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The ups and downs (and lefts and rights) of synaesthetic number forms: Validation from spatial cueing and SNARC-type tasks

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ABSTRACT

Typically, numbers are spatially represented using a mental 'number line' running from left to right. Individuals with number-form synaesthesia experience numbers as occupying specific spatial coordinates that are much more complex than a typical number line. Two synaesthetes (L and B) describe experiencing the numbers 1 through 10 running vertically from bottom to top, 10–20 horizontally from left to right, 21–40 from right to left, etc. We investigated whether their number forms could bias their spatial attention using a cueing paradigm and a SNARC-type task. In both experiments, the synaesthetes' responses confirmed their synaesthetic number forms. When making odd–even judgments for the numbers 1, 2, 8, and 9, they showed SNARC-compatibility effects for up–down movements (aligned with their number form), but not left–right (misaligned) movements. We conceptually replicated these biases using a spatial cueing paradigm. Both synaesthetes showed significantly faster response times to detect targets on the bottom of the display if preceded by a low number (1, 2), and the top of the display if preceded by a high number (8, 9), whereas they showed no cueing effects when targets appeared on the left or right (misaligned with their number forms). They were however reliably faster to detect left targets following the presentation of numbers 10 and 11, and right targets following numbers 19 and 20 (since 10–20 runs from left to right). In sum, cueing and SNARC tasks can be used to empirically verify synaesthetic number forms, and show that numbers can direct spatial attention to these idiosyncratic locations.

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1. Introduction

There is growing evidence suggesting that we represent numbers spatially in the form of a 'mental number line' with low numbers (1, 2) mentally represented on our left and high numbers (8, 9) on our right (Restle, 1970). Numbers have been shown to direct spatial attention to locations along this mental number line (Dehaene et al., 1993; Fischer et al., 2003; Sililllas et al., 2008), and the spatial representation of numbers can influence behaviours, such as counting and arithmetic calculations (Seron et al., 1992; Ward et al., 2009, this issue). Dehaene et al. (1993) demonstrated the link between the mental number line and behaviour using a parity judgment task. In this task, participants indicated their odd/even response by pressing a left button when the centrally presented digit was 'odd' and a right button when the digit was 'even'. Participants were faster when the response button was compatible with the location of the digit along the mental number line. For instance, participants were faster to make left-handed responses for small numbers versus large numbers (i.e., faster to identify the digit 1 as 'odd' via a left-hand response, than they were to identify the digit 9). Dehaene et al. (1993) labeled this phenomenon the Spatial Numerical Association of Response Codes (SNARC) effect, and it has been used repeatedly to demonstrate the robustness of the mental number line and its influence on behaviour (e.g., Daar and Pratt, 2008; Müller and Schwartz, 2007; Notebaert et al., 2006; Schwartz and Keus, 2004; Ito and Hatta, 2004; Shaki and Fischer, 2008; Wood et al., 1993).

Furthermore, cueing paradigms have demonstrated numerical effects on spatial attention. Fischer et al. (2003) showed that attention could be automatically directed to the left or right visual field by simply presenting a high or low digit on a computer screen. In their paradigm, the digits 1, 2, 8, or 9 were centrally presented and followed by a target (circle) to the left or right of fixation. Participants were asked to detect the presence of the target as quickly and accurately as possible by pressing a central button on the keyboard. Fischer et al. found that targets on the left side of the display were detected faster when preceded by a low number (1, 2), and right targets were detected faster when preceded by a high number (8, 9). They surmised that the presentation of the digit cues elicited shifts in spatial attention to the locations of the digits on the mental number line. Notably, this cueing of attention occurred even though the digits were not statistically predictive of the target locations. Recent electrophysiological evidence provides support for Fischer et al.'s findings and demonstrated that similar brain mechanisms are recruited during shifts of attention produced by irrelevant numerical cues compared to informative arrow cues (Ranzini et al., 2009).

For most people, the act of thinking about a given number does not consciously trigger an awareness of that number's spatial location on the number line. Indeed Tang et al. (2008) characterize the typical left to right number line as an "unconscious, number-space relationship" (p. 1). However, for approximately 10–12% of individuals (Sagiv et al., 2006; Seron et al., 1992; Tang et al., 2008), numbers do elicit a conscious awareness of a spatial location. These people experience very vivid 'number forms' that are much more complex than the typical number line (Galton, 1880, 1881; Price and Mentzoni, 2008; Seron et al., 1992; Tang et al., 2008).

Most researchers have considered these atypically strong number–space associations (*number forms*) a variant of synaesthesia (Hubbard et al., 2005; Piazza et al., 2006; Sagiv et al., 2006; Tang et al., 2008). Synaesthesia is a fascinating phenomenon whereby an ordinary stimulus (e.g., digit 5) elicits an extraordinary experience (e.g., the colour blue). For individuals with *number-form synaesthesia*, the extraordinary experience involves a conscious awareness of a specific location in space triggered by the number. These synaesthetic number forms can appear as rows, scales, or grids (Seron et al., 1992), spirals or oblongs (Galton, 1880), or even as infinite tunnels. Although the spatial organization of the numbers might vary considerably from one synaesthete to the next, their number forms seem to have important commonalities. First, the number–space relations tend to be very *consistent* within individuals (Seron et al., 1992); if on one occasion a number-form synaesthete draws a depiction of their number form, they will draw the same atypical number form on each subsequent occasion. Second, individuals who have vivid number forms indicate that they have had them since infancy (Seron et al., 1992) and cannot recall a time when they did not experience them. Finally, the synaesthetic number forms seem to be *involuntarily* and *automatically* activated (Seron et al., 1992). That is, whenever a number is seen, heard, or thought of, the synaesthete cannot (through an act of will) prevent themselves from also experiencing the associated spatial location (Sagiv et al., 2006; Seron et al., 1992). Studies exploring these characteristics of number-form synaesthesia are just beginning to emerge.

