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Special section: Research report

What information is critical to elicit interference in number-form synaesthesia?

Edward M. Hubbard[a,*], Mariagrazia Ranzini[a,b], Manuela Piazza[a,c] and Stanislas Dehaene[a,d]

[a]INSERM-CEA Cognitive Neuroimaging Unit, CEA/SAC/DSV/I2BM/NeuroSpin, Gif-Sur-Yvette, France
[b]Department of Psychology, University of Pavia, Italy
[c]Center for Mind/Brain Sciences, University of Trento, Rovereto (TN), Italy
[d]Collège de France, Paris, France

ARTICLE INFO

Article history:
Received 4 July 2008
Reviewed 11 March 2009
Revised 22 May 2009
Accepted 11 June 2009
Published online 7 July 2009

Keywords:
Synesthesia/synaesthesia
Number-forms
SNARC

ABSTRACT

Numerous behavioural paradigms have demonstrated a close connection between numbers and space, suggesting that numbers may be represented on an internal *mental number line*. For example, in the Spatial Numerical Association of Response Codes (SNARC) effect, reaction times are faster for left-sided responses to smaller numbers and for right-sided responses to larger numbers. One valuable tool for exploring such numerical–spatial interactions is the study of number-form synaesthesia, in which participants report vivid, automatic associations of numerical and other ordinal sequences with precise, idiosyncratic, spatial layouts. Recent studies have demonstrated the influence of synaesthetic spatial experiences on behavioural number tasks. The aim of the present study is to further explore these internal spatial representations by presenting a case-study of an unusual synaesthete, DG, who reports highly detailed representations not only of numerical sequences (including representations of negative and Roman numbers), but also different representations for other ordinal sequences, such as time sequences (months, days and hours), the alphabet, financial sequences and different units of measure (e.g., kilograms, kilometres and degrees). Here, we describe DG's synaesthetic experiences and a series of behavioural experiments on numerical tasks concerning the automaticity of this phenomenon. DG's performance on number comparison and cued-detection tasks was modulated by his synaesthetic mental representation for the numerical sequence, such that his reaction times were slower when the spatial layout was incompatible with the orientation of his mental number line. We found that the spatial presentation of stimuli, rather than the implicit or explicit access to numerosity required by tasks, was essential to eliciting DG's number-forms. These results are consistent with previous studies and suggest that numerical–spatial interactions may be most strongly present in synaesthetes when both numerical and spatial information are explicitly task-relevant, consistent with a growing body of literature regarding the SNARC and other related effects.

* *Corresponding author*. Present address: Vanderbilt University, Department of Psychology and Human Development, Peabody College #552, 230 Appleton Place, Nashville, TN 37203-5721, USA.
E-mail addresses: ed.hubbard@vanderbilt.edu, edhubbard@gmail.com (E.M. Hubbard).

0010-9452/$ – see front matter
doi:10.1016/j.cortex.2009.06.011

1. Introduction

One of the fundamental representations of numbers is the *mental number line*, a typically implicit representation of numbers in which small numbers are represented on the left side of space and large on the right in most left-to-right readers (e.g., Dehaene, 1997). The existence of such implicit links between numbers and space was first demonstrated by Dehaene et al. (1993), who showed that smaller numbers are responded to more quickly with left-sided responses, and larger numbers more quickly with right-sided responses, the ''Spatial Numerical Association of Response Codes'' (SNARC) effect (for reviews, see Fias and Fischer, 2005; Hubbard et al., 2005b, 2009). Although the SNARC effect has traditionally been taken as evidence for a mental number line, various authors have recently questioned this interpretation, arguing that the SNARC effect reflects the shared semantic markedness of ''left'' and ''small'' rather than spatial coding (Proctor and Cho, 2006), that it reflects stimulus-response compatibility, rather than spatial mappings (Fitousi et al., 2009), or, at the very least, that magnitude processing must occur prior to the elicitation of spatial representations (Santens and Gevers, 2008), thus undermining the traditional concept of a unified spatial number line.

However, the evidence for mappings between numbers and space is not limited to the SNARC effect. Other behavioural paradigms have similarly demonstrated automatic mappings between numbers and space. For example, in a cuing task that uses numbers at fixation as cues, left-sided targets are detected more quickly when cued with small numbers, and right-sided targets more quickly when cued with large numbers (Fischer et al., 2003). A subsequent study demonstrated that these shifts of attention can induce the phenomenon of prior entry, in which objects at attended locations are perceived as appearing earlier than objects at non-attended locations (Casarotti et al., 2007). Similarly, in a backward priming experiment, Stoianov et al. (2007) found that responses for smaller numbers were faster when they were followed by a cue on the left side of the screen than when they were followed by a cue on the right side of the screen; the converse was true for larger numbers.

Studies of patients with neglect (Zorzi et al., 2002, 2006) have demonstrated deficits in numerical tasks that closely correspond to those seen in physical line bisection tasks. Similarly, in a recent study, we demonstrated that numerical cues elicit event related potential (ERP) components similar to those elicited by arrow cues that lead to endogenous shifts of spatial attention (Ranzini et al., 2009). Finally, using functional magnetic resonance imaging (fMRI) we were able to show that a support vector machine (SVM) trained to discriminate leftward from rightward eye movements on the basis of patterns of activation in posterior parietal cortex, once trained, was also able to generalize to simple arithmetic operations, so that the left versus right classification of eye movements could be used to sort subtraction versus addition trials (Knops et al., 2009). Taken together, these studies suggest that numbers are automatically, consistently associated with spatial locations, and that such associations depend on interactions between parietal regions that are critically involved in representing numerical and spatial information.

Additional evidence for the reality of numerical–spatial interactions comes from the reports of synaesthetes for whom these spatial associations become conscious (Galton, 1880a, b; Flournoy, 1893; Sagiv et al., 2006; Seron et al., 1992; Piazza et al., 2006). As first noted by Galton, numbers and other sequences are often linked with spatial locations, and these ''number forms'' can take on almost any shape. Subsequent research has extended these observations and demonstrated that spatial forms may exist not only for numbers, but also for days of the week, months of the year and the alphabet (Flournoy, 1893; Sagiv et al., 2006), and that these forms tend to co-occur within individuals (Flournoy, 1893; Sagiv et al., 2006). In rare cases, individuals report a large variety of sequence forms including forms for shoe sizes, height, historical time periods, time of day, TV stations and body temperature (case CS in Cytowic, 1989/2002). Interestingly, as early as 1893, Theodore Flournoy had noted that certain types of synaesthetic forms tend to occur less commonly than others. He noted that the most common spatial forms occurred for numbers, days of the week and months of the year, but that alphabet forms ''are only present in people who already possess other forms, and who are therefore gifted with a strong tendency towards schematization.'' (Flournoy, 1893, p. 151; translation by EMH). Here, we report a case of an individual with an extremely large number of spatial forms, including forms for numbers, days of the week, and months of the year, but also rarer examples of spatial forms, including historical periods (c.f. Flournoy, 1893; Cytowic, 1989/2002), multiple forms for financial sequences, including stock prices and taxes, computer CPU speeds, hard disk space, and even the order of pure-bred dog names. The large number of spatial forms that DG reports for ordinal, non-numerical sequences suggests that sequence-form synaesthesia is most likely to depend on ordinal, rather than cardinal information.

These observations on synaesthetic associations between sequences and space may have relevance for questions about whether ordinal sequences are systematically associated with space in non-synaesthetes (Hubbard et al., 2005b; Cohen Kadosh and Henik, 2007). In their original experiments, Dehaene et al. (1993) failed to observe a SNARC effect for letters, leading them to conclude that cardinal, rather than ordinal information was critical for eliciting spatial mappings. However, subsequent studies by Gevers and colleagues demonstrated SNARC effects for letters and months (Gevers et al., 2003) and days of the week (Gevers et al., 2004). Conversely, another recent study replicated the cueing effects described above for numbers, but did not observe any cueing effects for letters, weekday names or month names (Dodd et al., 2008). Finally, when Zorzi et al. (2006) tested patients with neglect on letter, weekday name and month name versions of their interval bisection task, they replicated their previous findings of an effect for numbers, but not for other ordinal sequences. However, in the same study, the authors found evidence for a circular organization of the months sequence in non-synaesthetes. Taken together, these contradictory results with ordinal sequences suggest that, as in synaesthesia, the mappings between ordinal sequences and space are weaker than those seen for numbers, and may depend critically on more basic numerical–spatial interactions.

Although the heterogeneity of synaesthesia makes the study of this phenomenon difficult, demonstrating the automaticity of synaesthetic experiences can be particularly helpful in understanding cognitive processes that may be present in the broad population (Ramachandran and Hubbard, 2001b; Cohen Kadosh and Henik, 2007; Sagiv and Ward, 2006). Specifically, the study of sequence-form synaesthesia can be of theoretical importance for understanding the mechanisms of numerical–spatial interactions revealed by behavioural tasks such as the SNARC effect. Demonstrating that synaesthetic number forms obey the same rules as other numerical–spatial associations described in literature would further strengthen the link between synaesthetic and non-synaesthetic cognition. To do so, we collected data from a series of different numerical tasks with our synaesthete DG in order to empirically verify the existence of the numerical representation described in DG's self-reports, and to explore the role of various features of the task in triggering number forms. In particular, we examined the influence of the layout of numerical stimuli on the screen, the influence of response hand, and the explicit or implicit access to the numerical magnitude, which was suggested to be important in a previous study (Piazza et al., 2006).

Recent experiments have demonstrated the influence of synaesthetic spatial experiences in behavioural tasks with numbers (Piazza et al., 2006; Sagiv et al., 2006) and months of the year (Smilek et al., 2007; Price and Mentzoni, 2008). For example, when participants are required to name which of a pair of numbers is larger (''number comparison task''), synaesthetes were faster to respond when pairs of numbers were presented in spatial layouts compatible with their own number line. However, while previous studies have examined the effects of compatible versus incompatible mappings on reaction times, they have not explored the effect presenting stimuli orthogonal to the reported orientation of the synaesthetic sequence-form. Recent work with the SNARC effect has shown that a SNARC effect is observed only when the associated dimension is being held in memory as part of the relevant response set (Gevers et al., 2006a). If we assume that the synaesthetic number form will always be active in memory (see also Price, 2009, this issue), since it is thought to be automatically evoked, we would expect to observe interference effects when stimuli and responses are aligned with the synaesthetic number form (in DG's case, when numbers and/or responses are vertically aligned), but not when they are orthogonal to the synaesthetic number form. This result would strengthen the connection between synaesthetic number forms and numerical–spatial effects in non-synaesthetes, and would further argue against the possibility that previous findings with synaesthetes are due to strategic influences, but rather arise from the task relevance of the congruency with the spatial form (see also Jarick et al., 2009a, this issue, 2009b, this issue).

