June Must be Right and 9 is on Top:
An Investigation of Time-space and Number-form Synaesthesia

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

Synaesthesia is a fascinating condition whereby individuals report extraordinary experiences when presented with ordinary stimuli. In this thesis, we examine an individual (L) who experiences time units (i.e., months and hours) and numbers as occupying specific spatial locations (e.g., January is 30° to the left). This type of spatial-form synaesthesia has been recently investigated by Smilek et al. (2007), demonstrating that synaesthetic time-space associations are highly consistent, occur regardless of intention, and can direct spatial attention. We extended this work in Chapter 2 by showing that for L, her time-space vantage point changed depending on whether the time units were seen or heard. For example, when L saw the word JANUARY, she reported experiencing January on her left side, however when she *heard* the word "January" she experienced the month on her right side. In this thesis, we validated L's subjective reports using a spatial cueing task. The names of months were centrally presented followed by targets on the left or right. L was faster at detecting targets in validly cued locations relative to invalidly cued locations both for visually presented cues (January orients attention to the left) and for aurally presented cues (January orients attention to the right). We replicated these vantage-point dependent cueing effects also using hours of day. In Chapter 3, we further explored whether synaesthetic number forms could bias spatial attention using a spatial cueing and SNARC-type task. Two synaesthetes (L and B) both described experiencing the numbers 1 through 10 running vertically from bottom to top. Both experiments confirmed their synaesthetic number forms, such that 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. Likewise in the spatial cueing task, 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). Both synaesthetes were, however, reliably faster to detect left targets following the presentation of numbers 10, and 11, and right targets following numbers 19 and 20 (running from left to right). Hence, we demonstrated that cueing and SNARC tasks could be used to empirically verify synaesthetic number forms. Moreover, we showed that numbers could direct spatial attention to idiosyncratic locations similar to time-units, replicating and extending our findings from Chapter 2. Lastly, Chapter 4 was aimed to explore the automaticity and involuntary nature of L's number-forms. We continued to use the spatial cueing task and sought to eliminate any influence of strategy on L's performance by: (1) shortening the interval between the cue and target onset to only 150 ms and (2) having the targets only fall in synaesthetically cued locations on 14.2% of trials. As a result, these manipulations should eliminate any cuing effects if L's performance was attributable to intentionally using the cue to predict target location. However, our findings still showed an attentional bias consistent with L's synaesthesia. We attributed L's resilient cueing effects to the automaticity of her number-forms, thus demonstrating one of the hallmark attributes of synaesthesia. Overall, this series of studies convincingly demonstrated the reality of time-space and number-form synaesthesia and Chapter 5 concludes by discussing how this work has significantly contributed to the synaesthesia literature and to the study of perception overall.

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DEDICATION

Everything that I am, or ever hope to be, I owe to my mother, my angel.
I dedicate this thesis in loving memory of my mom, Debra Ann Jarick (1953-2007)
and to my niece, Lauren Debra Jarick, for being my strength and inspiration.

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L = synaesthete referred to as L
B = synaesthete referred to as B
RT = response time
SD = standard deviation
SOA = stimulus onset asynchrony
DG = synaesthete referred to as DG
MVP = mental vantage point
SNARC = spatial numerical association of response codes
H = synaesthete referred to as H
CRT = cathode ray tube
LCD = liquid crystal display
ANOVA = analysis of variance
RSDT = revised standardized difference test
fMRI = functional magnetic resonance imaging
IPS = intraparietal sulcus
VIP = ventral intraparietal
LIP = lateral intraparietal

1 : Introduction

For some individuals, 5 plus 2 equals yellow, chicken tastes square, frog's croak blue, June must always be right (or left), and 9 is always on top. This rare phenomenon referred to as synaesthesia has garnered much scientific attention over the past few decades, and has been identified as a condition in which ordinary stimuli or concepts (for example the number 7) elicit extraordinary conscious experiences (such as the colour yellow). From the first reported case by Sachs in 1812 (Jewanski, Day, & Ward, 2010) to the modern era, researchers have documented an increasing variety of synaesthetic inducers (stimuli that trigger synaesthesia) and concurrents (synaesthetic experience itself; Grossenbacher and Lovelace, 2001). Currently there are sixty-two different types of synaesthesia according to Sean Day's *Synaesthesia List* (Day, 2009, "types of synesthesia"). Grapheme-colour (colours triggered by letters and numbers), day-colour (colours triggered by different days of the week), and spatial-sequence synaesthesia (sequences such as time units, numbers, letters, temperature, occupy specific locations in space; Hubbard, Ranzini, Piazza, & Dehaene, 2009; Sagiv et al., 2006; Simner et al., 2006) are to date the most common forms. Yet it was only until very recently that spatial-sequence synaesthesia (also referred to as "time-space" or "number-form" synaesthesia) was of interest to researchers and accepted as a genuine form of synaesthesia. The following studies in the current thesis provided partial foundation for that acceptance.

1.1. ***Spatial forms***

In 1880, Francis Galton described how certain people possessed the ability to clearly visualize or "see" numbers in space (Galton, 1880, 1881). These people claimed that they could see numbers in the form of dominoes or dice patterns, grids or towers, or that they saw coloured digits in spaces. Most of the participants who "saw" numbers in space, described them as being organized in a particular spatial structure that remained stable from an egocentric reference point. Galton termed those number-space representations "number-forms”, and at least two key characteristics distinguish number-forms from the standard “mental number line” that we might all experience with low numbers to the left and higher numbers to the right. First, number-forms are typically very complex and idiosyncratic in structure. Second, number-forms are thought to be automatically activated without any conscious mental effort (Galton, 1880). Reports on number forms that researchers have documented over the years reveal an astounding variety of idiosyncratic structures, such as grids, spirals, staircases, ovals, infinite lines of rows and columns, ellipses, towers, and so on. As one participant described to Galton more than one hundred years ago,

> “If words such as fifty-six be spoken, I most clearly, easily and instantly visualize the figures. I do so almost automatically, I perceive that when I speak the word ‘thousand’ or hear it spoken, the figures at once group themselves together. I find it quite impossible to think of a date of a year without remembering and visualizing the figures, though I express myself in words. The figures are always printed; in type and size they resemble those commonly used for the headings of newspapers. I cannot, however, appreciate a background, the figures appear simply in space.” (Galton, *Nature*, 1880, p. 252).

Galton’s research was rapidly followed by Bertillon (1880) who documented similar experiences with digits, but also extended visuo-spatial ‘number-forms’ to include spatial representations of time units, like months of the year and days of the week.