Tang et al. (2008) used functional magnetic resonance imaging (fMRI) to investigate the brain areas underlying the number forms of synaesthetes versus the brain areas supporting the more ubiquitous left-to-right number lines. They selected synaesthetes whose number forms ran from left to right, and compared them to controls who presumably have the standard, left to right number line. Their results showed comparable brain regions involved when the task concerned processing numerical magnitude (e.g., number of items in the display). However, when the task required ordinal processing of the numbers (e.g., whether the number *N* was in the *nth* position), greater activation was found bilaterally in synaesthetes in the intraparietal sulci. These findings suggest that the number forms experienced by synaesthetes are a spatial representation of the sequential (as opposed to magnitude) aspects of numbers (Sagiv et al., 2006; also see Walsh, 2003 for a theory on magnitude processing).

This sequential interpretation of this form of synaesthesia may extend to other forms of synaesthesia as well. For instance, Smilek et al. (2007) have shown that for individuals with time–space synaesthesia, sequences such as time units (e.g., months of the year) are also assigned highly specific spatial locations. In a target detection task, Smilek et al. showed that month names could cue spatial attention to the left or right depending on the synaesthetic spatial location of the presented month. Similarly, Price and Mentzoni (2008) showed a month-SNARC effect for time–space synaesthesia. They highlighted how the idiosyncratic organization of month locations nevertheless had systematic SNARC effects. For two of their synaesthetes, early months were located on the left side of space and later months on the right side, whereas the other two synaesthetes experienced later months on the left and early months on the right. All four synaesthetes were asked to judge whether the presented month was in the first or second half of the year and make a left or rightward response to indicate their choice. The authors found a left-hand advantage for early months for synaesthetes whose early months were synaesthetically on the left, but a right hand advantage for those whose early months were synaesthetically on the right. Importantly, they did not find any hint of any month-SNARC effects in non-synaesthetes (but see, Gevers et al., 2003). Price and Mentzoni's results suggest that (at least for synaesthetes) SNARC-type tasks can be used to uncover not only interactions between numbers and space, but also a more general relationship between ordinal sequences (including time units like months of the year) and space.

The majority of investigations into the spatial properties associated with number sequences have focused primarily on representations that extend exclusively from left to right (with the exception of Piazza et al., 2006 and Sagiv et al., 2006). Our objective was to examine number-form synaesthetes who experience *unusual* mental number lines that do not run from left to right. In these experiments, we investigated two number-form synaesthetes (L and B) who report experiencing atypical number lines, such that the numbers 1 through 10 run vertically from bottom to top, and the numbers 10–20 extend horizontally from left to right (see Fig. 1 for a ''birds eye'' view of L's representation).

We first sought to empirically evaluate the synaesthete's atypical number forms using a SNARC-type task. If the SNARC effect is determined by the association between response codes and the spatial representation of numbers, then SNARC effects should result that correspond to L and B's idiosyncratically structured number line. That is, we should find larger SNARC effects when the synaesthetes make vertical (up and down) responses than when they make horizontal (left and right) responses because their numbers rise vertically from 1 to 9. Non-synaesthetes however, should produce the opposite pattern of results and show larger SNARC effects for

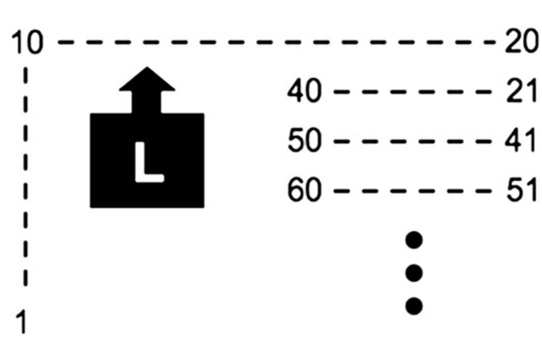

Fig. 1 – Example of the idiosyncratic number forms experienced by a Number-Form Synaesthete (L). Her numbers from 1 to 10 run bottom to top in the vertical dimension, while her numbers 10–20 run from left to right in the horizontal dimension.

horizontal than vertical responses consistent with their standard left-to-right mental number lines. Although for non-synaesthetes, some vertical SNARC effects may be present (Gevers et al., 2006; Schwarz and Keus, 2004) albeit to a smaller extent. The key here is that non-synaesthetes should show a *larger* SNARC effect for left–right movements than up–down movements, whereas synaesthetes should show the opposite pattern because of the vertical alignment of their atypical number forms.

Secondly, we aimed to further verify L and B's unusual number forms using the spatial cueing paradigm of Fischer et al. (2003). According to Fischer et al., low numbers directed attention to the left, and higher numbers directed attention to the right in accordance with the left–right alignment of the standard mental number line. Importantly, for the synaesthetes L and B, the left and right target locations in the Fischer task are *misaligned* with their synaesthetic number lines. Thus, if cued with the digits 1, 2, 8, and 9 preceding left or right targets, we expect no cueing effects to be observed. Yet, if the targets were presented on the top and bottom of the display, now *aligned* with L and B's number forms, we expect to find strong cueing effects (e.g., low numbers would facilitate detecting targets below fixation). Furthermore, we expect to find strong cueing effects with left–right targets when the numbers 10, 11, 19 and 20 are presented as cues, since recall that for both L and B the digits 10–20 run horizontally from left to right. Also note that while L took part in both the SNARC and Fischer cueing tasks, B could only participate in the cueing task (Experiments 2 and 3) due to injury that interfered with her making the repetitive movements required during the SNARC task.