Similarly, previous research with neuropsychological patients has suggested that whether the numerical task requires explicit or implicit access to numerical magnitude may modulate the degree to which numbers and space interact. Priftis et al. (2006) showed that patients with neglect made errors as if they were neglecting the left half of the mental number line when required to make a bisection judgement (magnitude explicit task) but not when they were asked to make a parity judgement (magnitude implicit task). In both cases, Priftis et al. (2006) assume that magnitude information has been activated, consistent with previous research (Fias et al., 1996, 2001), but argue that whether magnitude information is explicitly or implicitly used affects the degree to which numerical–spatial interactions should be observed. In order to explore the impact of explicit versus implicit access to numerical information in our synaesthete, we asked DG to perform two tasks in which numerical magnitude information was explicitly relevant to the task and two tasks in which implicit access to numerical information was sufficient to perform the task. The tasks requiring explicit access were a magnitude judgement with a pair of numbers and a magnitude judgement against a fixed standard (5) with only a single number. The tasks requiring only implicit access were a standard SNARC paradigm, which required a parity judgement, and a numerical cued-detection paradigm, modelled after that developed by Fischer et al. (2003). We predicted that DG's reaction times would be affected by the congruency between his spatial form and the various response alternatives when those responses were aligned (either compatibly or incompatibly) with his spatial form, but not when they were orthogonal to his spatial form. In addition, we predicted that the degree of interference observed would be reduced or absent in tasks that required only an implicit use of magnitude information. Based on these results, we hope to help make clearer the links between synaesthetic and non-synaesthetic cognition, and to illustrate how the study of synaesthesia can help to elucidate issues in the study of numerical cognition (Cohen Kadosh and Henik, 2007; Ramachandran and Hubbard, 2001b).

2. Case report: DG

DG first contacted us on November 13, 2005, in response to a French television program ''La Magazine de la Santé'' [Health Magazine] in which we described synaesthesia, and asked for individuals who thought that they experienced synaesthesia (especially sequence-form synaesthesia) to contact us. Based on DG's responses to our first questionnaire (see below) we classified him as having a variety of spatial forms, and then sent him a second questionnaire, probing his synaesthetic experiences in more detail. At the time of testing DG was a 41 year-old, right-handed French male, operating his own light-construction business installing shelving, acoustic ceilings, and so on. In our interviews with him over a period of nearly two years, he consistently described his synaesthetic experiences as being omnipresent, automatic, and overall useful for him. Indeed, he reports a feeling of being always connected with his place in space and time relative to the universe because he is always positioned in a certain place and moment in his spatial forms. While we have not tested his memory and mathematical abilities, recent work on these topics suggest that the presence of synaesthetic spatial forms may lead to an unusual pattern of strengths and weaknesses (Simner et al., 2009, this issue; Ward et al., 2009, this issue). Over the course of our interviews with him, DG described a total of 58 spatial forms in great detail, including a canonical orientation, direction and shape, although the present investigations focus exclusively on DG's spatial forms for numbers.

3. Questionnaires

We first asked to DG to fill out two questionnaires in order to evaluate the accuracy of his verbal reports and the degree of his synaesthetic experiences. We used two questionnaires taken from previous studies. The first questionnaire was based on previous questionnaires created by Ramachandran and Hubbard (2001a) and was translated into French in order to collect self-reports from a large number of French synaesthetic participants. It is composed of five parts:

1. Basic phenomenology: general questions about the main features of the participant's reported synaesthetic experience.
2. Detailed phenomenology: more specific questions concerning the description of synaesthetic experience.
3. Synaesthesia and the external world: questions related to the external projection or the internal representation of the synaesthetic representations (see also Dixon et al., 2004).
4. Synaesthesia and conscious perception: concerning the way in which participants can differentiate between synaesthetic experiences and the perception of the real world.
5. General information: demographic and health-related information (e.g., age, sex, any potential neurological conditions, etc).

All questions were open-ended, so the participant could thoroughly describe details of his experiences.

The second questionnaire focused specifically on the experiences of number-forms, their frequency, format and use. This questionnaire was created and used for the first time by Seron et al. (1992). It is composed of 21 questions, some of which are open-ended, and others which are multiple-choice. In particular, the questions were created in order to describe the development of the phenomenon since infancy, the possible genetic origins (i.e., if there are other known synaesthetes in the same family), the variability of synaesthetic experience, the usefulness of the numerical mental representation for mathematical calculation and how the participant does calculations by activating of his mental number line, and the automaticity of the phenomenon.

DG provided detailed descriptions of his synaesthesia, including drawings for each of his sequence forms. He reports a highly detailed representation of numerical sequences, including negative numbers and Roman numerals, but also mental representations for other ordinal sequences, such as time sequences (months of the year, days of the week, hours of the day), financial sequences (stock prices, tax rates, etc.), different units of measure (e.g., kilograms, kilometres and degrees), the alphabet, and even the sequence of pure-bred dog naming conventions. Clearly, these experiences are not limited to numerical sequences, but rather extend across a large range of ordinal sequences. DG's experiences were stable, in that the mental images always had the same features (direction, position and physical size), were not influenced by different external situation (e.g., different times of the day) and were reported to be elicited automatically and involuntarily.

4. Experiments

In order to explore DG's experiences, and to test whether they were sensitive to the same manipulations that have been shown to affect numerical–spatial associations in non-synaesthetes, we focused here on replicating and extending previous behavioural studies of number-form synaesthesia (Sagiv et al., 2006; Piazza et al., 2006). We collected data in five tasks meant to tap into numerical–spatial interactions:

Experiment 1: drawing the mental number line (including test-retest).
Experiment 2: number comparison between a pair of numbers presented on the screen.
Experiment 3: numerical cued-detection task.
Experiment 4: parity judgement task.
Experiment 5: number comparison with an internal reference of 5.

4.1. *General methods*

All tasks were executed in two different versions, differing on the horizontal or vertical alignment of the response hands and the stimuli on the screen (except for the number comparison and the parity judgement, where numbers were always centrally presented). We used two 14.1 in (36 cm) Dell laptop computers, running Windows XP and E-prime version 1.2 to collect data. Participants were seated a comfortable distance from the screen, approximately 50 cm. The control group was composed of eight participants matched for age (DG age = 41, controls age mean 41.3 range 37–45) and nationality (French). Seven of the controls were right-handed (as was DG), and all received a payment for their participation in the study. They performed the same tasks that DG did, except Experiment 2b.

Except for Experiment 1, in which the dependent measure was position, all reaction time data were cleaned with a cut-off of three standard deviations. We performed within-participants analyses on DG's data, considering each reaction time as an independent observation, and we performed repeated measures analyses for the control group on the participants' mean RTs for each condition. As standard statistical methods are liberal when comparing a single subject against a population of controls, we adopted a significance test (ST) adapted for comparing individual scores to a small normative sample (Crawford and Howell, 1998), and a method – also based on ST – which compares the discrepancy between scores on two tests observed for an individual with the mean discrepancy in a normative or control sample (DIFFLIMS, Crawford and Garthwaite, 2002).

4.2. Experiments 1a and 1b: drawing the number line

In order to test the consistency of DG's spatial representation for the numerical sequence, we asked him to draw his representation by clicking a computer mouse on the appropriate screen location for numbers from two different ranges (small scale: numbers from 1 to 12; large scale: numbers from 1 to 40). We then asked DG to repeat this task after a period of more than one year, for both the small and the large range.

4.2.1. Experiment 1: methods and procedure

This experiment required indicating the spatial location elicited by each number one at a time on a computer screen, with the help of a mouse (see Piazza et al., 2006). Participants were instructed to click the mouse button to indicate the position of each number on their mental representation of the numerical sequence. DG performed two versions of the task, a small numbers drawing task (Experiment 1a) with numerical stimuli from 1 to 12 (all numbers in the range), and a large numbers drawing task (Experiment 1b) with numerical stimuli from 1 to 40 (numbers: 1, 3, 5, 7, 10, 12, 15, 18, 20, 23, 25, 28, 30, 33, 35, 38, 40). Both tasks started with the presentation of the smallest number (i.e., 1) and of the largest number (12 for Experiment 1a and 40 for Experiment 1b), to allow DG to delimit the extremes of his spatial coordinates according to the range used in the experiment. Following the placement of the first two numbers, the remaining numbers were randomly presented and each number was repeated 10 times. White numerals were presented in Arial 30 point font, aligned vertically with the top of the screen and horizontally with the centre, on a black background. Each number was presented for 500 msec, but there was no time limit to indicate the exact position of the number. Once the answer had been given, there was an inter-trial interval of 300 msec before the next stimulus was presented. DG executed each Experiment (1a and 1b) two times, the first session (test) in February 2006 and the second (retest) in April 2007, in order to test consistency. Both for test and retest, Experiments 1a and 1b were executed in two different sessions with the large numbers drawing task being run after the small numbers drawing task in both cases.

Control participants were instructed to perform the same experiments (small-scale drawing task and large-scale drawing task), by trying to imagine the numerical sequence as spatially organized, in any form they wished. Test-retest data were collected in a second session, two to three weeks after the first session. While DG immediately understood the instructions and found the task easy, for all of the control participants it took some time during the first session for the experimenter to explain exactly what the task was, since the non-synaesthetes did not automatically report thinking about numerical sequences as spatially represented. During the second session, controls were required to try to place the numbers in the same positions as they had during the first session.