More than a century later, Seron, Pesenti, Noël, Deloche, and Cornet (1992) revived Galtons’ theories and provided exploratory data to support and extend his introspective reports of number-forms. Besides documenting two cases of individuals who claimed to see digits and time units in space, the authors noted that there seemed to be characteristics in common among the spatial-forms that they were encountering. The authors first noted that the spatial-forms were very reliable and highly consistent over long periods of time. Indeed, individuals typically reported having had number-forms ever since infancy and cannot remember a time when they did not have them. Secondly, based on the subjective reports of the synaesthetes it appears that spatial-forms seem to occur involuntarily and automatically, without any conscious effort or awareness. In other words, whenever the individual saw, heard, or thought of a number or time unit, the spatial representation would automatically arise. These characteristics were quite reminiscent of the defining characteristics of synaesthesia (Cytowic, 1989).

1.2. *Time-space "synaesthesia"*

In 2007, Smilek, Callejas, Dixon, and Merikle published one of the first empirical studies supporting the idea that the spatial representation for the months of the year was a form of synaesthesia. Four individuals were studied who claimed to "see" months in space, PD, ST, JK, and CS. Some of these individuals also experienced colours for digits and letters, known as *grapheme-colour synaesthesia*. Smilek et al. noted that although some synaesthetes had only spatial representations of time units, and others had only coloured graphemes, the two attributes often co-occur in synaesthesia. This commonality led Smilek et al. to believe that these lucid time-space experiences were indeed a variant of synaesthesia and thus, coined the term "time-space synaesthesia". Note that the nomenclature "time-space" is based on identifying the inducer (time unit) and concurrent (spatial representation) and has no relationship to the space and time concepts commonly used in physics.

Smilek et al. (2007) established that the time-space synaesthetes also demonstrated the key characteristics that defined other forms of synaesthesia (Baron-Cohen, Wyke, & Binnie, 1987), namely consistency and automaticity. Using a laser pointer mounted on a 360-degree compass, Smilek et al. assessed the consistency of the time-space mappings of two of the synaesthetes who experienced months as occupying locations in extrapersonal space (the other two had months that were experienced in a spatial arrangement on a small "screen" directly in front of them). Six non-synaesthetic controls were yoked to each synaesthete for comparison. Each control was given a description of the spatial representation experienced by the synaesthete and asked to "act as if" they also experienced that spatial representation while performing the task. For the synaesthetes whose months were arrayed in extrapersonal space, participants shined the laser pointer directly in front of them and this was assigned a value of 0°. The researchers then randomly read month names aloud, and participants were asked to point to the spatial location representative of each month. Once all 12 month names were selected, the participant was repositioned 90°, the laser level set back to 0°, and the task repeated. Smilek et al. calculated the variability (standard deviation) of the measured angles for each month over both testing sessions. Both synaesthetes, PD and ST, showed lower average variability scores (i.e., greater accuracy) than any one of their controls. PD resulted in a score of 5.1° compared to an average of

15.2° observed in controls. Likewise, ST showed only a score of 2.8° compared to an average of 12.8° for her controls. Thus, the findings from Smilek et al. (2007) clearly demonstrated that the time-space representations experienced by these individuals were highly consistent and reliable over time (e.g., days, weeks, months, etc.). This astonishing consistency has since been observed in many synaesthetes across a variety of laboratories, including the synaesthete (L) that we focused on in this thesis, whose variability score was low (4.7°) at the time of first testing (see Chapter 2), and 3 years later was even lower (2.8°).

Another key characteristic of synaesthesia is the automaticity by which it appears. In order to assess this *automaticity* component, Smilek et al. (2007) used a classic Posner-type cueing paradigm to examine whether month names could rapidly cue the synaesthetes' spatial attention. This cueing paradigm measures participants' response times (RT) to detect targets presented to the left or right of a central cue. Prior to the targets' appearance, the centrally presented month names served to direct attention either to the target location (valid trial) or the opposite location (invalid trial). Imagine for example that for a given synaesthete, "January" is located on her left side of space. If attention is successfully directed by the cue, then in theory, if the word January is presented, this participant should respond significantly faster to a target on her left (valid trials) than a target on her right (invalid trial). In Smilek et al.'s version of the cueing task, the central cue was a month name presented for either a very short (150 msec) or relatively long (600 msec) period of time, followed by a peripheral target to the left or to the right of the participants' visual field. On half the trials, the target would appear in the location synaesthetically cued by the month name (*valid* trials), and on the other half of the trials, the target appeared in the synaesthetically uncued location (*invalid* trials). Smilek et al.'s version of the cueing task showed that three of the four synaesthetes performed in accordance with their synaesthetic experiences. That is, each synaesthete responded significantly faster when the target landed in the synaesthetically valid location, compared to the invalid location. Importantly, these cueing-effects were observed even at the shortest stimulus onset asynchrony (SOA) of 150 msec between cue and target onset. Thus, not only were the month names cueing the synaesthetes' attention to the spatial locations, they seemed to influence attention rapidly, within 150 msec, furthering the claim that time-space associations occur *automatically.*

While Smilek et al. (2007) had laid the initial groundwork for establishing time-space representations as a form of synaesthesia, researchers have only recently begun to investigate the cognitive processes and associated neural mechanisms that give rise to this rare phenomenon. In this thesis, we add an intriguing piece to this puzzle. We conducted an in-depth exploration of a time-space synaesthete who reports that she can view her space from different mental vantage points. Just as we might be able to imagine ourselves viewing a Raptors game from different vantage points within the Air Canada Centre (vantage points based on our experience of different seat locations), this synaesthete claimed that she was also able to take different vantage points when viewing her spatial arrangements of time. This thesis presents empirical evidence that bolsters her claims. In addition to proving "the reality" of these mental vantage point shifts, we ultimately discuss some parallels that might exist between synaesthetic spatial forms and our mental representations of the spatial locations of the real world.

1.3. *Number-form "synaesthesia"*

From the work of Galton (1880) and Seron et al. (1992), it seems quite plausible that the individuals they described who "visualized numerals" would now be recognized as having "number-form synaesthesia" (Cytowic, 1989; Grossenbacher & Lovelace, 2001; Ramachandran & Hubbard, 2001a). Sagiv, Simner, Collins, Butterworth, and Ward (2006) found the prevalence of number-forms to be significantly greater in synaesthetes who experience colours for digits (number-colour synaesthetes), compared to synaesthetes who have different experiences (such as digit-taste synaesthesia), or non-synaesthetes. In fact, previous studies have highlighted the common presence of number-forms in grapheme-colour synaesthetes (e.g., Baron-Cohen, et al., 1987; Collins, 1929; Odgaard, Flowers, & Bradman, 1999; Ostwald, 1964; Wheeler & Cutsforth, 1921). Sagiv et al. (2006) noted that if an individual has spatial forms for digits, they also were highly likely to have spatial forms for other sequences as well, such as time units (Smilek et al., 2007) or letters of the alphabet. For example, Hubbard et al. (2009) described an individual (DG) who experienced over fifty sequences in space, including rare forms like: historical periods, stock prices, computer hard disk space, the order of pure-bred dog names, and more. Although number-forms have yet to be accepted as an indisputable form of synaesthesia, these characteristics raise the definite possibility that number-forms are indeed so.