2. Experiment 1

For the SNARC-type task, our predictions are straightforward: non-synaesthetes should show larger SNARC effects for left/right responses, whereas the synaesthetes, because of their vertical number form, should show the opposite pattern, larger SNARC effects for up/down responses.

2.1. *Methods*

2.1.1. *Participants*

One healthy 21-year-old female number-form synaesthete (L) and 14 age-matched non-synaesthetic controls (four males, $M = 23.4$ years old) volunteered to participate in this study for an honorarium. When L and B initially reported their vivid number–space associations, they were asked to illustrate their number form on paper (May 2007) and asked a year and ten months later (March 2009) to illustrate them again. Both synaesthetes provided very precise and highly consistent drawings, each accurately resembling their verbal reports of their unusual number lines. Controls on the other hand, reported no unusual number–space associations. All participants had normal or corrected to normal vision, were right-handed, and reported no reading or language difficulties. The University of Waterloo Office of Research Ethics approved all procedures and participants gave written consent before participating.

2.1.2. Stimuli and design

Stimuli were presented on a 17 '' monitor controlled by a G4 Macintosh computer. SuperLab 4.0 Experiment programming software was used to display the stimuli and collect the response times for each participant. All responses were made on a response pad (Cedrus RB 530), which had four rectangular buttons located on the left, right, top, and bottom of a circular button in the center. Stimuli were the Arabic numerals 1, 2, 8, or 9 (Geneva font, 72 pt.) presented in the center of the screen. Each trial began with a fixation cross whose arms subtended a visual angle of .6°.

We conducted the different response-mapping conditions in two sessions: a horizontal session (left ''odd'' and right ''even'') and a vertical session (up ''odd'' and down ''even''). All participants were given the same response options as L to better enable us to compare the non-synaesthetes to the synaesthete (L). Participants completed the horizontal session first and the vertical session second. Each session contained two blocks of 160 randomized trials (separated by a self-paced break), and began with 20 practice trials to acquaint the participants with the task. In each block the four numbers were presented 40 times each. Since 1 and 8 led to compatible responses, and 2 and 9 led to incompatible responses, there were 80 compatible trials per block and 80 incompatible trials per block.

2.1.3. Procedure

Participants were seated unrestrained in front of a computer monitor at a distance of 57 cm. Participants were instructed that each trial would begin with a fixation cross in the center of the screen and that they were to press the center key on the keypad to initiate the trial. Once the trial was initiated, a centrally presented number cue (1, 2, 8, or 9) appeared until a response was made or 3000 msec had elapsed. They were to indicate whether the number was ''odd'' by pressing the left button or ''even'' by pressing the right button (horizontal condition). For the vertical condition, participants were told to press the top button to indicate ''odd'', and the bottom button for ''even''. It was stressed that these responses were to be made as quickly and accurately as possible, as their response times were being recorded.

2.2. Results and discussion

Correct responses for L and the controls were submitted to an outlier analysis in which observations ±3 standard deviations were discarded. This resulted in .61% of trials discarded for L and an average of 3.86% of trials for the non-synaesthetic controls. The remaining response times of L and the 14 controls were analyzed separately using 2-factor analyses of variance (ANOVA), with Response Dimension (horizontal or vertical), and Compatibility (SNARC compatible *vs* incompatible) as factors. For the horizontal dimension, we classified 1-left, and 8-right as SNARC compatible, and 2-right and 9-left as SNARC incompatible responses. For the vertical dimension, we classified 1-down, and 8-up as SNARC compatible, and 2-up and 9-down were SNARC incompatible responses (Gevers et al., 2006). As well, we performed an error analysis to see if the synaesthetes' unusual number forms influenced their propensity to make errors on this task and to ensure that any obtained response time effects were not attributable to speed accuracy tradeoffs.

Fig. 2A illustrates the mean response times for L in the horizontal and vertical response conditions (error bars represent the 95% confidence intervals). Our critical prediction was that L would show a substantial SNARC effect in the vertical dimension (aligned with her synaesthetic number forms), but a smaller (or absent) SNARC effect in the horizontal dimension (misaligned with her number forms). Supporting our prediction, L showed a significant 2-way interaction between response dimension and compatibility, $F(1, 614) = 8.74$, $p = .003$. When she was asked to make horizontal (left-right) responses her response times were similar for compatible ($M = 626$ msec) and incompatible ($M = 634$ msec) responses, $t(313) = -.81$, *n.s.* By contrast when she was asked to make vertical (up-down) responses, she was significantly faster in making compatible ($M = 628$ msec) than incompatible responses ($M = 683$ msec), $t(301) = -4.22$, $p < .001$. These findings clearly show that the SNARC effect obtained with L was consistent with her unusual number forms running from bottom to top in the vertical plane.