4.2.2. Experiment 1: analyses and results

For each number and testing session, we computed the mean *x*- and *y*-coordinates and the mean of the standard deviations and standard errors in the *x* and *y* directions across trials. Fig. 1a shows the relative locations selected for each number, and shows that DG's number position is accurate (the diameter of the circle represents the mean of the standard errors in the *x* and *y* directions) and consistent across time (compare Session 1 and Session 2). In order to test DG's consistency across time we computed two values: the angle, expressed in degrees, between each number and the number 1; and the distance in pixels between each number and the number 1 (Fig. 1b). Correlations between angles were highly significant both for the small-scale drawing task (Pearson $r = .987$, $R^2 = .976$, $p < 1 \times 10^{-8}$) and for the large-scale drawing task (Pearson $r = .993$, $R^2 = .986$, $p < 1 \times 10^{-14}$). Distance measures were also highly correlated (small-scale drawing task: Pearson $r = .986$, $R^2 = .973$, $p < .10^{-7}$; large-scale drawing task: Pearson $r = .993$, $R^2 = .987$, $p < 1 \times 10^{-14}$).

For each participant, we combined data from the first and the second session and then computed standard deviations for the mean *x* and *y* coordinates for each number (see Fig. 1c). We compared the *x* and *y* standard deviations for the controls with that for DG with an independent sample *t*-test, separately for small and large scales. The mean standard deviations for the control group were larger than those for DG in the *x*-direction [small scale: DG = 24.29, controls = 65.14, $t(106) = -2.028$, $p < .05$ large scale: DG = 33.15, controls = 59.25, $t(151) = -1.752$, $p < .05$ one tailed], but not in the *y*-direction [small scale: DG = 27.09, controls = 54.37, $t(106) = -1.625$, $p = .11$; large scale: DG = 29.20, controls = 38.67, $t(151) = -.836$, $p = .404$]. Direct comparison of the mean standard error for *x* and *y* in each experiment between DG and control with the ST for comparing individual scores to a small normative sample (Crawford and Howell, 1998) did not reveal significant differences.

Closer inspection of the control participants' data suggests that these statistical measures may underestimate the differences between DG and the controls, as control participants tended to create the same forms for each scale across the two testing sessions, but not across the two scales within the same testing session. Of the eight control participants, four created significantly different forms for the small-scale and large-scale drawings, which might be thought of as an immediate test-retest measure. Three others created purely straight-line forms, which have nearly no variability in the *y*-direction. Indeed, one of the controls who created a straight-line form aligned his form with the upper edge of the screen, thereby nearly completely eliminating the possibility of variability in the *y*-direction. The only participant who created the same non-straight-line forms within both the small-scale and large-scale drawing tasks, C6, was consistently among the most variable participants. To quantitatively test these observations, we calculated the correlation in positions across scales within sessions (small session 1-large session 1; small session 2-large session 2) for DG and for the controls. The mean between-scale correlation in the *x*- and *y*-directions was .97 for DG, and .25 for the 8 control participants. A direct comparison of the correlation coefficients (IIMA; Crawford et al., 2003) between DG and controls showed that DG's across-scale consistency was significantly greater than that for controls [IIMA: $t(7) = 3.63$, $p < .01$]. Taking these additional considerations into account, the similarity of DG's forms, over a test-retest interval of 14 months, compared against 14 days, is all the more remarkable.

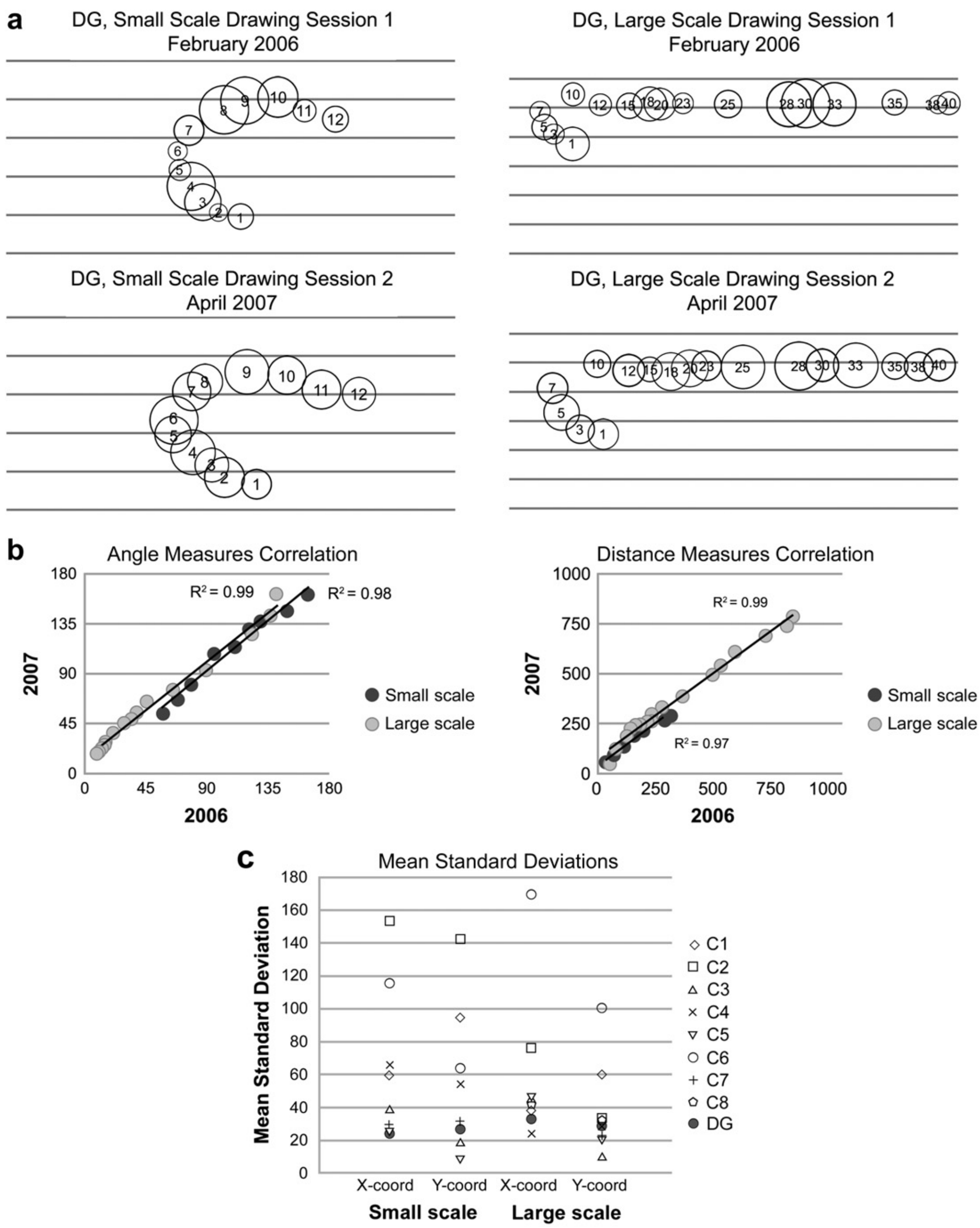

Fig. 1 – (a) Spatial forms as drawn by DG in two testing sessions, separated by 14 months. Each circle indicates the centre of the positions indicated for the tested numbers, and the size of the circle indicates the mean standard error of his placements. DG's spatial forms are highly consistent. (b) Correlations between the angles and distances from 1 for each number in the testing session between the 2006 and 2007 testing sessions. Dark grey circles indicate the angles and distances calculated for the small-scale drawing task, while light grey circles indicate the corresponding measures for the large-scale drawing task. DG was very consistent in his placements, even over a test-retest interval of 14 months. (c) Mean standard deviations in the *x* and *y* directions for DG and the eight control participants (C1–C8). Control participants are indicated by different open symbols, while DG is indicated by the filled circles. DG was among the most consistent participants, especially in the *x*-direction. The lack of variability in the *y*-direction for certain control participants is probably due to the fact that they simply drew a straight left-to-right line when required to place numbers at spatial locations. Indeed, C3 even went so far as to align his responses along the top of the screen, where he could use the edge of the screen as a reference point.

4.2.3. Discussion of Experiment 1

We assessed the consistency of DG's spatial forms by asking him to draw his spatial form on a computer screen in two sessions separated by 14 months, while control participants were asked to draw spatial forms in two sessions separated by 14 days. On several different measures of consistency, DG was more consistent in his spatial locations than controls, even though controls were tested over a much shorter test-retest interval. Additionally, DG's form was quite similar across the two different drawing scales (small scale: 1–12, large scale: 1–40) while many of the control participants created remarkably different forms across the two drawing scales, which was essentially an immediate retest. The consistency of DG's spatial forms, as assessed both across the two drawing scales and a test-retest interval of more than one year, is consistent with previous research (Piazza et al., 2006; Smilek et al., 2007; Price and Mentzoni, 2008) that has demonstrated consistency of spatial forms across time, and support the claim that DG's synaesthetic reports are veridical.

Interestingly, although DG drew his number form as being horizontal in this computer based task, he also reports that he places himself inside the curve of the number line, with small numbers descending on his left and the larger numbers ascending and passing him on his right. At some point, which is still unclear, his vantage point shifts as he reports facing the long segment with smaller numbers to his left and larger numbers to his right. This is additionally complicated by the fact that DG reports that his spatial forms have a default orientation relative to the Sun and the surface of the planet Earth. This is a critical issue, as whether 9–12 should be thought of as part of a horizontal or vertical representation depends on whether we privilege DG's verbal reports or his drawing in this drawing task. In what follows, we have treated 9–12 as being part of an ascending vertical segment, consistent with DG's phenomenological descriptions.

4.3. Experiment 2: number comparison task

In order to further demonstrate the reality of DG's experiences, we tested him on a task that has been used to demonstrate synaesthetic interference between numbers and space in previous studies (Piazza et al., 2006; Sagiv et al., 2006). Pairs of numerical stimuli were drawn from the range of numbers from 1 to 12 with a fixed numerical distance of two (10 pairs overall). Participants were asked to respond with a button press at the location of the larger of the two numbers. There were two tasks, differing on whether the stimuli were aligned vertically (Experiment 2a) or horizontally (Experiment 2b) on the screen, as well as on response hand-position pairing. We predicted that DG's RTs would be affected by the stimulus layout, and in particular that an association between small numbers and bottom-sided responses and large numbers and top-sided responses would emerge in the vertical task. As observed in previous experiments (Piazza et al., 2006; Sagiv et al., 2006), we expected to find a compatibility effect for the direction of the numbers in the pair, and in particular that DG's performance would be facilitated when large numbers were presented on the top, consistent with his mental representation. Additionally, due to the curve in DG's numerical representation (see Fig. 1), we predicted that his compatibility effects would be affected by numerical magnitude relative to 5, the midpoint of the curved portion of his spatial form. Finally, we expected to find a different pattern of results for controls in the vertical task, where interactions between numbers and space should not emerge as for DG.