Sagiv et al. (2006) were the first to support the notion of number-form synaesthesia with empirical evidence. The authors tested five synaesthetes with number-forms in a digit comparison task. For this task, synaesthetes were presented with two digits that appeared in the same arrangement as their number-form (congruent trials) or appeared in the reverse arrangement (incongruent trials). The synaesthetes were required to identify which digit was greater of the two by pressing the button corresponding to the digit on the computer display as quickly and accurately as possible. Responses were aligned with the direction of each individual 'synaesthetes number representation', for example, vertical, horizontal, or diagonal. For instance, if the synaesthetes' numbers ran from left-to-right, with small numbers on the left and high numbers on the right (akin to the mental number line, see below), then a congruent trial would be if the two digits appeared on the computer screen with, for example, 4 on the left and 9 on the right and the synaesthete in this case would press the right button to indicate the higher digit. An incongruent trial would be if, for example, 7 was on the left and 1 was on the right. In this case, the synaesthete would be expected to always press the right button for the higher number, but instead the response would be with the left button.

For each of the five synaesthetes, RTs were significantly faster to detect the higher digit when the arrangement was congruent with the synaesthetes' number-form than when it was incongruent. This was true for synaesthetes whose number-forms ran from left-to-right, but more importantly right-to-left, bottom-to-top, and diagonally. Thus, it appears that synaesthetic number-forms can influence behaviour and impact their performance on simple cognitive tasks. Assuming that the synaesthetes were naïve to the purpose of the task, Sagiv et al.'s findings objectively confirmed the subjective reports given by each of the synaesthetes tested. Note however, that the authors did not compare the synaesthetes to a control group of non-synaesthetes. Therefore, the behavioural evidence provided by Sagiv et al. (2006) neglected to show whether the performance of the synaesthetes was exceptional compared to those without synaesthesia.

A large body of evidence suggests that non-synaesthetes also represent numbers in a spatial arrangement along a number line from left-to-right (for reviews see Fias & Fischer, 2005; Hubbard et al., 2005, 2009), referred to a the "mental number line". In fact, Dehaene, Bossini, and Giraux (1993) designed a task to demonstrate how strong this spatial association is and termed it the Spatial Numerical Association of Response Code (SNARC) effect. Using this task, Dehaene et al. showed that small numbers were responded to faster with the left hand and high numbers were responded to faster with the right hand. Even though recent research has tried to undermine the underlying assumptions of the SNARC effect, suggesting that it instead reflects stimulus-response compatibility (Fitousi, Shaki, and Algom, 2009), the notion of a left-to-right number line continues to be demonstrated across a variety of tasks and laboratories worldwide. Thus, a question of interest is exactly how number-form synaesthesia is any different than the mental number line inherent within all of us.

According to the description offered by Seron et al. (1992) of what is now considered number-form synaesthesia, the key differences seem to involve the *vividness* of the experience and *automaticity* with which they arise. Although most of us could imagine a number line running from left to right in our mind, synaesthetes actually claim to "see" those numbers out in space. Crucially, where non-synaesthetes have been shown to successfully imagine a variety of number-lines conforming to task instructions to optimize performance on experimental tasks, such as number lines extending from right-to-left, top-to-bottom, or circular like a clockface (Bächtold, Baumuller, & Brugger, 1998; Ristic, Wright, & Kingstone, 2006), synaesthetes are only able to represent their numbers in one, stable structure - their number-*form* (Gernter, Henik, & Kadosh, 2009). As stated by Seron et al., the mental number line experienced by non-synaesthetes is "nothing more than the capacity to visualize the elements given in the problem and the classical steps of a written solution, and shares no evident relationship with an automatic activation of a stable spatial representation of numbers" (Seron et al., 1992, p. 188). The present thesis follows up on the work of Seron et al., and addresses two fundamental attributes of time space and number form synaesthesia: their authenticity and automaticity.

1.4. *The case of L*

The variability in synaesthetic experience from one synaesthete to the next produces major challenges to performing group studies of synaesthesia. This has motivated us to focus most of our work on one exceptional synaesthete (L). At the time of testing L was a 21-year old university student living in the United States and had just recently been exposed to reports about synaesthesia. Prior to learning of this condition, L had always believed that everyone experienced the world as she did. In L's world, years, months, days, hours, as well as numbers occupied incredibly vivid and highly specific spatial locations around her. Thus, she has both time-space *and* number-form synaesthesia, which together could also be classified as *spatial sequence* synaesthesia according to Eagleman (2009).

In laymans terms, L's month-space is in the form of a "scoreboard 7" (see Figure 1.1 in Chapter 2 for a schematic depiction). As shown in this figure, if L thinks about months of the year, or hears a month of the year spoken then she views this 7 shaped space with April directly in front of her (her [A]uditory vantage point is shown by the A with the arrow pointing downward to april). January is to her right, and July is to her left. The months turn at June and extend away from her until December. The [A]uditory vantage point with which she views this space, only applies if L *hears* or *thinks* about the months of the year. But if L [v]isually, *sees* the month names, then she takes the reverse mental vantage point and views the "7" from the crux of the seven. For instance, she still stands centered at April, however January would now be to her left, July to her right, and the months from June to December would curve around and extend behind her. Intriguingly, L also has a spatial representation for hours of the day that resembles that of a standard clockface. The one important difference is that rather than our vertically aligned canonical representation of the clockface (as it appears on a wall), L's clock face appears as though the clock were lying on the floor. Importantly, like her representation for months, she also takes different mental vantage points depending on whether she hears or thinks of an hour, versus when she sees a visual depiction of an hour name (e.g., "3 a.m"). This reversal in mental vantage point triggered by the type of inducer (auditory versus visual) had not yet been reported in the literature, and indeed, no member of the synaesthesia research group at Waterloo had ever heard such a case until L. This motivated us to examine L further to see if we could empirically validate these claims. To be clear, although verbal reports from other synaesthetes had suggested that some do have the ability to navigate around their spatial forms, this had never been empirically documented and no synaesthete has ever reported a coupling of vantage point with inducer modality (auditory or visual).