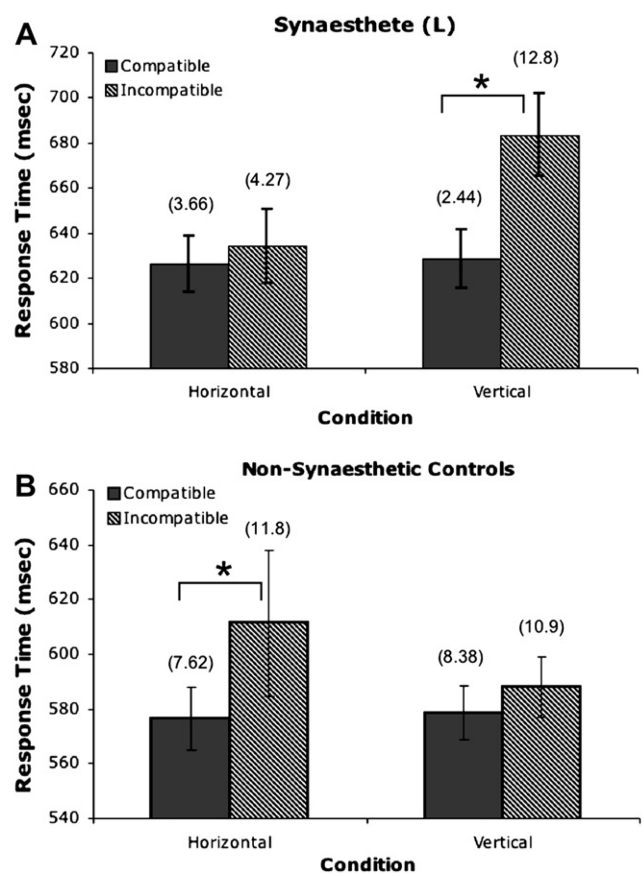

Fig. 2 – Mean response times for the synaesthete L and non-synaesthetic controls pertaining to the SNARC task in Experiment 1. The horizontal response condition (left–right button presses) was *misaligned* with L's number forms, while the vertical response condition (up-down button presses) was *aligned*. Error bars represent the 95% confidence intervals and the bracketed values are the percentage of errors made in each condition.

In terms of errors, L showed no effect of compatibility for horizontal responses. She made 6 errors on compatible trials and 7 errors on incompatible trials, $\chi^2 = .08$, $p > .05$. However, L showed strong compatibility effects for vertical responses. She made 4 errors on compatible trials, but 21 errors on incompatible trials, $\chi^2 = 12.51$, $p < .001$ (see bracketed values in Fig. 2A). L's errors provide converging evidence for compatibility effects for vertical responses in this parity judgment task – L was slower to respond *and* made more errors on incompatible trials for vertical responses.

Fig. 2B illustrates the average response times for the non-synaesthetic controls, with error bars reflecting the 95% confidence intervals. As expected, controls showed a significant 2-way interaction, $F(1, 13) = 13.02$, $p = .003$. Unlike L, non-synaesthetes on average made significantly faster responses to SNARC compatible than incompatible trials in the *horizontal* dimension, $t(13) = -5.7$, $p < .0001$. Their compatible and incompatible responses in the vertical dimension were not significantly different from one another, $t(13) = -1.78$, *n.s.* In terms of errors, non-synaesthetes showed no significant differences between compatible and incompatible trials for the vertical condition, $t(13) = -1.99$, *n.s.*, but made significantly more errors when making incompatible versus compatible responses in the horizontal condition, $t(13) = -2.87$, $p < .01$ (see bracketed values in Fig. 2B). Thus, the error data provide converging evidence for SNARC-compatibility effects for horizontal movements.

To directly compare L's SNARC effects to those of the control sample we used Crawford and Garthwaite's (2005) Revised Standardized Difference Test (RSDT). This test assessed whether the difference between L's response times on compatible and incompatible trials was significantly larger than comparable differences obtained in our sample of non-synaesthetic controls. We assessed these differences for both horizontal and vertical dimensions. For horizontal movements, her response times on compatible and incompatible trials are comparable to those of the controls [RSDT $t(13) = .93$, *n.s.*]. However for vertical movements, she showed significantly larger differences between compatible and incompatible response times (SNARC effects) than controls [RSDT $t(13) = 1.87$, $p < .05$, *one-tailed*].

In sum, we found SNARC effects for both L and non-synaesthetes that were in accordance with the manner in which they spatially represent numbers. L showed a larger SNARC effect when making responses in the vertical dimension (up/down), whereas non-synaesthetes demonstrated larger SNARC effects when making responses in the horizontal dimension (left/right). While the SNARC effect results are a positive first step, it is crucial for case studies to provide converging evidence for behavioural effects using different tasks. Thus, we sought an alternative task that would allow us to test both L and B, and to provide converging empirical evidence for these unusual number forms.

3. Experiment 2

In Experiment 2, we used the Fischer cueing task to provide converging evidence for L and B's unusual number forms. As with the SNARC task, we ran versions of the Fischer task that were either aligned or misaligned with L and B's number forms. The digits 1, 2, 8, or 9 were presented at fixation, followed by target circles that appeared in boxes either to the left or the right of the display (misaligned with the synaesthetes' vertically rising number forms) or above and below fixation (aligned with the synaesthetes' number forms). We predicted that both L and B would show cueing effects in the aligned (vertical) condition but fail to show any cueing effects for the misaligned (horizontal) condition. Since the task involved a single "target detected" response that was far less strenuous than the upward and downward movements of the SNARC task, both L and B were able to participate.

3.1. Methods

3.1.1. Participants

L who participated in Experiment 1 and B a second number-form synaesthete volunteered in this study. B is a healthy 61-year-old female with a very similar number form as L. Twelve of the fourteen non-synaesthetes (three males; $M = 24$ years old) that served as a control group in Experiment 1 participated in Experiment 2. They were compensated with an honorarium. The University of Waterloo Office of Research Ethics approved all procedures and participants gave written consent before participating.

3.1.2. Stimuli and design

Stimuli were presented on a 17″ monitor. Experimental software (SuperLab 4.0) was used to display the stimuli and collect the responses. Digit cues were the four Arabic numerals 1, 2, 8, or 9 (Arial font, subtending approximately 2° of visual angle at a distance of 57 cm) presented in the center of the screen. All stimuli were displayed in white against a black background. Each trial began with a fixation dot (~.1°) flanked by two boxes (~1° in length and width). In the horizontal (misaligned) condition, these boxes were positioned 5° to the left and right. In the vertical ('aligned') condition, these boxes were positioned 5° above and below fixation. A white circle (~.7°) appeared inside one of the boxes that served as the target stimulus.