4.3.1. Experiment 2a: methods and procedure

Participants were asked to identify which of a pair of numbers presented on the computer screen was numerically larger by pressing the button corresponding to the position of the larger number as quickly as possible. Each trial started with a central fixation cross lasting 300 msec, followed by a blank screen lasting 300 msec, and then the numerical pair appeared in a vertical orientation. The time limit for responding was 5 sec, and after the response there was an ITI of 1 sec in which a black screen was displayed. Stimuli were white 30 pt Arial font numbers on a black screen. The task was composed of 10 practice trials at the beginning of each session, and 120 randomly ordered experimental trials for each session. The position of numbers in each pair was counterbalanced, so that each pair of numerical stimuli in each condition (compatible or incompatible) was repeated 6 times. The task was run in two consecutive sessions, in order to counterbalance the position of the hands on the keyboard (left-top, right-top).

4.3.2. Experiment 2a: analyses and results

DG's performance was relatively accurate (9% error rate, 9 and 12 errors in the compatible and incompatible conditions, respectively). DG's overall reaction times were faster in the compatible condition (i.e., top-larger responses, mean RT: 459 msec) compared to incompatible condition (i.e., bottom-larger responses, mean RT: 477 msec), although this effect did not reach significance [$t(214) = -1.472$, $p = .143$]. We then plotted the RTs as a function of numerical magnitude (Fig. 2a) and found a strong association between small numbers and the lower portion of space and large numbers and the top portion of space. This association can be seen more clearly by computing mean RTs for trials where the mean of the pair was less than or equal to 5 (small pair condition), versus greater than 5 (large pair condition), as shown in Fig. 2a. In the small pair condition, reaction times were significantly faster when the correct response was on the bottom [mean RT: bottom response = 445 msec, top response = 492 msec, $t(86) = 2.371$, $p < .05$], and in the large pair condition RTs were faster when correct response was on the top [mean RT: bottom response = 503 msec, top response = 439, $t(126) = -4.191$, $p < .0001$]. Eight controls performed the same task. Error rate never exceeded 3%. Results are shown in Fig. 2b. Performance of controls did not differ significantly between top and bottom response conditions overall nor in the small pair condition, but RTs were significantly faster for top-sided responses than for bottom-sided responses in the large pair condition [$t(7) = -2.509$, $p < .05$].

We then computed the difference in mean RTs (dRT) for top-larger responses minus bottom-larger responses. The linear regression between dRT and magnitude was significant for DG [$R^2 = .80$, $F(1,8) = 32.14$, $p < .001$, see Fig. 2c] and marginally significant for the controls [$R^2 = .39$, $F(1,8) = 5.11$, $p = .054$, see Fig. 2c]. These results support the conclusion that DG's spatial representation for the numerical sequence can interfere with his performance in numerical tasks, but also suggest a similar, but weaker, representation in controls. In order to directly test whether this spatial representation of numbers led to greater interference in DG, for whom it was explicit, than in controls, for whom it was implicit, we directly compared the top versus bottom difference between the small and large pairs, and found that it was significantly larger for DG than for controls (DIFFLIMS: $t = -2.415$, $p < .05$). In addition, direct comparison of the slope of DG's linear regression and controls' slopes demonstrated a significantly stronger association between numbers and space for DG compared to the control group [ST: $t(7) = -2.2369$, $p < .05$, one tailed, see Fig. 2c].

4.3.3. *Experiment 2b: Methods and procedure*

We asked to DG to perform a second comparison task, but in this case the pair of numbers was horizontally presented on the screen, in an orientation that was either compatible or incompatible with the classic left-to-right orientation of the mental number line, and we ran only one block, with uncrossed hands. In all other respects, stimuli and trials were the same as in Experiment 2a. For this task we did not collect data from the control group.

4.3.4. *Experiment 2b: Analyses and results*

DG was highly accurate in executing the task (3% errors). Mean RTs were computed for the larger-left and larger-right conditions. DG's responses were faster when the larger number was on the right (467 msec), than when it was on the left (488 msec), and the difference between conditions was significant [$t(227) = 2.903$, $p < .005$]. We then analyzed the advantage for the larger-right condition as a function of magnitude (given by the mean of each pair of number). If DG's performance is affected in the same way as suggested by the classical mental number line (i.e., with small magnitudes on the left and large magnitudes on the right), the advantage for larger numbers on the right should increase in function of the numerical magnitude (Fig. 2d). The linear regression on the dRTs between larger-right and larger-left conditions was not significant [$y = -1.33 - 13.30$, $R^2 = .03$, $F(1,8) = .25$, $p = .6$], indicating that DG's performance was not affected by magnitude in the horizontal orientation. Again, clustering data into two sub-groups with respect to the mean of the numbers in a pair (smaller or equal/greater than 5), we find a significant advantage for larger-right in both cases [small pair: $t(94) = 2.094$, $p < .05$; large pair: $t(131) = 2.035$, $p < .05$]. Thus, unlike in the vertical case, we find no interaction between numerical magnitude and response side, consistent with DG's reports that he experiences numbers as vertically oriented. The main effect of response side (larger-right) may simply reflect the fact that DG was right handed, and therefore would be expected to respond more quickly with his right hand.

4.3.5. *Discussion of Experiment 2a and 2b*

In Experiments 2a and 2b we tested whether we could use tasks that have been used in previous research to demonstrate an association between numerical magnitude and space in a unique synaesthete, DG. As predicted, we found a strong spatial effect in the vertical task (Experiment 2a), in that DG responded more quickly on the bottom for small pairs, and on the top for large pairs, independently of the orientation of the two numbers (i.e., larger on the top or on the bottom). Contrary to previous experiments (Piazza et al., 2006; Sagiv et al., 2006), we did not observe an effect of compatibility (which would correspond to faster RTs for the compatible condition, where larger numbers were on the top), but rather found that small pairs were associated with the bottom part of the space, and large pairs with the top. This may reflect the fact that number pairs were always separated by a constant numerical distance of 2, and therefore were primarily composed of either small or large numbers. We find a similar effect for controls, although it just fails to reach statistical significance. The effect in controls, unlike that observed for DG was mostly driven by faster response times for top responses for the large pairs. These findings are similar to those that demonstrate a vertical SNARC effect, and further suggest vertical associations between numbers and space in non-synaesthetes (Ito and Hatta, 2004; Schwarz and Keus, 2004). The significant difference between DG and his controls suggests that such associations are stronger for DG than for non-synaesthetes, and are consistent with previous suggestions that synaesthetic number-forms and non-synaesthetic numerical–spatial interactions arise from similar brain mechanisms (Cohen Kadosh and Henik, 2007; Eagleman, 2009, this issue; Hubbard et al., 2005b). Conversely, in the horizontal task, which is orthogonal to the orientation of DG's reported spatial form, we did not observe a significant interference effect. Although we did not test control participants on this task, based on extensive previous literature on the SNARC effect (for a recent meta-analysis, see Wood et al., 2008) we predict that we would have observed a significant horizontal interference effect.

Although these results are consistent with DG's self-reported spatial forms, from the standpoint of numerical cognition, this is a relatively complex task. In this number comparison task numerical magnitude is explicitly relevant to the task, since participants had to respond with a button press in the location of the larger number, and the presence of two numerical stimuli on the screen elicited strong spatial representations. In order to further explore which of these components were critical to eliciting synaesthetic spatial forms, we ran an additional series of experiments, in which we manipulated the explicit/implicit aspect of numerical information tasks and the degree to which spatial information was explicitly represented, to determine which of these factors was most relevant to eliciting DG's synaesthetic experiences.

4.4. *Experiment 3: numerical cued-detection task*

In order to assess whether numerical magnitude information needed to be explicitly represented to elicit synaesthetic number forms, we tested whether the mere perception of an irrelevant numerical stimulus could elicit a shift of attention in DG. Previous experiments have found that the perception of an uninformative numerical cue can elicit shifts of attention in a simple detection task as a function of numerical magnitude (Fischer et al., 2003; Galfano et al., 2006; Casarotti et al., 2007). This numerical cued-detection task requires detecting a target that can appear either to the left or to the right of a central fixation point and that is preceded by a non-informative central number. Fischer et al. (2003) found that reaction times were faster when a left-sided target was preceded by a smaller