L's number-space is a bit more difficult to describe (see Figure 2.1 in Chapter 3). L describes how her digits 1 through 10 rise vertically from bottom to top, while the numbers 10 through 20 extend across her midline from left-to-right. However, the digits from 20 through 100 seem to follow a grid-like pattern from right-to-left. Once the number-form reaches 100, L describes how her digits extend out into infinite space beyond her immediate grasp, which makes her unsure of the precise structure. Similar to the different mental vantage points L can take when viewing her months and hours, she also claims to be able to "zoom in and out" and focus on certain parts of her number-form, or reorient herself to be looking at the digits from different standpoints. She acknowledges that being able to navigate around her number-space has helped her to perform mathematical calculations. Although we have not yet empirically verified this for L, the beneficial role of synaesthetes' number-forms for performing mental arithmetic has been verified by Ward et al. (2009).

Even though all of L's representations are individual spatial forms elicited by different stimuli, they all seem to have characteristics in common. For one, L cannot remember a time when the spatial forms did not exist. She can, however, recall having them when she was very young, but does not have any theory of how or why they might have developed. L also claims that the spatial forms appear involuntarily whenever a time unit or number is presented. Even through an act of will, she claims she cannot inhibit them from being elicited. In essence, L's spatial forms seem to be activated automatically, similar to other reports of synaesthesia. Furthermore, L, like other synaesthetes claims to be able to utilize her spatial forms to perform calculations and remember special dates and appointments, thus improving her memory (see also Simner et al., 2009). In this way, she views her synaesthesia as being advantageous to her life. Finally, L speculates that her brother might also possess number-forms (he is the only person that does not think she is crazy when she describes them), and her grandmother might have time-space associations (she was 92 years old and still had a superb memory for dates and appointments).

1.5. *The present thesis*

Relative to the other types of synaesthesia, spatial-sequence synaesthesia seems to be overlooked in the literature. Prior to this thesis, little empirical research had been devoted to investigating the genuineness of spatial forms and whether or not they were distinguishable from other spatial representations that the majority of people have been shown to experience (i.e., mental number line). Fortunately, we were introduced to L who claimed to have spatial forms for months, hours, *and* numbers. Having multiple spatial forms allowed us to gather converging evidence that would ultimately lead to a more advanced understanding of the phenomenon.

The most intriguing aspect of L's representation of time (i.e., months and hours) involved her claimed ability to view the spatial forms from different mental vantage points depending on whether she saw or heard the time unit presented. Thus, in Chapter 2 we aimed to objectively verify L's unusual subjective reports using the same spatial cueing paradigm as Smilek et al. (2007). We predicted that L would show cueing effects consistent with her visual vantage point when the cues were presented visually, but that these effects would reverse when the cues were aural. To conceptually replicate the vantage-point-dependent cueing effects with a different spatial form (and one that the majority of people might have), we examined L's vantage point difference with the representation she has for the hours (the "on the floor" clockface). Both experiments contrasted L's performance to that of non-synaesthetes. This distinction was particularly important for her hours of the day – because arguably the standard clockface is a time-space mapping that would make sense to many non-synaesthetes, it allowed us to compare cueing effects arising from synaesthetic time space mappings to non-synaesthetic (but plausible) time-space mappings.

Once we had validated that L did in fact have synaesthesia, we then aimed to investigate how extraordinary and concrete her number-forms were. In Chapter 3, we applied two of the most popular methods for investigating the mental number line (in non-synaesthetes) in order to investigate the mechanisms underlying L's number-forms: the Fischer-cueing task (Fischer, Castel, & Dodd, 2003) and a SNARC-type task. Since L's number-forms were aligned vertically and the mental number line is typically aligned horizontally, we expected to find orthogonal effects when comparing L to controls. That is, where L should exclusively show cueing and SNARC effects only when the targets or responses were aligned in a vertical orientation with her 1-9 segment of her number forms, non-synaesthetes should exclusively show cueing and SNARC effects for targets (or responses) aligned horizontally with the left-to-right mental number line.

In Chapter 4 we extended our investigation with L to assess the automaticity and involuntary nature of her number-forms. By modifying the Fischer-cueing task, we were able to pit automaticity against strategic influences by proportionally loading up on invalid trials (85%) and shortening the SOA between the cue and target onset to be 150 msec. Therefore, if L were to use a strategy to optimize her performance on this task, it would benefit her to direct her attention to a location in space that was *opposite* to the synaesthetic location cued by her numbers. As such, by loading up on invalid trials we sought to assess whether automatic cueing effects would still emerge in the face of strategic demands to orient her attention to locations that were opposite to the synaesthetic locations cued by the numbers.

Lastly, Chapter 5 concludes with a summary of the main findings from all of the experiments presented in this thesis. We leave the reader with a discussion of whether synaesthesia should be considered a discrete condition (i.e., you have it or you do not), and the overall implications that synaesthesia can have on areas within cognitive neuroscience, specifically numerical cognition, automatic processes, and spatial perception.

2

: A Different Outlook on Time[1]

Visual and auditory month names elicit different mental vantage points for a time-space synaesthete

Ever since Francis Galton (1880, 1881) reported that some individuals appear to visualize numbers in space, researchers have identified other concepts such as time units that certain individuals mentally allocate to specific spatial locations (Seymour, 1980; Smilek et al., 2007). These individuals have reported experiencing the months of the year, days of the week, and hours of the day as occupying highly consistent spatial locations relative to their own body (Duffy, 2001; Smilek et al., 2007). The propensity to allocate units of time to specific spatial locations has been referred to as *time-space synaesthesia* (Smilek et al., 2007), and there is still debate in the literature as to whether this condition is truly a form of synaesthesia. After all, if requested to assign spatial locations to hours of the day, many non-synaesthetes would align the hours according to the traditional clock face. Unlike the clock face however, the time-space associations observed in synaesthesia tend to be much more elaborate, idiosyncratic and vivid than those found in non-synaesthetes. For instance, one synaesthete (H) described her time-space experience as the following,

> "When someone mentions a year, I see the oval with myself at the very bottom, Christmas day to be precise. As soon as a month is given, I see exactly where that month is on the oval. As I move through the year, I am very aware of my place on the oval at that current time, and the direction I am moving in. For example, now I am moving upwards, in a northwesterly direction. It is always anti-clockwise".

