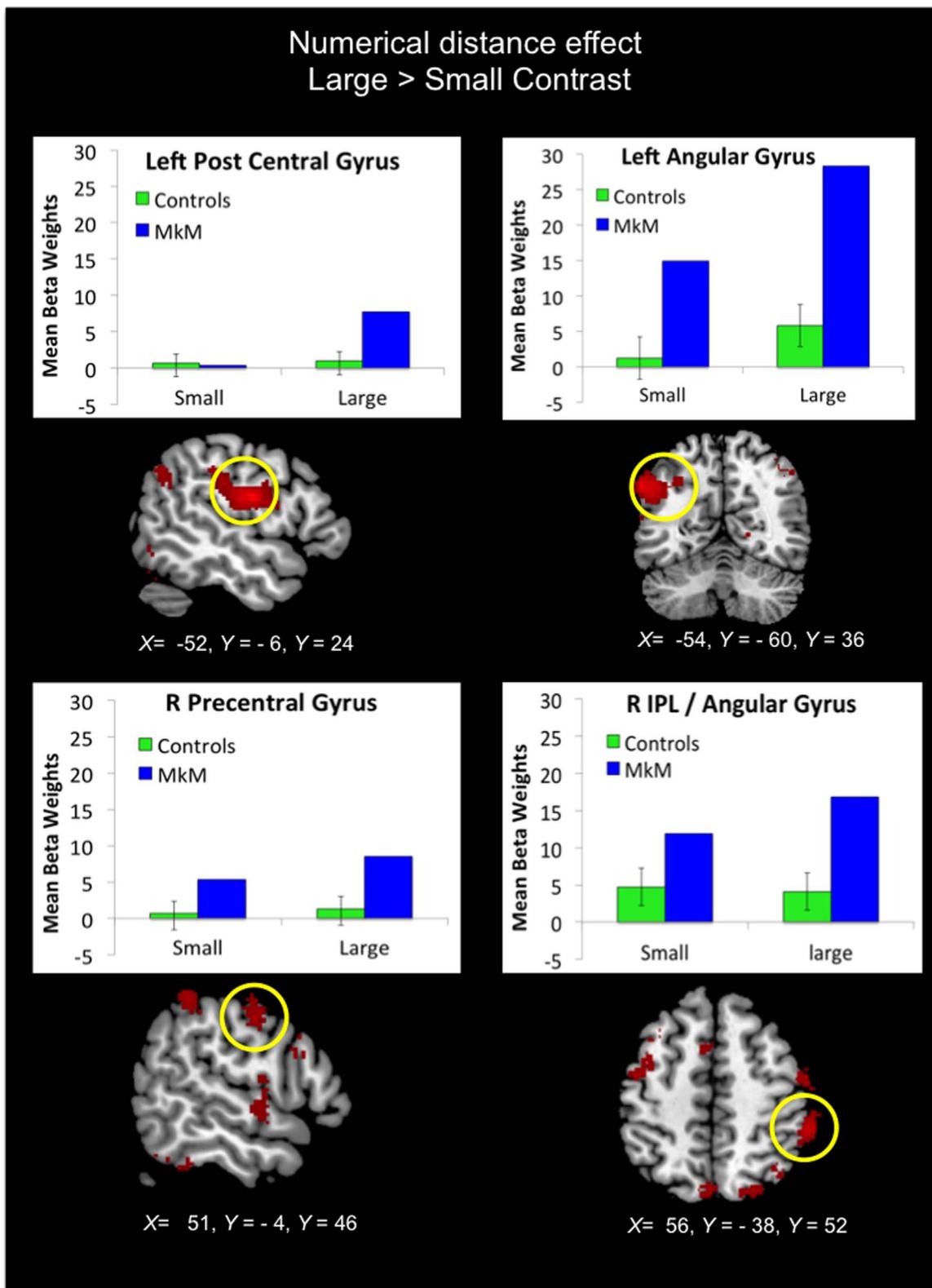
<sup>1</sup> We would like to thank two anonymous reviewers for pointing out the need for examining the pattern of activation elicited by numbers for the control sample.