3.1.3. Procedure

Participants were seated unrestrained in front of a computer monitor. The horizontal condition was run first. Participants were instructed that each trial would begin with a fixation dot in the center of the screen followed by a digit (1, 2, 8, or 9) for 300 msec. After one of six variable delays (ISI's of 50, 100, 200, 300, 400 or 500 msec) following the offset of the digit, a target (white circle) would appear in one of the boxes until the participant responded or 1000 msec elapsed. In the horizontal condition, on half of the trials the target circle appeared to the left and the other half the target appeared to the right of fixation. Thus, the digit cues were non-predictive of the target location. In the vertical condition the target circle appeared half the time above and half the time below fixation. For both the horizontal and vertical conditions, on 20% of the trials no target was presented and participants were asked to withhold their response. These 'catch' trials were to ensure that participants were attending to the task and performing accurately. There were 16 blocks per condition, (each with 48 target trials and 9 catch trials per block). Trials were randomly presented, amounting to 912 trials per condition in total. Participants completed five practice trials at the beginning of each condition to acquaint them with the task. There were scheduled breaks every two blocks. Following completion of the horizontal condition, and a break, the vertical condition was completed.

3.2. *Results and discussion*

L and B both performed perfectly (100% correct) on ‘catch’ trials. All control participants performed above 80% on catch trials. Correct response times were trimmed for outliers using a ± 3 standard deviation cut-off. This resulted in .58% of trials being discarded for L, 1.94% discarded for B, and an average of 4.38% for controls. Separate 3-factor ANOVAs involving Dimension (vertical *vs* horizontal), Validity (valid or invalid), and cue-target ISI (50, 100, 200, 300, 400, or 500 msec) were conducted for each synaesthete and for the twelve controls (we conducted a group analysis, and individual analyses for each of the controls separately). For all ANOVAs validity in the horizontal condition refers to the typical mental number line, where low digits are on the left and high digits are on the right. For example, a target presented on the left following a low digit would be considered a valid trial. Validity in the vertical condition is in accordance with L and B’s unusual number lines running from bottom (low digits) to top (high digits). Thus, a target on the bottom following a low number would be considered a valid trial.

Mean response times are illustrated in Fig. 3 for both horizontal (panel A) and vertical (panel B) conditions. For both synaesthetes the ANOVAs revealed a significant main effect of cue–target ISI with faster responses associated with longer delays. This effect is representative of the Variable Foreperiod effect (Vallesi et al., 2007), where response times decrease with the increase in time between cue and target presentation. Critically, for both L and B there were no interactions between delay and any of the other variables, meaning that when cueing effects were observed they were evident even at the shortest delay of 50 msec (i.e., cue–target onset interval of 350 msec). As predicted, both synaesthetes had significant 2-way interactions between Dimension and Validity indicating that the cueing effects were different for the horizontal and vertical conditions, $F(1, 1504) = 127.31$, $p < .0001$ for L and $F(1, 1483) = 18.10$, $p < .0001$ for B. For the digits 1, 2, 8, 9 and *horizontal* targets (misaligned with their number forms), L and B did not show any cueing effects for valid compared to invalid targets (see Fig. 1). For these same digits and *vertical* targets (aligned with their number forms), both L and B showed significantly faster response times for valid trials than invalid trials, $t(760) = -16.85$, $p < .001$ for L and $t(749) = -7.02$, $p < .001$ for B. These findings are in accord with L and B’s subjective reports of experiencing an unusual number line running from bottom to top for the digits 1–10.

Fig. 3 shows the mean response times of controls, with error bars reflecting the 95% confidence intervals. The three-way ANOVA conducted on the group of 12 non-synaesthetes revealed only a main effect of ISI (the variable foreperiod effect), $F(5, 24) = 67.39$, $p < .001$, and a main effect of dimension, $F(1, 24) = 10.4$, $p < .01$, caused by faster responses to horizontal as opposed to vertical cues. Unlike the two synaesthetes, no validity $\times$ dimension interaction was observed. We repeated this 3-way ANOVA for all 12 non-synaesthetes. Not one non-synaesthete showed this 2-way interaction (F-values ranged from .001 to 3.03, all p-values $>.05$). As can be seen in Fig. 3, response times on average did not differ across valid and invalid trials when targets were presented in either the horizontal or vertical dimension.

To directly compare L and B’s cueing effect sizes to those of the control sample we again used Crawford and Garthwaite’s (2005) RSDT. When targets were placed horizontally, the difference between L’s valid and invalid trials did not differ from these differences in the control sample [RSDT $t(11) = .25$].