The linkage of time to space shares many of the defining characteristics of other forms of synaesthesia (e.g., grapheme-colour; Sagiv et al., 2006). The time-space mappings are consistent over time and appear to be experienced involuntarily (Smilek et al., 2007). Already noted in the previous chapter, consistency was first assessed by Smilek et al. (2007) using a laser pointer mounted on a 360-degree compass. Synaesthetes were asked to align the laser pointer through the centre of each month and the compass angle was recorded.

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[1] A version of this chapter was originally published in *Cortex, 45,* pp. 1217-1228.

Synaesthetes were significantly more consistent at pointing to their month locations across repeated testing sessions than control participants. As a behavioural measure, Smilek et al. used a spatial cueing task to assess the involuntary nature of the time-space representations. Four time-space synaesthetes were presented months of the year (e.g., APRIL) in the center of a computer screen, followed by a target square presented either to the left or the right of the month name. The authors predicted that if the month names could trigger shifts of visual attention to their synaesthetically associated spatial locations, then the synaesthetes would be quicker at detecting targets that fell in the synaesthetically cued location versus the invalid location on the opposite side of space. Smilek et al. (2007) found that three of the four synaesthetes showed significant synaesthetic cueing effects. Because these cueing effects occurred even though the months were not actually "predictive" of the target location (i.e., on half the trials they cued the wrong location), and because the cueing effects occurred even when the target appeared almost immediately (150 msec) after the onset of the month name, Smilek et al. concluded that at least for some synaesthetes time units were capable of involuntarily directing synaesthetes' attention to locations in space.

Here we examine an individual (L) whose time-space synaesthesia has features that are common to other time-space synaesthetes described in the literature thus far, but one salient feature that is to our knowledge unique. Like other time-space synaesthetes, L reports experiencing the hours of the day and months of the year as being represented in her egocentric space. She represents the months of the year arranged in the form of a giant "scoreboard 7" (see Fig. 1.1a for a "bird's eye" view of what her mental calendar looks like). When presented visually with month names, L reports that her mental vantage point is standing in the crux of the 7, looking directly ahead at April. Thus from this vantage point, she experiences January, February and March on her left, and May and June on her right. From her preferred vantage point at the crux of the 7, the arm and tail of the 7 extend approximately one meter around her midline in egocentric space. The unique aspect of L's time-space synaesthesia is that when L *hears or thinks about* the names of the months of the year, her 7-shaped space does not alter, but her mental vantage point within this space changes. Relative to her preferred vantage point (at the crux of the 7 when seeing the month names) for heard months it is as though she walked around the top of the 7 to the other side of April. Thus, from this 'auditory' mental vantage point she now experiences January, February and March on her right and May, June and July on her left. The subsequent months are on her left extending out into distal space. This change in vantage point is also apparent when L sees versus hears the hours of the day (Fig.1.1b).

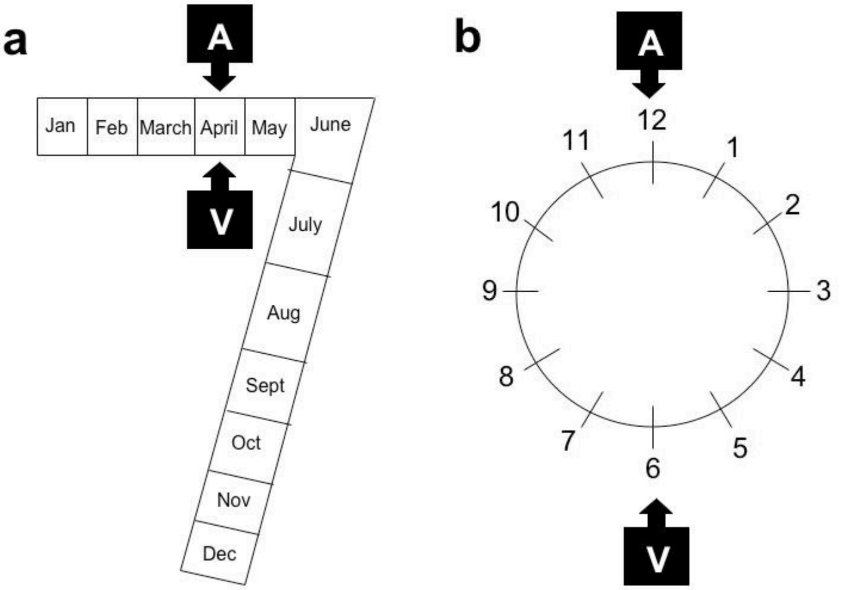

Figure 1.1: **Bird's-eye view of L's spatial organization of months of the year (Experiment 1) and hours of the day (Experiment 2)**. As illustrated, her representations of the months form the shape of a 'scoreboard 7' (*a*) and her hours take the form of a 'clock face' (*b*).

To objectively verify L's unusual subjective reports, we used the same spatial cueing paradigm as Smilek et al. (2007). Visual month names were centrally presented followed by a target square to the left or right of the month cue. We predicted that if the visually presented month name can trigger shifts of L's visual attention to its synaesthetically associated spatial location, then L should be quicker at detecting targets that fall in the synaesthetically cued (or valid) location versus the opposite (invalid) side of space. For instance, she should be faster to detect the targets on the left side of the display when cued by the early months of January, February, and March, because her synaesthetic experience would orient her attention to her left side of space. Crucially, if it is also true that L's vantage point changes when she *hears* the months instead of seeing them, then aurally presenting those same early months that visually cued her to her left side of space should now orient her attention to her right side of space (hence right targets should be detected faster than left targets). Statistically, if the visual and aural inducers lead to different mental vantage points we should find an interaction between the type of inducer (visual and aural), the month cues (early months versus later months) and side of target (left and right). Of course, we predict that only the synaesthete will show this triple interaction – non-synaesthetes tested under the same experimental regimen will not show any cueing effects related to the month names.

2.1. Experiment 1 (Months)

2.2. Methods

Participants

A healthy 21-year-old female with time-space synaesthesia (L) and ten naïve non-synaesthetic controls (two males, *M* = 24.4 years old) volunteered to participate in this study for an honorarium. The controls were fully debriefed at study completion regarding the characteristics and different forms of synaesthesia, at which time the participants were asked if they experienced any such associations. None of the participants reported any form of time-space associations and were surprised to learn of the phenomenon. When the synaesthete (L) initially reported her vivid time-space associations, she was tested for consistency using the same method as Smilek et al. (2007). We used a laser level situated at her midline that measured 0°. The experimenter randomly asked her to point the laser level to the location of each month and the degree of angle was recorded (0°– 360°), returning to 0° after each trial. We then asked L to turn her body 90° and repeated the process. These rotations were done three times in order to make certain that landmarks in the room (e.g., a mark on the wall) could not be used as reference points from which to align her months. We then computed the standard deviation (SD) associated with each month and averaged them together to get an overall variability score (Smilek et al., 2007). L showed high test-retest consistency for each month, with an average deviation of less than 4.75°. This low variability for L is directly comparable to the consistency values in Smilek et al. who showed average variability scores of 4° for the synaesthetes PD and ST and 14° for twelve non-synaesthetic controls. Thus, L's highly consistent performance falls within the range of synaesthetes in Smilek et al. and outside the range of controls, confirming that the spatial forms she experienced were indeed reliable over time. Finally, all participants had normal or corrected-to-normal vision and hearing, 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.