The brain correlates associated with the size congruity effect as a function of numerical distance were examined by testing the contrast incongruent > congruent and the reverse contrast for small and for large distances separately. For the incongruent > congruent contrast for large distances, neither the control group nor MkM showed significant activations. The incongruent > congruent contrast for small distances revealed activations for MkM relative to the control group (see Table 4) in frontal and parietal sites, including the right supramarginal gyrus. The reverse contrast, congruent > incongruent for small distances, did not elicit any significant activity for MkM or controls. For the congruent > incongruent contrast for large numerical distances, activations for MkM were statistically significant compared to those of the control group in a number of cortical areas (see Table 5) including the precuneus and the inferior frontal and middle frontal cortices.

## 5. Discussion

The findings of the present study provide strong evidence for the role of the parietal cortex – specifically the anterior IPS, the angular gyrus, and the supramarginal gyrus – in numerical-space association in synaesthesia. For MkM, the NDE elicited significant activity in these areas even though numerical quantity was task irrelevant, endorsing the suggestion that quantity and space coding in synaesthesia occur automatically. In contrast to the pattern observed for MkM, the control group did not show a NDE for task-irrelevant numbers in the parietal cortex. The brain activation patterns associated with numerical distance for MkM nicely resembled those reported for nonsynaesthetes when numbers constituted the *task-relevant* dimension (Pinel et al., 2001). These findings show that the number-space association that characterizes the synaesthetic experience recruits an overlapping neural network with that of nonsynaesthetes.

The triple-code model of number processing predicts that, depending on the task, three distinct systems of representation may be recruited: a quantity system (a nonverbal semantic representation of the size and distance on a mental number line) based on the activation of the IPS; a verbal system (where numerals are represented much like any other type of word, related to retrieval of well learned arithmetical facts) based on the activity of the left angular gyrus; and a spatial attention system based on the activity of the superior parietal lobe (Dehaene, 1992; Dehaene and Cohen, 1995; Dehaene et al., 2003). Hence, in our results MkM showed significant activity for the automatic numerical distance effect both in the verbal system of number processing and in the innate quantity system.



**Fig. 3.** Brain activations related to the numerical distance effect for Mkm and controls. Activation maps show increased activation for large versus small numerical distances, but only for Mkm. Statistical maps are superimposed on a MNI template.  $p < .05$ , FWE corrected. Error bars represent standard deviations.

The main contribution of the present work is to show that parietal activation is determined by the semantic distance parameter (the NDE effect), which is independent of the ordinality of the mental number line in our synaesthete. Previously, [Tang et al. \(2008\)](#) reported that activations in the anterior IPS were associated with the ordinal representation of numbers, which led the authors to conclude that the synaesthetic mental

number line is ordinal in nature. The NDE observed for Mkm shows that the anterior IPS hosts the coding of numerical quantity in synaesthesia and that such coding is not derived by an ordinal sequence. As we mentioned in the introduction, Mkm's mental number line does not follow an ordinal arrangement because even and odd numbers were divided across left and right sides of space. The occurrence of the NDE

**Table 2**  
Regions Activated for MkM by the Numerical Distance Effect.

<i>p</i> *	No. Voxels	<i>T</i>	x	y	z	Location	<i>t</i> Crawford	<i>p</i> Crawford
.001	2346	4.06	-52	-6	24	L postcentral gyrus	1.98	.03
.001	812	4.28	-54	-60	36	L AG	1.61	.06
		3.32	-32	-80	42	L LOC Extending/AG	1.98	.03
.004	352	3.77	51	-4	46	R premotor cortex BA6	3.20	.003
		3.33	48	14	46	Extending/Mid frontal gyrus		
.001	437	3.64	56	-38	52	R IPL supramarginal gyrus (posterior)	2.23	.02
		3.21	41	-60	48	R AG Extending/ LOC		

Note. L = left hemisphere; R = right hemispheres; *p* < .05 (FWE corrected values); *t* Crawford = *t* test value for one-tailed probability; LOC = lateral occipital complex; IPL= inferior parietal lobule; AG = angular gyrus.