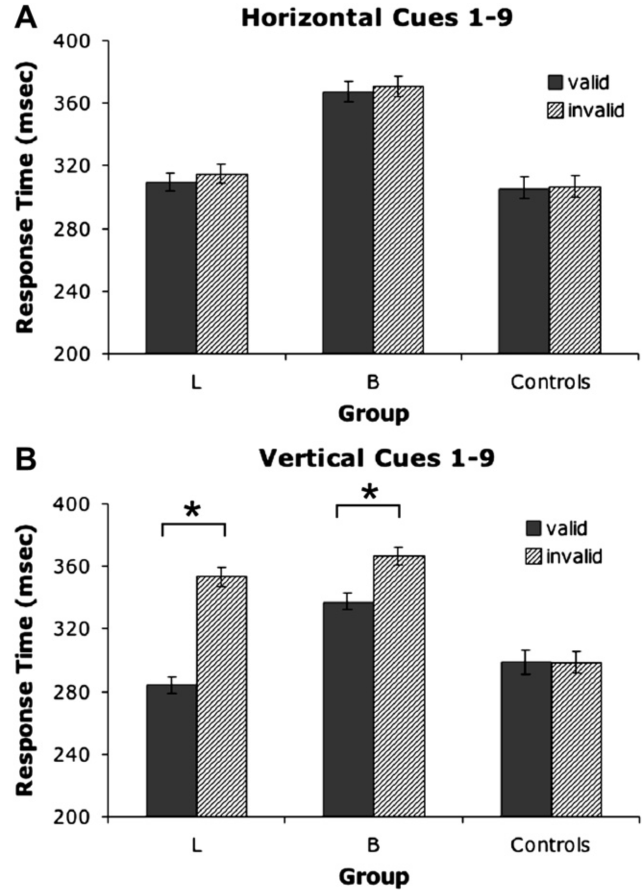

Fig. 3 – Mean response times for the synaesthetes (L and B) and non-synaesthetic controls during the horizontal condition (panel A) and vertical condition (panel B) of the Fischer cueing task in Experiment 2. The number cues were the low digits (1, 2) and the high digits (8, 9). Targets appeared to the left or right of fixation for the horizontal condition and validity referred to the target locations in relation to the numbers 1–9 along the ‘mental number line’. Targets appeared above and below fixation for the vertical condition for which validity was in reference to the synaesthetes number forms. Targets that appeared in the synaesthetically “correct” locations were considered valid trials and “incorrect” locations were invalid trials. Error bars represent the 95% confidence intervals.

Non-significant differences were also found for B [RSDT $t(11) = .26$ for B, *n.s.*]. However, when the targets were placed vertically, L showed significantly larger differences between valid and invalid response times (i.e., larger cueing effects) than controls [RSDT $t(11) = 3.10$, $p < .01$, *one-tailed*]. B also demonstrated larger cueing effects than controls with her response differences approaching significance [RSDT $t(11) = 1.44$, $p = .08$, *one-tailed*].

Taken altogether we found strong synaesthetic cueing effects consistent with the number forms of both L and B that differed significantly from a group of twelve non-synaesthetic controls. In contrast to our expectations we did not replicate the cueing effects observed by Fischer et al. (2003) for non-synaesthetes with horizontal targets. Such cueing effects should have led to main effects of validity and/or validity by dimension interactions. Recent research by Ristic et al. (2006) and Galfano et al. (2006) highlight how context and task-dependent number cueing effects are. In our experiments, participants might have easily ignored the digit cues since they were not predictive of target location, and were irrelevant for performing well on the task. It should be noted that we employed far more trials at each ISI than Fisher et al. – hence our results cannot be considered an exact replication. However, we extend the findings of Fischer et al. (2003) by showing that the atypical number forms present in number-form synaesthesia can induce shifts in spatial attention to the *synaesthetic* locations occupied by the digits. Here, although both L and B failed to exhibit cueing effects when the Fischer task was misaligned with their number forms, they demonstrated strong cueing effects when the task was aligned with their number forms. These findings also provide a conceptual replication of the SNARC effect findings in Experiment 1.

4. Experiment 3

The Fischer task provided converging evidence for the SNARC effects shown in Experiment 1. Only when the targets were aligned with the synaesthetes' number forms, were strong cueing effects observed. The Fischer task has an advantage over the SNARC task in that two digit numbers can be used in the Fischer task, while it is impossible to demonstrate SNARC effects for two digit numbers in a parity task (participants simply ignore the leftmost digit). This allowed us to empirically validate the next segment of L and B's number forms, namely the digits 10–20 which run from left to right (see Fig. 1). In Experiment 3, we modified the Fischer task to include the numbers 10, 11, 19, 20, with targets to the left and right aligned with their number forms. Since the numbers 10–20 run from left to right, we predicted that lower numbers (10, 11) would cue attention to the left and the higher numbers (19 and 20) would cue attention to the right. In short, the horizontal cueing effects which were absent in the synaesthetes for the numbers 1, 2, 8 and 9, should now be present for the numbers 10, 11, 19, and 20 based on the alignment of the targets with the synaesthetes' number forms. Once again, we compared the synaesthetes' performance to a group of non-synaesthetic controls.

4.1. Methods

4.1.1. Participants

The same number-form synaesthetes (L and B) and twelve non-synaesthetic controls (five took part in Experiments 1 and 2; 7 males; $M = 22.2$ years old) participated for an honorarium.

4.1.2. Stimuli and design

The design was similar to Experiment 2, but the stimuli were the four Arabic numerals 10, 11, 19, and 20 and targets only appeared horizontally to the left and right. We did not run a vertical condition (where we would expect null effects for the synaesthetes).

4.1.3. Procedure

The procedure was identical to Experiment 2.

4.2. Results and discussion

L again performed perfectly (100% correct) on 'catch' trials and B only had one error (99.4% correct). Controls performed above 80% on 'catch' trials. Response times were submitted to an outlier analysis in which observations ± 3 standard deviations were removed. This resulted in .88% of trials being discarded for L, 2.63% discarded for B, and an average of 4.97% discarded for controls. The remaining response times were analyzed using 2-factor ANOVAs, involving Validity (valid or invalid), and cue–target ISI (50, 100, 200, 300, 400, or 500 msec). Mean response times are illustrated in Fig. 4. The error bars represent the 95% confidence intervals.