Materials

We adopted the same spatial cueing task as that used by Smilek et al. (2007). All stimuli were presented on a 17" cathode ray tube (CRT) computer monitor in black on a white background. The fixation-cross subtended 0.6° of visual angle in all directions. There were six different month cues: three early months (*January, February, March*) and three later months *(May, June July*). The visual month cues were written in black text (Geneva font, 72 pt. created in SuperLab 4.0), measuring 0.7° in height and maximally 6.5° in length – *February*). Targets were black squares (each side 0.6°) presented to the left or right of the cue. The targets were placed 10.5° in eccentricity from the center of fixation. The auditory month cues were the same month names broadcast over the computer speakers located on each side of the computer monitor facing the participant. A button-box was located on the table in front of the participant to collect the participants' responses. The stimuli were presented and response times recorded using SuperLab 4.0 experimental software.

Procedure

Participants were seated unrestrained at a distance of 57 cm in front of the computer monitor. Participants were asked to press a centrally located key on a button-box as quickly and accurately as possible with their right (dominant) hand once they detected the targets' presence. In the case where the target was absent (i.e., 'catch' trials), they were instructed to withhold their response and wait for the next trial. Participants were advised that the month cues were in no way related to the target location. For all participants the session involving the visual presentation of month names was presented first, followed by a session in which the month names were presented aurally. Trials began with a fixation cross for 680 msec, which was then replaced randomly by a month cue (either *January, February, March, May, June*, or *July*). The month cue remained on screen for 600 msec, followed by a target square presented to the left or right of the cue for 3500 msec or until the participant responded. The auditory trials followed the same procedure as the visual trials except the month cues were broadcast over the computer speakers. Month cues were not statistically predictive of target locations since on half (50%) of the trials, the target was presented on the side of the display synaesthetically cued by the month name whereas on the other half (50%) of the trials the targets were presented on the opposite side (synaesthetically invalid trials). The separate visual and auditory cueing sessions each contained 10 practice trials (4 valid, 4 invalid, 2 catch) and four blocks of 132 randomized trials (60 valid, 60 invalid, and 12 catch trials). The 'catch' trials contained no target and were inserted to make sure that the participants were attending to the task as well as to discourage participants from making anticipatory responses. Sessions lasted about 30 minutes each, amounting to about an hour of testing in total.

2.3. Results and Discussion

L made few errors on 'catch' trials (95% correct). Only those control participants who performed above 80% correct on the catch trials were included in the analysis. Two participants were excluded on this basis. Response times of each participant were submitted to an outlier analysis in which observations +/- 2.5 SDs were discarded. A total of 2.81% of trials were discarded for the synaesthete and an average of 5.04% for the controls. The remaining response times of each participant were analyzed using separate 3-factor analyses of variances (ANOVA's) involving inducer type (visual or auditory), month cue (early versus later months), and target location (left and right). To control type-I error rates for multiple tests, we used a Bonferroni correction resulting in an alpha level of .005. As predicted, L showed a significant 3-way interaction between type of inducer, month cues and side of target, $F(1, 925) = 155.35$, $p < .0001$. Each control was analyzed separately and after the Bonferroni correction, for no control was this triple interaction significant (*F*-statistics of the controls ranged from .002 to 7.16. None of these *F*-values were associated with probabilities below our Bonferroni corrected alpha level of $p < .005$).

Planned comparisons revealed the source of the 3-way interaction for L. The means involved in the planned comparisons are connected by the black and grey lines in Fig. 1.2 (the bars around the means reflect the 95% confidence intervals). We predicted that for visual presentations, only early months would cue attention to the left. In support of this prediction, left targets (*M* = 315 msec) were detected faster than right targets (*M* = 352 msec) following early month presentations – see the positively sloped solid line in Fig. 1.2A. As well, we predicted that later months should cue attention to the right. Following the later month presentations, right targets (*M* = 304 msec) were detected faster than left targets (*M* = 334 msec) – see the negatively sloped dotted line in Fig. 1.2A. For aural cues (shown in Fig. 1.2B), we predicted the opposite pattern. Namely, early months should now cue attention to the right. Supporting our prediction, right targets (*M* = 282 msec) were detected faster than left targets (*M* = 328 msec) following early month presentations – see the negatively sloped solid line in Fig. 1.2B. Likewise, we predicted that later months should now cue attention to the left. Following later months presentations, left targets were detected faster (*M* = 291 msec) than right targets (*M* = 331 msec), - see the positively sloped dotted line in Fig. 1.2B. For these planned comparisons all $\underline{t}$ values > 4.0, and all $\underline{p}$ values < .0001.

On both valid and invalid trials, we believe that L's attention was *automatically* cued to her synaesthetic spatial location. As evidence, a recent extension of the current study (Jarick, Jensen, Dixon, and Smilek, under review) patterned after Smilek et al. (2007), revealed that L’s valid and invalid response time differences emerged not only at long SOAs but also at short SOAs (150 ms) indicating the effects were due to the months automatically cueing her spatial attention. These automatic cueing effects even emerged when 85% of the trials cued her attention to an invalid location. In light of this new work, we view the present results as reflecting automatic cueing of L’s spatial attention.