**Table 3**  
Regions Activated for the Control Sample in Response to Numbers.

<i>p</i> *	No. Voxels	<i>T</i>	x	y	z	Location
.001	360	12.91	8	16	26	R ant cingulate
.001	324	12.74	-64	-16	32	L post central gyrus
			-46	-34	42	L IPS
.001	80	12.46	-50	-26	14	L rolandic operculum
.001	172	11.61	32	-60	44	R AG/extending postcentral gyrus
.001	197	10.52	46	-38	52	R IPS

Note. L = left hemisphere; R = right hemispheres; AG = angular gyrus; IPS= intraparietal sulcus.

**Table 4**  
Regions Activated for MkM by the Congruity Effect (Incongruent > Congruent) for Small Numerical Distance.

<i>p</i> *	No. Voxels	<i>T</i>	x	y	z	Location	<i>t</i> Crawford	<i>p</i> Crawford
.001	2152	4.35	-2	22	22	L anterior cingulate	6.10	.0001
.002	386	3.83	-22	48	30	L inferior frontal operculum	5.20	.0002
.001	561	3.75	42	-6	48	R precentral gyrus	3.07	.004
.001	727	3.59	46	30	22	R mid-frontal	3.04	.004
.003	361	3.55	50	-30	40	R supramarginal gyrus	2.54	.012

Note. L = left hemisphere; R = right hemispheres; *p* < .05 (FWE corrected values); *t* Crawford = *t*-test value for one-tailed probability.

**Table 5**  
Regions Activated for MkM by the Congruity Effect (Congruent > Incongruent) for Large Numerical Distance.

<i>p</i> *	No. Voxels	<i>T</i>	x	y	z	Location	<i>t</i> Crawford	<i>p</i> Crawford
.0001	3665	4.64	-2	-50	44	L precuneous	3.48	.002
.0001	3496	4.41	46	-74	6	R mid occipital	5.57	.0003
.001	413	3.97	-34	-86	6	L mid occipital	4.18	.0004
.0001	474	3.75	-32	46	34	L mid frontal	.88	.195
.0001	748	3.73	-66	-50	-16	L inferior temporal	.21	.49

Note. L = left hemisphere; R = right hemispheres; *p* < .05 (FWE corrected values); *t* Crawford = *t*-test value for one-tailed probability.

illustrates that the processing of numerical quantity is superior to his idiosyncratic spatial arrangement. Previous behavioural studies on the NDE in number-space synaesthesia provide further support for our conclusion. Piazza et al. (2006) reported a reliable NDE for S.W., a number-space synaesthete whose shape of the mental number line consisted of both straight and circular shapes, depending on the numerical value (see Piazza et al. (2006), for the synaesthete's hand drawings). For this synaesthete, the numerical distance effect followed the representation of the numerical quantity and not the geometrical distance between the numbers. That is, the semantic coding of numbers, reflected by the distance effect, occurred across different visual spatial representations. Our brain imaging results show that the quantity representation reflected by the NDE activates parietal circuits, which are devoted to number processing, even though the numbers are task irrelevant.

We do not suggest that the role of the parietal cortex is specifically devoted to the number domain or that the activation pattern reported here is only derived from quantity coding. It has been systematically

documented that parietal areas are involved in manipulating visuospatial information. The parietal cortex is recruited in various visual-spatial tasks, including eye movements (Kawashima et al., 1996), spatial-visual attention (Corbetta et al., 1998), and spatial working memory (Diwadkar et al., 2000). Therefore, it is possible that the role of the parietal areas – for example, the activation for large and small distances – reflects the combined activation of number neurons and neurons that are involved in manipulating visuospatial information. We propose that the activity observed for MkM in parietal areas reflects the activation of spatial coordinates, which occurs whenever numbers are processed.