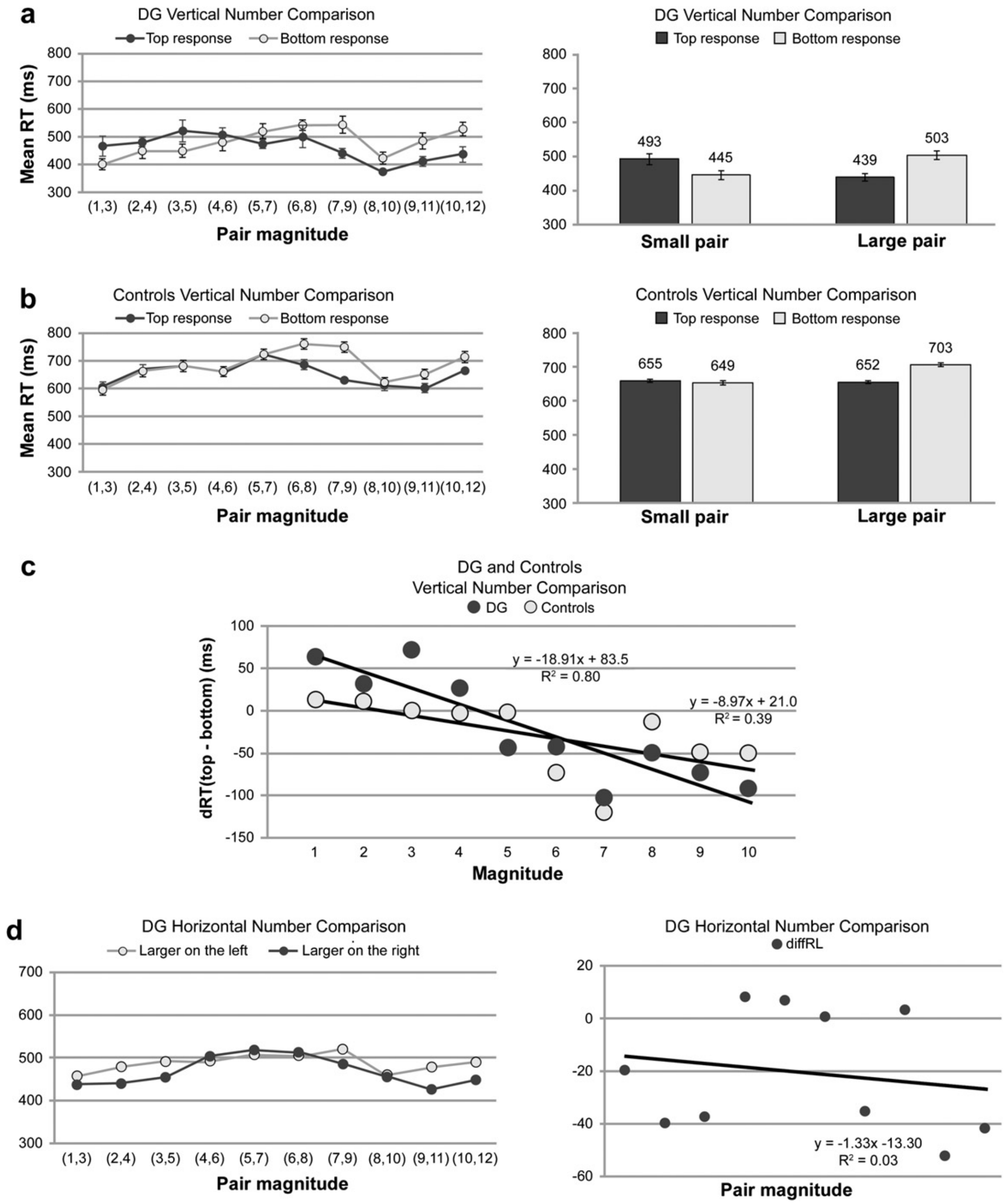

Fig. 2 – (a) and (b) Mean RTs as a function of response position (top or bottom) and pair tested for our synaesthetic participant DG and for the eight control participants. The line graphs on the left show the mean RTs for top (dark grey) and bottom (light grey) responses, while the bar graphs on the right show the mean reaction times collapsed across small (mean less than 5) and large (mean greater than 5) pairs of numbers. Error bars indicate the SEM. DG showed a continuous increase in reaction time for bottom responses as numerical magnitude increased, and a corresponding decrease for top responses, leading to an overall congruency effect such that bottom responses were faster for small pairs while top responses were faster for large pairs, consistent with DG's reported synaesthetic spatial form. Control participants show a slight effect in the same direction with top responses being faster than bottom responses for large pairs, but no such effect for small pairs.
(c) Regression slopes for DG and controls calculated on the dRTs (top–bottom) as a function of numerical magnitude. Shorter RTs for bottom-sided responses than top-sided responses thus yield difference scores greater than 0, while shorter RTs for top-sided responses yield difference scores less than 0, and an association between small numbers and the bottom side of space is indicated by a negative regression slope. DG's data points are indicated in dark grey, and controls in light grey, with the corresponding regression slopes in black. DG's regression slope was more negative than the mean for the controls, consistent with his stronger association between small numbers and the bottom side of space. (d) DG's performance on the horizontal number comparison task. The line graph on the left shows the mean RTs for right (dark grey) and left (light grey)

number and when a right-sided target was preceded by a larger number. However, subsequent studies using different paradigms have suggested that this effect can be over-ridden by the participant's mental set (Galfano et al., 2006), and that it can be modulated by the relevance of the number for the task (Casarotti et al., 2007), suggesting that this effect may be weak in non-synaesthetes. In some studies with entirely irrelevant cues this effect is not reliable at the behavioural level (Bonato et al., 2009) even when numerical cues have been shown to be sufficient to affect ERP components related to shifts of visuospatial attention (Ranzini et al., 2009). In order to test whether DG's synaesthesia could induce stronger shifts of attention than for controls due to the simple perception of a number, in a way that is compatible with his internal numerical representation, we asked DG and the same eight controls to execute a numerical cued-detection task similar to that developed by Fischer et al. (2003) in two different versions: in one case the spatial locations of the target were vertically aligned (Experiment 3a), and in the other case they were horizontally aligned on the screen (Experiment 3b). We expected that DG's performance would be affected by the magnitude of the numerical cue only in the vertical task, compatible with his number form. We thus predicted that small numbers would direct attention towards the bottom, whereas large numbers would direct attention towards the top of the screen. Moreover, contrary to the results observed in the general population, we expected DG to show no effects of numerical cueing in the horizontal task. We predicted that DG's attention would not shift to the left for small numbers and to the right for large numbers, since his number form for this range does not correspond to the classical left-to-right oriented mental number line. Finally, based on previous studies, we predicted that control participants would show a horizontal, but not vertical, compatibility effect.

4.4.1. *Experiment 3a: method and procedure*

Each trial started with a central fixation and two vertically aligned boxes for 500 msec followed by a central numerical cue for 300 msec (modified from Fischer et al., 2003). After a variable delay (100, 300 or 600 msec) the target appeared in one of the two boxes. Participants were required to press the spacebar as soon as possible after the target appeared. The cue was either a *small* (1 or 2) or a *large* (8 or 9) number and the target was a black circle on a white background. The experiment thus consisted of 12 trial types (2 cue magnitudes $\times$ 2 target sides $\times$ 3 delays), and each trial type was presented 12 times, yielding a total of 144 experimental trials. We also presented catch trials where no target appeared in order to discourage automatic responding. Each of these was coded as corresponding to one of the 12 trial types listed above, although no target was presented making delay meaningless here. Participants performed 168 randomly selected trials (144 experimental trials and 24 catch trials) preceded by a block of 10 practice trials.

4.4.2. *Experiment 3a: analyses and results*

DG was 100% accurate, both in the experimental and in catch trials. We computed mean RTs for the *compatible* (small number/bottom target and large number/top target) and *incompatible* conditions (small number/top target and large number/bottom target) with respect to the orientation of DG's mental number line, overall and for each delay (Fig. 3a, DG on the left and controls on the right). DG's reaction times were clearly faster for compatible trials and an analysis of variance (ANOVA) with compatibility and delay as factors showed that the effect of compatibility was significant [$F(1,142) = 11.61$, $p < .001$]. Importantly, this effect did not interact with delay [$F(2,137) < 1.0$, $p = .92$], suggesting that these effects are elicited automatically (see also Jarick et al., 2009a, this issue, 2009b, this issue; Smilek et al., 2007). For the eight controls mean RTs were analyzed in a repeated measure design with congruency and delay as factors. For the controls, there were no significant main effects or interactions (Fig. 3a). Direct comparison between DG and the control group showed that DG had a significantly greater interference effect than controls did [DIFFLIMS: $t(7) = -2.008$, $p < .05$, one tailed]. RTs were overall faster in compatible trials than in incompatible trials for DG, but this advantage was not observed in the control group (DG: compatible = 273 msec, incompatible = 304 msec; controls: compatible = 388 msec; incompatible = 391 msec).

4.4.3. *Experiment 3b: method and procedure*

Experiment 3b was exactly the same as Experiment 3a, except that the vertical orientation of the boxes where the targets appeared was changed to a horizontal orientation as originally used by Fischer et al. (2003).

4.4.4. *Experiment 3b: analyses and results*

DG's performance was once again 100% accurate, both in the experimental and in catch trials. Mean RTs were computed for the *compatible* (small number/left target and large number/right target) and *incompatible* conditions (small number/right target and large number/left target), with respect to the orientation of the classical mental number line (i.e., from left to right), overall and for each delay condition (Fig. 3b, DG on the left and controls on the right). An ANOVA with congruency and delay as factors did not reveal any significant effects or interactions. Eight controls performed the same task and mean RTs were analyzed in a repeated measure design with congruency and delay as factors. Again, there were no significant main effects or interactions (Fig. 3b). Comparison between DG and the control group in the discrepancy between compatible and incompatible condition was not significant. Although the effect of congruency did not reach significance, RTs were overall faster for compatible trials both for DG and for controls (DG: compatible = 261 msec, incompatible = 274 msec; controls: compatible = 407 msec, incompatible = 417 msec; (for

responses, while the regression line on the right shows dRTs (right–left) as a function of numerical magnitude. Shorter RTs for left-sided responses than right-sided responses therefore yield difference scores greater than 0, while shorter RTs for right-sided responses yield difference scores less than 0. An association between small numbers and the right side of space is indicated by a negative regression slope. Left and right-sided responses did not consistently differ, and the regression slope was not significantly different from 0.