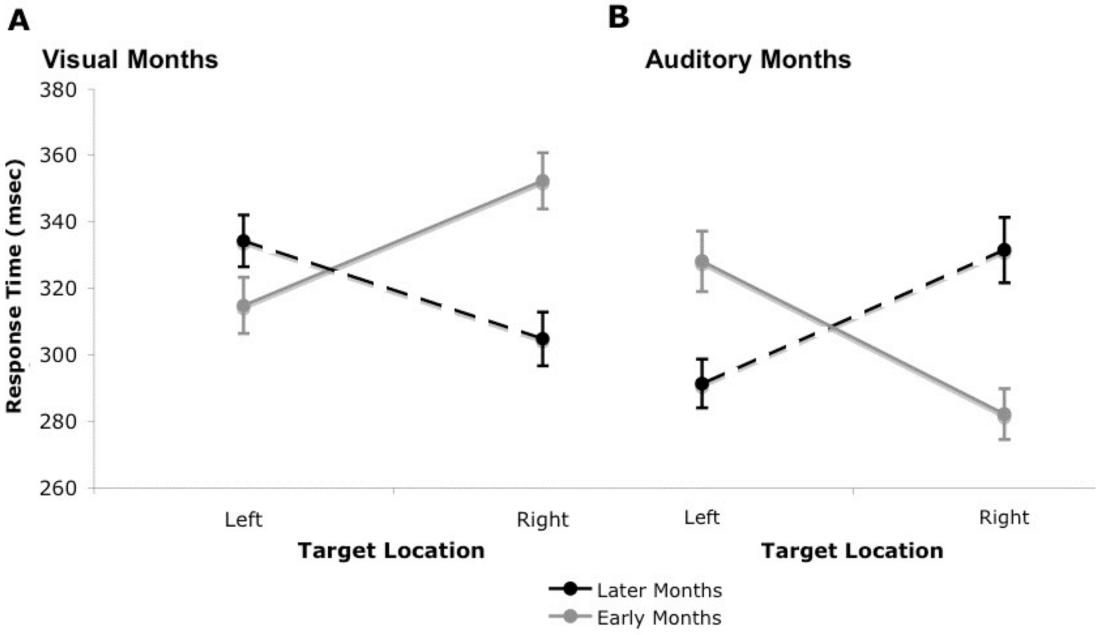

Figure 1.2: **Mean response times of the synaesthete (L) for Experiment 1 (Months) across the two conditions: visual (Panel *A*) and auditory (Panel *B*).** Note that the error bars represent the 95% confidence intervals around the mean.

Fig. 1.3 shows the mean response times of the control participants, with bars around the means reflecting the range of control performance. A 3-way analysis of variance on the group data of the controls revealed no significant main effects or interactions. As can be seen in the Fig. 1.3, for both visual and auditory month presentations L's means (represented by the asterisks) lie within the range of control means for the synaesthetically valid trials, but outside of the range of control performance for synaesthetically invalid trials where her attention was cued to the incorrect location. From this figure it can be seen that although L is not faster than controls to orient her attention to the cued location, she is slower than controls at detecting targets in the uncued locations. We interpret this slowing, as being caused by having to disengage her attention from the cued location in order to reorient to the uncued location.

The fact that L's responses for validly cued trials lies within the range of controls' response times was initially surprising. In fact, she is clearly slower than the average of controls for these validly cued targets – a finding that at first glance appears to run counter the contention that month names cue her attention to locations in space. Even on these valid trials, however, one must interpret her performance within the context of an experiment. On 50% of the trials the month name cues her attention to an invalid location and she must disengage attention from the wrong location and move her attention towards the correct location of the target. While this moving of attention elevates response times on invalid trials, it likely also impacts her response times on valid trials – the fact that her attention is being cued to the wrong location on half of the trials would likely cause her to adopt a more cautious approach for completing the experiment (see Berteletti, Hubbard, and Zorzi, 2010 for a similar argument).

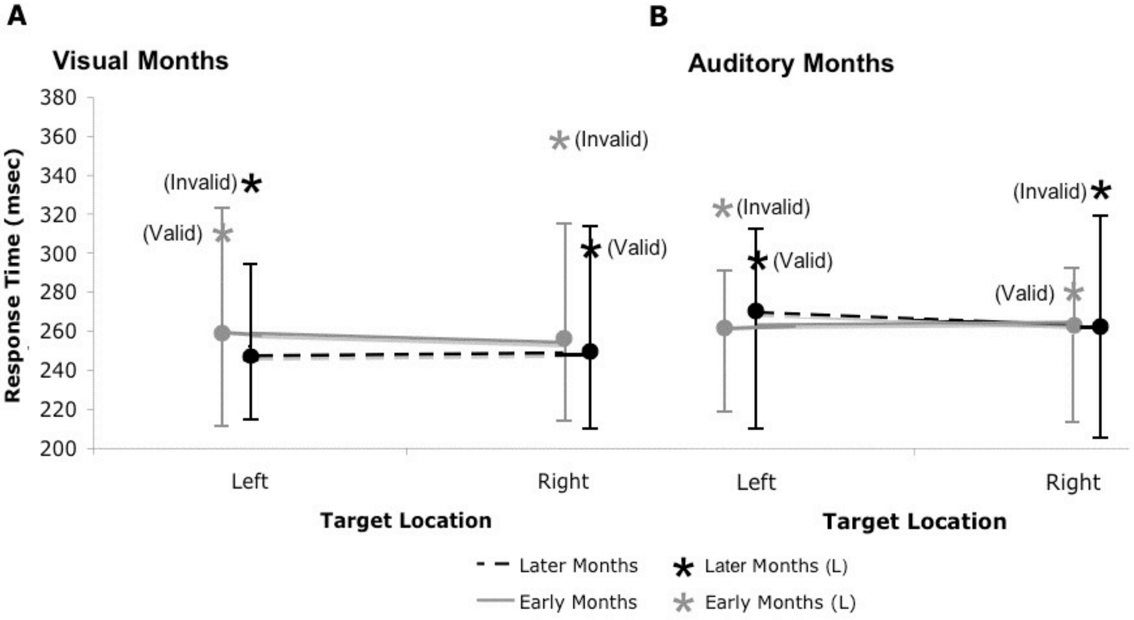

Figure 1.3: **Mean response times of the Controls for Experiment 1 (Months) across the two inducer conditions: visual (Panel *A*) and auditory (Panel *B*).** The error bars represent the 95% confidence intervals of participant means. The asterisks represent L's data, showing that her means fall inside the range of Controls during the valid trials (*valid*), while she is an outlier during invalid trials (*invalid*).

This overall slowing effect has been shown in other studies of synaesthesia. In a study using the synaesthetic Stroop effect (e.g., Dixon, Smilek, Cudahy, and Merikle, 2000; Dixon, Smilek, and Merikle, 2004), Lupiáñez and Callejas (2006) showed that their synaesthete MA had overall longer response latencies compared to controls when naming the text colour or photism colour of a grapheme. Importantly, although on incongruent trials this effect was likely due to interference, an overall slowing effect also occurred on congruent trials (as in the current study). The Stroop literature also reveals that for non-synaesthetes congruent trial response times become slower as the proportion of incongruent to congruent trials is elevated (Lowe and Mitterer, 1982; Bugg, Jacoby, and Toth, 2008). For non-synaesthetes there are effectively no invalid trials (months never direct their attention to either the "right" or "wrong" side of space). The presence of many invalid trials may have served to elevate L's response times to valid trials. Since there are no invalid (or valid) trials for non-synaesthetes, it may be easier for them to follow instructions and completely ignore the month cues to solely focus on the targets presented. If, as suggested by Smilek et al. (2007), month cues automatically cue attention in synaesthetes, it may prove more difficult for L to ignore these month cues. This splitting of her cognitive resources between processing the month cues and detecting the targets may serve to elevate both valid and invalid response times. If so, then what is most important is not where the synaesthete falls relative to controls on valid and invalid trials, but rather the magnitude of the cueing effect.