For both synaesthetes and controls, the ANOVA revealed a significant main effect of delay, but delay did not interact with any other variables. For both synaesthetes, the ANOVA also revealed a significant main effect of validity, $F(1, 12) = 1919.83$, $p < .001$ for L and $F(1, 12) = 126.42$, $p < .001$ for B. Thus, both synaesthetes were much faster to detect valid targets than invalid targets. Again, we used Crawford and Garthwaite's

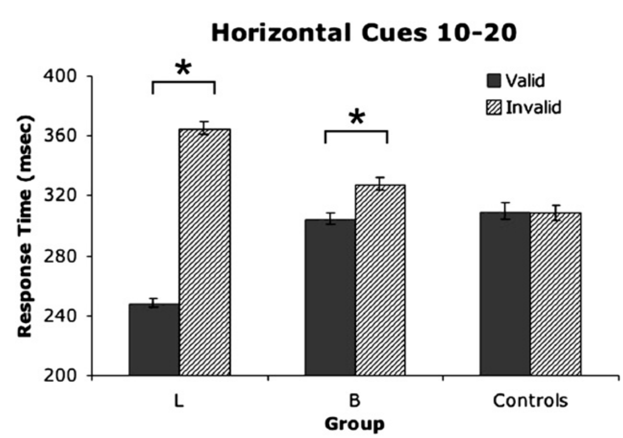

Fig. 4 – Mean response times for the synaesthetes (L and B) and non-synaesthetic controls during the Fischer cueing task in Experiment 3. The number cues were the low digits (10, 11) and the high digits (19, 20). Targets appeared to the left or right of fixation aligned with the synaesthetes number forms and validity was in reference to this. Error bars represent the 95% confidence intervals.

(2005) RSDT to directly compare L and B's cueing effect sizes to those of the control sample. L showed significantly larger differences between valid and invalid response times (cueing effects) than controls [RSDT $t(11) = 4.75$, $p < .001$, *one-tailed*]. Unfortunately B did not demonstrate significantly larger cueing effects than controls using this procedure [RSDT $t(11) = 1.04$, *n.s.*]. Once again, our results provide empirical support for the synaesthetes' contention that the segment of their number forms containing the numbers 10–20 run from left to right. Thus, our findings extend the results of Experiment 2 by objectively verifying L and B's spatial organization of the numbers 10–20. Here we demonstrated that the digits 10 and 11 could bias the synaesthetes' spatial attention to the left side of space and the digits 19 and 20 to the right side of space, further confirming this segment of their synaesthetic number forms.

5. General discussion

This series of experiments provides empirical confirmation of synaesthetic number forms using two types of tasks: the SNARC task (Dehaene et al., 1993) and a spatial cueing task (Fischer et al., 2003). The SNARC effect has been used widely to show the automatic response activation of implicit spatial representations of sequences in synaesthetes (Price and Mentzoni, 2008) and non-synaesthetes (e.g., Dehaene et al., 1993; Gevers et al., 2003; Gevers et al., 2006). While the 'mental number line' may be implicitly associated with spatial codes for non-synaesthetes, our findings support the notion that synaesthetes experience very explicit number forms that are much more elaborate than the standard left-to-right number line. Two number-form synaesthetes (L and B) reported unusual number–space associations that extended vertically for the numbers 1–10 and then horizontally for the numbers 10–20 (Fig. 1). In our first experiment using a variation of the SNARC task, our findings confirmed these differences between non-synaesthetes and synaesthetes (Fig. 2).

5.1. *The SNARC effect with non-synaesthetes*

In this study, the non-synaesthetes showed significant SNARC effects when movements were made in the horizontal, but not the vertical dimension. These findings for left–right responses are consistent with the classical SNARC effect demonstrated by Dehaene et al. (1993), showing automatic response activation aligned with an implicit spatial representation of the 'mental number line' from left to right. We failed to replicate the findings of others, who showed small SNARC effects in the vertical dimension (Gevers et al., 2006; Ito and Hatta, 2004; Santens and Gevers, 2008; Schwartz and Keus, 2004). Schwartz and Keus (2004) for example showed that saccades were more quickly initiated downward following lower numbers and upwards following high numbers. Using a unimanual response like the present study, Santens and Gevers (2008) observed a SNARC effect in the vertical dimension with responses that they classified as *close* and *far*. They revealed that *close* responses were facilitated by low numbers and *far* responses by high numbers. According to these studies, it appears as though the SNARC effect is not solely triggered by a left to right number line, but can also be triggered by how non-synaesthetes implicitly represent numbers in up and down (and near and far) space. It should be noted that although there is a general consistency for non-synaesthetes to list low numbers on the left and high numbers on the right, the mappings of numbers in the vertical plane is far less uniform. If one thinks of volume or temperature, low amounts are on the bottom, and high amounts are on the top. If one thinks of lists or spreadsheets, the low numbers are on the top and the high numbers are on the bottom. Similarly, in written text, (think galley proofs!) the first sentence on a page is at the top, the fifth sentence is lower down etc. The point here is that there is an inherent variability in our experiences when it comes to mapping numbers to up and down, whereas there is a remarkable consistency in the manner in which non-synaesthetes map low numbers to the left and higher numbers to the right. As such, it may not be surprising that we showed strong SNARC effects in the horizontal dimension but not in the vertical dimension. It may well be the case that showing a vertical SNARC effect may depend on how a particular individual aligns his or her numbers in the vertical dimension.