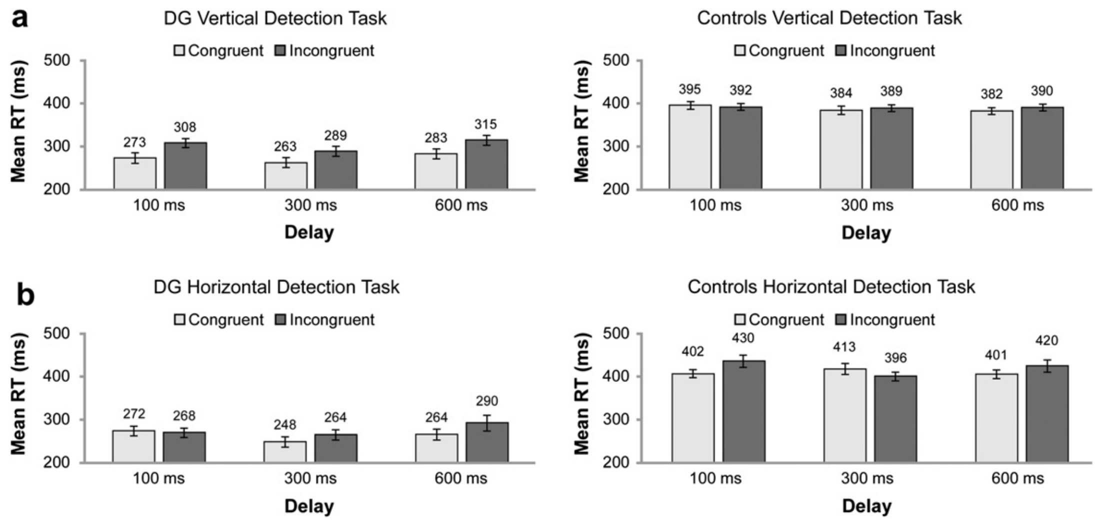

Fig. 3 – (a) and (b) Mean reaction times as a function of delay for the compatible and incompatible mappings for DG and the control participants. Compatible conditions are indicated in light grey and incompatible conditions in dark grey. Error bars indicate the SEM. DG's responses were faster for the compatible mapping in the vertical condition (bottom targets preceded by small numbers, and top targets preceded by large numbers) but were not affected in the horizontal mapping. Control participants showed no congruency effect in the vertical mapping, but showed a non-significant congruency effect in the horizontal mapping.

a similar non-significant trend towards behavioural congruency effects, see Ranzini et al., 2009).

4.4.5. *Discussion of Experiments 3a and 3b*

Experiments 3a and 3b showed that in a purely spatial task which did not require explicit access to numerical magnitude information, DG's reaction times were modulated by his internal number form. We found a significant effect of congruency between the magnitude of the numerical cue and the position of the following target when target stimuli were vertically aligned, but did not find significant differences between compatible and incompatible conditions when the target stimuli were horizontally aligned. DG was faster when small number cues were followed by bottom-sided targets, and when large number cues were followed by top-sided targets, but was not significantly affected by classical mental number line, as revealed by the absence of effects for the horizontal layout. Importantly, this effect was significantly different from control participants, who did not show any RT effects induced by numerical magnitude in the vertical task. Although this task was purely spatial and did not require explicit access to magnitude information, DG's personal number form seemed to be triggered by the simple perception of irrelevant numbers and to strongly affect his performance, suggesting that numerical magnitude need not be explicitly represented to elicit synaesthetic inference (see also Jarick et al., 2009a, this issue). However, given the spatial nature of the task, it is possible that explicit spatial information is necessary to elicit synaesthetic interference.

4.5. *Experiment 4: parity judgement*

Experiments 3a and 3b demonstrated the influence of DG's number form in a purely spatial task that did not require direct processing of the numerical cue. In Experiment 4 we tested whether the influence of DG's numerical representation on his behavioural performance would extend to numerical tasks where neither numerical magnitude nor spatial location was explicitly relevant for performing the task. We asked DG and the same eight controls to perform two parity (odd/even) judgement tasks. The task consisted in judging the parity of a number presented at fixation and responding with vertically (Experiment 4a) or horizontally (Experiment 4b) aligned hands. Based on his phenomenological reports, we predicted that DG would demonstrate a SNARC effect with the vertical alignment, but not with the horizontal alignment, extending the results obtained in Experiments 3a and 3b. Finally, we predicted a classical SNARC effect in the control group for the horizontal alignment, but possibly not for the vertical one, strengthening the difference between DG and controls in the underlying spatial representation for numbers.

4.5.1. *Experiment 4a: methods and procedure*

Numbers from 1 to 9 except 5 were presented at fixation in random order. Participants responded with a given hand when the number was odd and with the other when it was even, counterbalanced across blocks. Each trial began with a fixation cross lasting 300 msec, followed by a blank screen lasting 300 msec. Target numbers were then presented for 200 msec and participants had up to one second to respond. Each response was followed by a 1500 msec ITI. Stimuli were centrally presented Arabic numerals (30 pt Arial) in white on a black screen. The response keys were vertically arranged and the experiment was conducted in four different sessions, in order to counterbalance response hand and hand position (i.e., top response-right hand/bottom response-left hand and top response-left hand/bottom response-right hand). The task was composed of four blocks of 80 trials (10 repetitions of each stimulus) for a total of 320 trials, and 9 practice trials at the beginning of each session (all numbers from 1 to 9 were used for the practice trials).

4.5.2. *Experiment 4a: analyses and results*
DG was quite accurate (4% error rate) with slightly more errors in the incompatible mapping than in the compatible mapping (4% *vs* 3%, 7 *vs* 5 errors) while controls made errors on 6.8% of trials, with fewer errors in the incompatible than in the compatible mapping (6.6% *vs* 7.1%). For each number, we calculated the dRT by subtracting the mean RT for bottom-sided responses from the mean RT for top-sided responses. We then computed the linear regression on the dRTs as a function of numerical magnitude, following standard methods for analysis of the SNARC effect (Fias et al., 1996; Lorch and Myers, 1990). Contrary to the hypothesis that synaesthetic interference can be elicited in the absence of explicit magnitude and spatial information, we did not observe a vertical SNARC effect for DG [$y = -.31x + .22$, $R^2 = .001$, $F(1,6) < 1$, $p = .9$]. As predicted, we did not observe a vertical SNARC effect for the control group [$y = 3.96x - 26.13$, $R^2 = .21$, $F(1,6) = 1.63$, $p = .2$]. Direct comparison of DG's slope against that of control group was not significant [ST: $t(7) = -.30$, $p = .7$]. Examination of individual participants' data showed that three controls had a significant positive slope [C1, C5 and C8, all $t(6)$s > 2.2, $p < .05$] and one (C6) showed a significant negative slope [$t(6) = -2.53$, $p < .05$], while the slopes for the remaining four controls did not differ significantly from 0 (Fig. 4a). Additionally, because the SNARC effect can sometimes have a step-like shape (especially in magnitude judgements, see Gevers et al., 2006b) we also tested whether a step-like SNARC was present by comparing dRTs for small numbers with large numbers. We find that DG's mean dRTs do not differ [$t(6) = 1.82$, $p = .12$] between small numbers (−2.2 msec) and large numbers (−.5 msec), further confirming that he does not show a SNARC effect in this condition.

4.5.3. *Experiment 4b: methods and procedure*
The method and procedure for Experiment 4b were the same for Experiment 4a, except that response hands were horizontally oriented. The response keys were horizontally arranged and the experiment was conducted in two different sessions, with response hand counterbalanced. The task was composed of two blocks of 160 trials (10 repetitions of each stimulus) for a total of 320 trials, and 9 practice trials at the beginning of each session (all numbers from 1 to 9 were used for the practice trials).

4.5.4. *Experiment 4b: analyses and results*
DG made errors on 7% of trials, with slightly more errors in the compatible mapping than in the incompatible mapping (8% *vs* 6%, 13 *vs* 9 errors) while controls made errors on 8.0% of trials, with more errors in the incompatible than in the compatible mapping (9.3% *vs* 6.8%). For each number, we calculated the mean difference in reaction time (dRT), by subtracting the

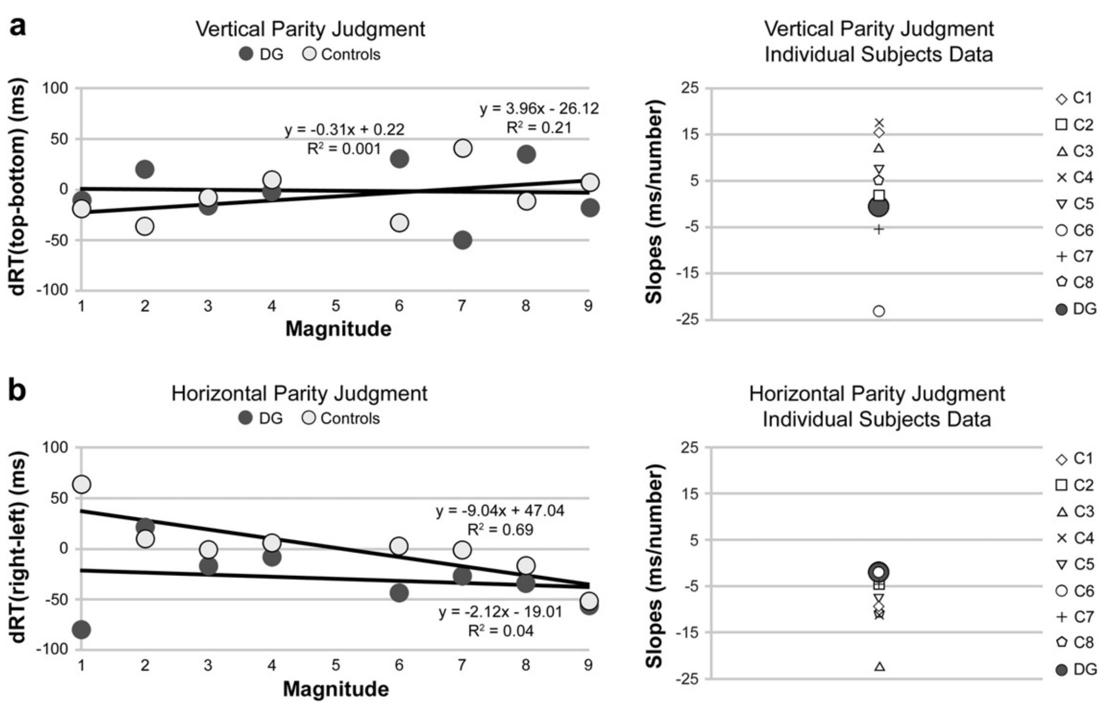

Fig. 4 – (a) and (b) Regression slopes for DG and controls as a function of numerical magnitude in the vertical (a) and horizontal (b) mappings for the parity judgement task. The left side of the figure shows the mean dRTs for DG in dark symbols and for the controls in light symbols, with the corresponding regression lines. The right side of the figure shows the regression slope for each of the eight controls, and for DG. Control participants are indicated by different open symbols, while DG is indicated by the filled symbols. Neither DG nor the control group shows a significant association between space and numerical magnitude in the vertical condition. However, the control participants, but not DG, do show a classic SNARC effect, in which small numbers are responded to faster on the left side of space and large on the right side of space, as indicated by the negative regression slope for the control participants.