Furthermore, our results are consistent with previous behavioural findings suggesting that synaesthetes and nonsynaesthetes may be quantitatively rather than qualitatively different with respect to the processing of numerical information. The findings of the present study expand this view to the functional domain. MkM's explicit number-space association recruits, to a greater extent, number areas that are activated in the control group under conscious processing of numerical information (Fias et al., 2007; Pinel et al., 2004; Tang et al., 2006).

In terms of neural mechanisms underlying the synaesthetic experience, our results show continuity among synaesthetes and nonsynaesthetes (Esterman et al., 2006; Grossbacher and Lovelace, 2001; Hubbard et al., 2005; Rouw et al., 2011). However, our findings should be taken with caution when trying to distinguish different models accounting for the neurobiological origins of the synaesthetic experience. That is, the increased activation observed for MkM in cortical sites could reflect disinhibition or greater cortical connections. It is still under debate whether the synaesthetic experience arises from disin-

hibited feedback involving different cortical pathways (Grossenbacher and Lovelace, 2001), or from increased connectivity (Ramachandran and Hubbard, 2001). According to the disinhibition feedback model, synaesthetic experience arises from the convergence of signals involving the inducer and the concurrent: “In synaesthetes, information entering such convergence area through the inducer pathway could propagate down the concurrent pathway through disinhibition of these feedback signals” (Grossenbacher and Lovelace, 2001, pg. 40). According to the increased connectivity model, synaesthesia is due to abnormal rich connections between brain areas (Ramachandran and Hubbard, 2001). The increased connectivity is understood to arise from incomplete pruning during development (Kennedy et al., 1997). The increased connectivity model considers that certain types of synaesthesia (e.g., grapheme-colour) relate to specific brain areas (e.g., increased connectivity around the fusiform gyrus) (for a revised version of this model see Hubbard et al., 2011). It is important to note that both these models have been recently challenged by findings showing that brain correlates of synaesthetic experience are not domain-specific as once claimed (Rouw et al., 2011, for a review). For example, activations in grapheme-colour synaesthesia have been found to go beyond the striate cortex. Likewise, several parietal areas were observed in different types of synaesthesia. Therefore, it is possible that both disinhibited feedback and increased connectivity mechanisms may contribute to different types of synaesthetics. As we mentioned in the introduction section, most brain imaging studies have examined the brain mechanisms of synaesthesia by looking at grapheme-colour synaesthetes. We believe the present findings will foster future research aimed at examining the brain correlates of number-space synaesthesia using different imaging techniques.

Finally, the posterior parietal cortex has been shown to be associated with different synaesthetic experiences, for example in grapheme-colour synaesthesia (Esterman et al., 2006; Paulesu et al., 1995; Weiss et al., 2005); specifically, the IPS in grapheme-colour synaesthesia (Weiss et al., 2005). Posterior parietal activity has been interpreted to reflect binding of different dimensions in synaesthesia (Rouw et al., 2011, for a review). A two-stage model of grapheme-colour synaesthesia has been proposed, according to which the grapheme-colour association is the result of an abnormal cross-activation of shape area and colour area in the fusiform gyrus. The colour percept is then bound together with shape by the posterior parietal mechanism as a “hyper binding.” A number of studies using brain imaging and transcranial magnetic stimulation (TMS) protocols provide support for this model (Hubbard, 2007; Rouw et al., 2011; Weiss et al., 2005). The implications of such a model for the neural mechanisms of synaesthesia are that, even though different sensory modalities may recruit domain-specific regions a general binding mechanism orchestrated by the posterior parietal cortex may be a common mechanism shared by all types of synaesthesia, including sequence-space associations. In the specific case of number-space association, the role of the parietal cortex is consistent with the idea that the synaesthesia experience is a magnitude-based phenomenon (Gertner et al., 2012, 2013a).

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