5.2. *The SNARC effect in number-form synaesthetes*

Whereas non-synaesthetes may have relatively vague intimations of how they align numbers in space, for those with number-form synaesthesia these mappings are extremely vivid. For the synaesthete L, SNARC effects were found only when the responses she had to make were directly aligned with the relevant segment of her synaesthetic number form. For the numbers 1, 2, 8 and 9 she displayed no hint of a SNARC effect when responses were misaligned with her number forms but did show dramatic SNARC effects when the responses were aligned with her number forms. These results conflict with the findings of Piazza et al. (2006) who failed to show atypical SNARC effects in their number form synaesthetes, but consistent with Hubbard et al. (2009, this issue), Sagiv et al. (2006), and Gertner et al. (2009). These differences may reflect individual variability in the strength of number forms, the strength of the SNARC effect in a given individual, or both. Piazza et al. suggest that this variability might be correlated with individual visuo-spatial abilities, providing a plausible explanation for the potential differences found across synaesthetes as well as controls. Although our positive findings fail to replicate the negative findings of Piazza, they do complement the findings of Price and Mentzoni (2008) who showed SNARC effects that were consistent with synaesthetes' spatial layout of calendar months (but also see Price, 2009, this issue for an extension). Together these results demonstrate that for both numbers and time units, the spatial arrangement of the synaesthetic forms will underlie the type of SNARC effect that emerges.

5.3. *Spatial cueing with numbers among non-synaesthetes*

Although we did not support the cueing effects found by Fischer et al. (2003) in our group of non-synaesthetes, our results may align with recent reports claiming that the cueing effects seen in non-synaesthetes is highly task-dependent and susceptible to cognitive strategies. For instance, Ristic et al. (2006) was able to completely reverse the left-to-right mental number line cueing effects found in Fischer et al. (2003) by simply instructing participants to imagine a number line extending from right to left. Furthermore, Ristic et al. asked participants to imagine the hours on a clock face and demonstrated cueing effects congruent with where the central locations of the numbers were positioned on the clock face. Similar findings have also been reported by Galfano et al. (2006) and Price (2009, this issue). These results highlight just how fragile these cueing effects are and how dependent they can be on the mental set of the individual. Our controls in the current study were not provided with any mental set for representing the digits and were advised that they were uninformative of target location. Thus, it may not be too surprising that we found null effects for our controls if they were just ignoring the digits and focusing on the targets. Casarotti et al. (2006) also found null effects to centrally presented digits and proposed that irrelevant numbers constitute a weak cue for triggering shifts of attention. Our results support this claim but only for non-synaesthetes. Yet, Hubbard et al. (2009, this issue) lends a similar claim towards synaesthetes, suggesting that strong interference from the digit cue might require explicit activation of a spatial representation and conscious access to numerical magnitude.

5.4. *Spatial cueing and numbers among synaesthetes*

Importantly, we replicated and extended our SNARC findings with the Fischer task, and were able to provide converging evidence for multiple segments of L and B's unusual number forms using spatial cueing (i.e., we validated that for both synaesthetes, 1–10 rose vertically and 10–20 ran from left to right). Even though L and B were both aware that the number cues were not predictive of target location, our findings show that they still oriented their attention to the synaesthetic location of the presented number in space. Taken together with the SNARC results, we would suggest that these atypical synaesthetic effects of numbers occur *prior* to any manual response selection.

The Fischer results in the present study provide converging evidence for similar cueing effects with months and hours using a similar spatial cueing paradigm (Jarick et al., 2009, this issue and Smilek et al., 2007). Taken together, these studies show that both numbers and time units can reliably cue the spatial attention of synaesthetes to locations within both number and calendar forms. Finally, these findings are consistent with Hubbard et al. (2009, this issue) who also demonstrated interference effects specific to DG's synaesthetic spatial-forms.

5.5. *Overall conclusions*

In sum, our findings clearly show that the extraordinary number forms experienced by synaesthetic individuals can be objectively verified using SNARC-type tasks and spatial cueing paradigms. These findings demonstrate that the number–space relationships experienced by synaesthetes can unintentionally influence their behaviour. Even though digit magnitude and spatial position presumably should have nothing to do with making a parity judgment (SNARC task), when determining whether a given number was odd or even L still responded faster when the movement she had to make corresponded the location of that number within her spatial form (e.g., down for 1, up for 8). The fact that their SNARC and spatial cueing effects were shown to directly reflect the unusual structure of their number forms, highlights the fact that for synaesthetes the mappings between numbers and space are not culturally learned. Despite growing up and being educated in a culture dominated by the standard left-to-right number line (Berch et al., 1999; Dehaene et al., 1993), these two synaesthetes are unswerving in their contention that the numbers 1–10 do not go from left to right but rise vertically. How these unusual forms develop is a question that is yet to be answered.

Also unanswered is the extent to which the number forms experienced by synaesthetes rely on the same neural mechanism(s) as the number–space relations observed in non-synaesthetes. In a review by Hubbard et al. (2005), the authors propose that synaesthetic individuals might be genetically predisposed to develop such spatial-forms through the random profusion of cortical pathways between brain areas responsible for numerical concepts and those that process spatial representations. It will be of interest to know just how random these processes are, and in turn, whether there is an inherent systematicity overlaid on top of the seemingly arbitrary mappings of numbers and space in number-form synaesthesia. In other words, is it simply a quirk of chance that we found two synaesthetes with number forms that rise vertically and "turn the corner" at 10. Similarly, the number form of SW (the number-form synaesthete reported by Piazza et al., 2006 who "turns the corner at 12"), is remarkably similar to the number form of a synaesthete first reported by Galton (1880, 1881). One might conjecture that although idiosyncratic number–form pairings characterize synaesthetes, there may be certain commonalities across synaesthetes (as in the pairings between numbers and colours in grapheme-colour synaesthesia). While these, and other intriguing questions remain unanswered, the current study unequivocally demonstrates that cognitive tasks like the SNARC task and the spatial cueing paradigm can provide valuable empirical confirmation of these unusual number forms. More importantly, the current study shows that despite the atypicality of these highly unusual number forms, these synaesthetic forms nevertheless can influence the behaviour of synaesthetes in systematic ways.

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