mean RT for the left-sided response from the mean RT for right-sided responses and then calculated the linear regression as in Experiment 4a (Fig. 4b). Although the linear regression calculated from DG's performance was not significantly different from 0 [$y = -2.13x - 19.01$, $R^2 = .04$, $F(1,6) = 2.58$, $p = .63$], DG's behaviour was consistent with a classical SNARC effect (i.e., a negative slope, with faster RTs for small numbers with left-sided responses and for large numbers with right-sided response). The control group, however, showed a classical significant SNARC effect [$y = -9.04x + 47.04$, $R^2 = .69$, $F(1,6) = 13.50$, $p < .05$, 8% overall errors excluded from analyses]. Direct comparisons of DG's slope with that of the control group using the ST described in the general methods demonstrated that this difference was not significant [ST: $t(7) = 1.03$, $p = .3$, see Fig. 4b]. Although the slopes for all eight controls were negative in this experiment (Fig. 4b), only two participants' individual slopes differed significantly from 0 [C3 $t(6) = -3.94$, $p < .01$ and C8, $t(6) = 2.32$, $p < .05$]. However, two of the controls whose slopes failed to reach significance were marginally significant [C1 $t(6) = -1.91$, $p = .0525$ and C4 $t(6) = 1.90$, $p = .053$]. Even if we include these marginally significant slopes as significant, this implies that four of the controls had slopes that were non-significant [max $t(6) = 1.32$, $p > .05$]. As in Experiment 4a, DG's mean dRTs did not differ between small (−20.1 msec) and large numbers [−39.3 msec; $t(6) = .20$, $p = .42$] although the difference was in the predicted direction, with large numbers yielding a more negative dRT than small numbers for him.

4.5.5. *Discussion of experiments 4a and 4b*

Because of the vertical orientation of DG's mental number line, we predicted a significant SNARC effect in the vertical parity judgement task, but not in the horizontal task. This would have extended findings from Experiments 2a and 2b to a purely numerical task with implicit access to numerical magnitude information. Contrary to our hypotheses, DG did not show a SNARC effect in either the horizontal or vertical alignment. DG's SNARC slope in the horizontal layout, although not significant, was in line with control's slopes (Fig. 4a, right panel) and consistent with a classical SNARC effect. For the vertical alignment, the variability among controls placed DG's slopes in the middle of the controls (Fig. 4b, on the right). There are three possible explanations for these findings: First, it is possible that DG's number form was not elicited because the task required only implicit access to numerical information, in line with the suggestion that explicit access to magnitude information plays a key role in modulating the presence of numerical–spatial interactions (Priftis et al., 2006). Second, it is possible that the presence of only one number on the screen elicited a spatial reference more weakly than did either the presence of two numbers (Experiment 2) or a central cue with spatially separated target stimuli (Experiment 3). Third, it is possible that our instructions, which focused more on the hands than on response buttons, minimized the use of a spatial reference frame, as this has also been shown to affect the magnitude of the SNARC effect (Muller and Schwarz, 2007; Viarouge et al., in preparation). In order to more fully explore the importance of explicit magnitude information in eliciting synaesthetic number forms, we conducted a final experiment, which was identical to Experiments 4a and 4b, except that we asked participants to compare centrally presented numbers against an internal reference, a task which is classically thought to require explicit access to numerical magnitude (Dehaene et al., 1993; Gevers et al., 2006b).

4.6. *Experiment 5: comparison with an internal reference*

It is possible that a single stimulus presented at fixation is insufficient to elicit a representation of a line (which requires two points) and therefore was not sufficient to demonstrate congruity effects. Alternatively, it could be that the parity task does not require deep enough processing of numerical quantity, and therefore failed to lead to activation of the mental number line. In order to test whether a deeper level of numerical processing could more strongly reveal the relationship between the numerical and the spatial representations, we asked DG and controls to perform a number comparison task against an internal reference. The experiment was composed of two parts, differing only in the alignment of the response keys. In Experiment 5a the keys were aligned vertically and in Experiment 5b they were aligned horizontally. This experiment is identical to Experiment 4, except for the explicit access to numerical magnitude required by this task.

4.6.1. *Experiment 5a: methods and procedure*

The task consisted in judging whether a number was larger or smaller than 5. Stimuli were numbers from 1 to 9 except 5. The method and procedure was the same as Experiment 4a. Participants responded with left and right hands vertically aligned. The experiment was conducted in four sessions, in order to counterbalance response hand and hand position. For each number, we calculated the dRT by subtracting the mean RT for bottom-sided responses from the mean RT for top-sided responses. We then calculated the linear regression on these differences.

4.6.2. *Experiment 5a: analyses and results*

DG made errors on 4% of trials, with slightly more errors in the incompatible mapping than in the compatible mapping (5% *vs* 3%, 8 *vs* 5 errors) while controls made errors on 3.0% of trials, with more errors in the incompatible than in the compatible mapping (3.6% *vs* 2.9%). Although the regression slope for DG was in the predicted direction (i.e., faster reaction times for smaller numbers with bottom-sided responses and for larger numbers with top-sided responses), it did not reach significance [$y = -7.26x + 22.59$, $R^2 = .28$, $F(1,6) = 2.41$, $p = .17$]. No significant vertical SNARC effect was observed for the control group [$y = -1.88x + 18.27$, $R^2 = .08$, $F(1,6) = .58$, $p = .40$, 3% overall errors excluded from analyses, participant C6 who misunderstood the instructions and made errors on 63% of trials was excluded]. A direct comparison of DG's slope against that of control group was not significant [ST: $t(6) = -.62$, $p = .50$], consistent with the high variability in control participant's slopes (see Fig. 5a, right panel). Examination of individual participant's slopes indicated that three controls (C2, C3, C7) exhibited significant differences from 0 (see Fig. 5a). However, this difference was in the predicted direction for only two of the three participants [C3 and C7, $t(6) = -3.71$ and -2.39, $p < .05$, respectively], and was in the opposite direction for the other [C2, $t(6) = 3.05$, $p < .05$]. Contrary to our findings in Experiments 4a and 4b, direct comparison of DG's mean dRTs for small (15.6 msec) and large (−43.0 msec) numbers was significant [$t(6) = 2.61$, $p < .05$] and in the predicted direction, consistent with a step-like SNARC effect in this task. These findings are consistent with previous studies that have suggested that the SNARC effect may be stronger and more step-like in conditions where access to numerical magnitude is explicitly required to perform the task (Gevers et al., 2006b), and provides further evidence for the reality of DG's vertical association between numbers and space.

4.6.3. *Experiment 5b: methods and procedure*

Experiment 5b was identical to Experiment 5a, except for the horizontal orientation of the response hands. The task was composed of two different blocks in order to counterbalance response side. Each block contained 8 practice trials and 160 experimental trials (10 for each number and each response mapping), for a total of 320 experimental trials. Participants executed 8 practice trials at the beginning of each block.

4.6.4. *Experiment 5b: analyses and results*

DG made errors on 3% of trials, with slightly more errors in the incompatible mapping than in the compatible mapping (4% *vs* 3%, 6 *vs* 4 errors) while controls made errors on 5.9% of trials, with more errors in the incompatible than in the compatible mapping (7.3% *vs* 4.5%). The difference between the right minus left condition was analyzed, and the linear regression computed as for the parity judgement task (Fig. 5b). The typical SNARC effect was not observed for DG when the response keys were aligned horizontally, in that the magnitude of the numerical stimulus did not significantly affect RTs as a function of response side [$y = 2.56x - 21.85$, $R^2 = .3$, $F(1,6) = 3.46$, $p = .10$]. On the contrary, the classic SNARC effect was significant for the control group [$y = -8.56x + 44.65$, $R^2 = .77$, $F(1,6) = 19.97$, $p < .005$, 6% overall errors excluded from analyses]. Despite the difference between the direction of DG's and control group's slopes, the comparison was not significant [ST: $t(7) = .89$, $p = .40$], likely driven by the high variability observed in controls slopes (see Fig. 5b on the right). Fig. 5b shows that seven of eight controls' slopes were negative, and examination of individual participants' slopes revealed that four of the eight controls [C3, C4, C6 and C8, all $t(6)\text{s} > 2.03$, $p < .05$] showed a typical SNARC effect in this

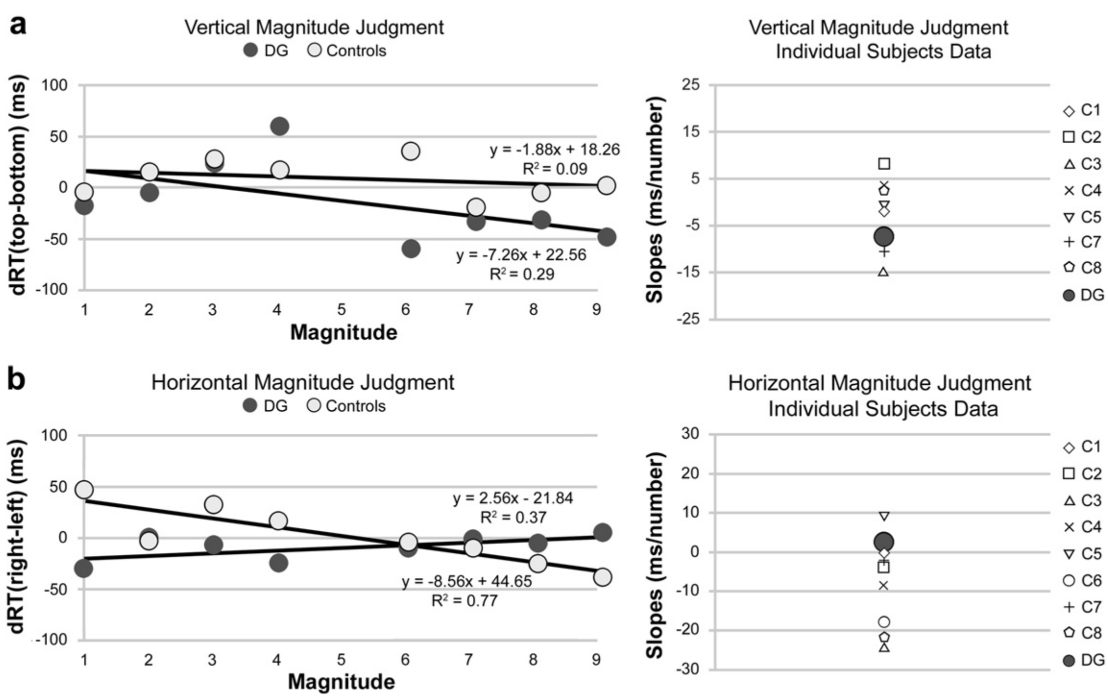

Fig. 5 – (a) and (b) Regression slopes for DG and controls as a function of numerical magnitude in the vertical (a) and horizontal (b) mappings for the magnitude task. The left side of the figure shows the mean dRTs for DG in dark symbols and for the controls in light symbols, with the corresponding regression lines. The right side of the figure shows the regression slope for each of the eight controls, and for DG. Control participants are indicated by different open symbols, while DG is indicated by the filled symbols. Although DG's slope was in the predicted direction in the vertical condition (slope = −7.26), this was not significantly different from 0. The control group shows no such association between numbers and space. However, the control participants, but not DG, do show a classic SNARC effect, in which small numbers are responded to faster on the left side of space and large on the right side of space, as indicated by the negative regression slope for the control participants.

magnitude task. The slope for the one control who showed a reversed SNARC effect was also significant [C5 $t(6) = 2.54$, $p < .05$]. For DG, the mean dRTs for small (−15.4 msec) and large (−2.7 msec) were not significantly different [$t(6) = 1.08$, $p = .16$], further confirming the absence of a SNARC effect for him in the horizontal condition.

4.6.5. *Discussion for Experiments 5a and 5b*

In Experiment 5, as in Experiment 4, we did not find any significant effects of DG's synaesthetic number line on his behavioural performance, nor significant differences between DG and controls. However, DG's slope in the vertical task was in line with our hypotheses of an effect of DG's number form on his performance. On the other hand, the high variability observed in the control group placed DG within the range observed for control participants. Given that the experimental paradigm in Experiments 4 and 5 was identical, with the exception of the numerical task (parity *vs* comparison), the absence of an effect in Experiment 4 cannot be due to the use of a task which only implicitly taps numerical information. Rather, combined with the results of Experiment 5, we suggest that the fact that spatial information is only implicitly coded in these tasks is critical to eliciting synaesthetic interference.

5. General discussion and conclusions

In the current study, we report on a unique synaesthetic participant, DG, who reports spatial forms for 58 different sequences. Although the sheer number of spatial forms reported by DG is unique in the literature, we have here focused on an in-depth exploration of his spatial forms for numbers. Experiment 1 used the current ''gold-standard'' (Ward and Mattingley, 2006) method for demonstrating the reality of synaesthetic experiences, test-retest reliability, and as in previous studies, we ''stacked the deck'' against ourselves, by using a test-retest interval of 14 months for DG, compared against control participants who were tested over an interval of 14 days. Despite this substantial difference in the test-retest intervals, we found that DG was more consistent than control participants on several measures of consistency.

Having established DG's consistency, and by inference, the reality of his synaesthetic reports for numerical sequences, we then turned our attention to the main topic of this investigation, establishing what sources of numerical and spatial information are critical for eliciting synaesthetic interference. In Experiments 2 and 3, we found that DG's number-form elicited interference when the stimuli were vertically arranged, but not when they were arranged horizontally, consistent with the reported orientation of his spatial form, and contrary to effects obtained with non-synaesthetic participants. However, in Experiment 4, we failed to find any effects of his spatial form on DG's behavioural performance, although we did find significant numerical–spatial interactions in the horizontal orientation for controls, consistent with previous literature. In Experiment 5, although the traditional regression analysis was not significant, we did observe a significant step-like SNARC effect when we compare dRTs for small and large numbers, consistent with prior reports that magnitude judgements elicit a more step-like SNARC effect (Gevers et al., 2006b).

Taking all the experiments presented here into consideration, we can conclude that interference elicited by synaesthetic number forms – at least in DG's case – requires explicit representation of spatial information, and may require explicit access to numerical magnitude information in order to clearly emerge. As observed in previous experiments, when two numbers are presented on the screen (Experiment 2) or when two spatial locations are relevant for the task (Experiment 3) we observed that DG's performance was affected by the vertical nature of his representation for numbers from 1 to 9. On the other hand, a single centrally presented number seems to be insufficient to elicit DG's representation of his number line (Experiment 4), unless numerical magnitude was explicitly relevant to the task (Experiment 5). Contrary to the hypothesis that explicit access to numerical magnitude information is required to elicit synaesthetic number forms, we observed synaesthetic interference in a task that required only implicit processing of numerical magnitude information (Experiment 3), which is in conflict with previous findings (Piazza et al., 2006). While it is possible that both the idiosyncratic synaesthetic representation and the classical left-to-right representation co-exist in synaesthetes (Piazza et al., 2006), we did not find clear confirmation of this hypothesis, as we did not observe any significant effects in any of the horizontal tasks for DG, although he often fell within the range of variability observed for non-synaesthetic participants.

A secondary aim of this study was to test whether synaesthetic interference is specific to the orientation of the reported spatial form, or whether it also generalizes to the orthogonal orientation. While previous studies have demonstrated the reality of synaesthetic number forms by exploring the effect of presenting numbers either compatibly or incompatibly with the orientation of the reported number-form (Piazza et al., 2006; Sagiv et al., 2006), the current experiments tested whether presentation of stimuli or alignment of response hands orthogonal to the orientation of DG's spatial form would also activate DG's number-form and consequently affect his performance (see also Jarick et al., 2009a, this issue, 2009b, this issue). In Experiments 2, 3 and 5 we found interference when the stimuli and/or responses were vertically oriented, compatible with the orientation of DG's reported spatial forms, while we did not find any compatibility effects when the stimuli/responses were horizontally oriented, orthogonal to the orientation of DG's number-form. This is especially striking given that non-synaesthetic participants have previously demonstrated interference effects in these paradigms in a horizontal orientation (e.g., Fischer et al., 2003) and given that we find interference in the horizontal arrangement in Experiments 4 and 5 for non-synaesthetic participants, replicating previous research (Dehaene et al., 1993). By demonstrating that synaesthetic interference, like the SNARC effect, is modulated by whether the responses are oriented in line with or orthogonally to the elicited spatial representations, these studies help to establish further links between the study of sequence-form synaesthesia and other topics within numerical cognition.

Given the individual variability among synaesthetes (Hubbard et al., 2005a; Rouw and Scholte, 2007; Sagiv et al., 2006), it would be useful to extend these results to other synaesthetes, and to test how general our conclusions here are. In addition, running larger samples of synaesthetes would better permit us to establish which effects here might be unique to DG and which might be true of synaesthetes more generally (Hubbard and Ramachandran, 2005). To date, there has been only one similarly detailed, systematic study of a number of paradigms in number-form synaesthesia (Piazza et al., 2006) and this study also demonstrated that synaesthetic interference may appear with some behavioural paradigms, but not with all paradigms. Similarly, in a series of experiments analogous to our studies here, (Jarick et al., 2009a, this issue) tested two synaesthetes, L and B, both of whom had vertical number forms for the digits 1–9. They tested L on a SNARC paradigm and L and B using a cued-detection paradigm similar to the one employed in the current study. Contrary to our results with DG, Jarick et al. find synaesthetic interference in the SNARC experiment for their subject L. Similar to the current study they also find synaesthetic interference for both L and B in the vertical orientation, but not the horizontal orientation.

Recent studies (Smilek et al., 2007; Price and Mentzoni, 2008) have demonstrated similar patterns of interference in calendar–form synaesthesia. The fact that calendars, which are purely ordinal and do not contain any cardinal information, also elicit spatial interference is further evidence that ordinal information, rather than cardinal information, is critical for eliciting synaesthetic spatial forms. While the Smilek et al. (2007) study used a paradigm very similar to our Experiment 3, in which a centrally presented month cued either left- or right-sided targets, the Price and Mentzoni (2008) study conducted two experiments analogous to our Experiments 4 and 5. Unlike in our case, Price and Mentzoni found month-SNARC effects in their group of four synaesthetes, both in a task where order information was explicitly relevant (first half/second half of the year) and in a month analogue of the standard parity task (odd or even month). One possible difference between these experiments is that our instructions focused on response hand, while the Price and Mentzoni instructions may have focused on response button. Recent studies have demonstrated that the SNARC effect can be coded either in terms of space or in terms of hands, and instructions can modulate the strength of the association (Muller and Schwarz, 2007; Viarouge et al., in preparation) and it is possible that such instructional differences will play an additional role in modulating the presence or absence of such interference effects in synaesthetes, as they do in non-synaesthetes, despite the fact that such associations appear to be automatic once the stimulus-response mappings are set up. Future studies will be needed to explicitly explore the effects of such variables in the generation of synaesthetic interference.

In sum, we have here presented a detailed series of experiments using standard paradigms in numerical cognition which varied the task relevance of both numerical information (explicit: Experiments 2 and 5, implicit: Experiments 3 and 4) and spatial information (explicit: Experiments 2 and 3, implicit: Experiments 4 and 5). We find that the explicit representation of spatial information is critical for eliciting number-form interference in our synaesthete, DG. In addition, we demonstrate that interference effects, when present, do not generalize to orthogonal dimensions, but rather are limited to the orientation of the synaesthetic number-form, as would be predicted by the response discrimination theory of the SNARC effect (Gevers et al., 2006a) further strengthening the links between the study of synaesthesia and numerical cognition (Cohen Kadosh and Henik, 2007; Eagleman, 2009, this issue; Hubbard et al., 2005b). Finally, we note that ordinal information is most likely to be critical for eliciting such interference effects, and that instructional set may play an additional role in these effects. Future studies will need to take into consideration these variables, as they may systematically affect the pattern of results obtained in studies of synaesthesia.

Acknowledgements

This research was supported by the Institut National de la Santé et de la Recherche Médicale (S.D.), a James S. McDonnell Centennial Fellowship (S.D.), and a Marie-Curie Numeracy and Brain Development (NUMBRA) postdoctoral fellowship (E.M.H.). We thank DG for his continued participation in these experiments, the control participants for their helpfulness and interest, and Lisa E. Williams for helpful comments.

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