Cue effect sizes are reflected by the difference between response times in the invalid and valid conditions (Cueing effect = invalid RT minus valid RT). To analyze these cueing effect sizes and to foster comparisons with other spatial cueing studies we compared the magnitudes of spatial cueing effects for each of the control observers as well as for L. The left side of Table 1 shows the RTs for valid and invalid trials and the magnitude of the cueing effect for visual month cues. For the visual month cues "valid" trials are valid from the synaesthete's perspective; early months followed by targets on the right and late months followed by targets on the left comprise valid trials. To estimate cueing effect sizes for controls, one merely reverses the sign and looks for large negative cue effect sizes since a linear left-to-right association for months has been demonstrated for some nonsynaesthetes (Price, 2009). For the auditory cues "valid" trials for both synaesthetes and controls involve early months followed by targets on the right, and later months followed by targets on the left. As can be seen in Table 1, the cueing effect sizes are much larger for the synaesthete L, than for any of the controls in both the visual and auditory presentations.

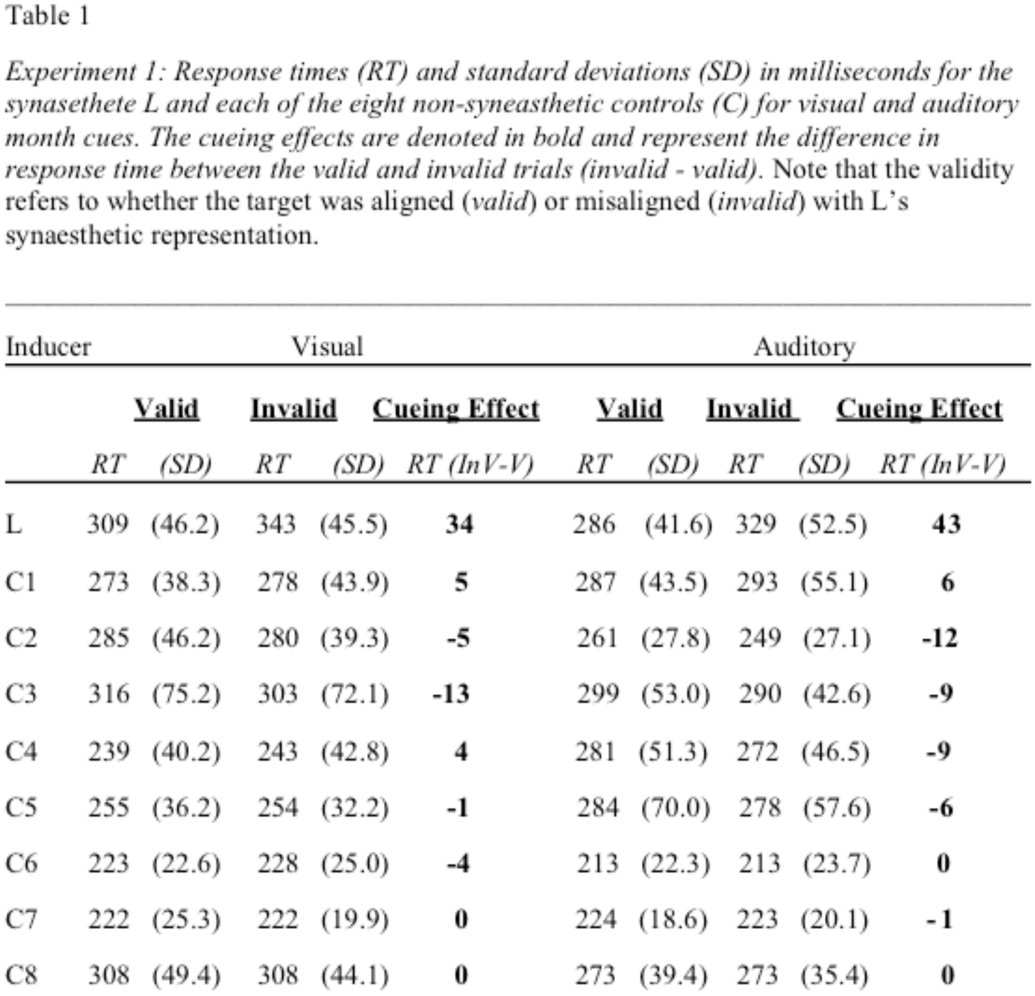

Table 1

Experiment 1: Response times (RT) and standard deviations (SD) in milliseconds for the synasethete L and each of the eight non-syneasthetic controls (C) for visual and auditory month cues. The cueing effects are denoted in bold and represent the difference in response time between the valid and invalid trials (invalid - valid). Note that the validity refers to whether the target was aligned (*valid*) or misaligned (*invalid*) with L's synaesthetic representation.

Inducer	Visual					Auditory				
	Valid		**Invalid**		**Cueing Effect**	**Valid**		**Invalid**		**Cueing Effect**
	RT	*(SD)*	*RT*	*(SD)*	*RT (InV-V)*	*RT*	*(SD)*	*RT*	*(SD)*	*RT (InV-V)*
L	309	(46.2)	343	(45.5)	**34**	286	(41.6)	329	(52.5)	**43**
C1	273	(38.3)	278	(43.9)	**5**	287	(43.5)	293	(55.1)	**6**
C2	285	(46.2)	280	(39.3)	**-5**	261	(27.8)	249	(27.1)	**-12**
C3	316	(75.2)	303	(72.1)	**-13**	299	(53.0)	290	(42.6)	**-9**
C4	239	(40.2)	243	(42.8)	**4**	281	(51.3)	272	(46.5)	**-9**
C5	255	(36.2)	254	(32.2)	**-1**	284	(70.0)	278	(57.6)	**-6**
C6	223	(22.6)	228	(25.0)	**-4**	213	(22.3)	213	(23.7)	**0**
C7	222	(25.3)	222	(19.9)	**0**	224	(18.6)	223	(20.1)	**-1**
C8	308	(49.4)	308	(44.1)	**0**	273	(39.4)	273	(35.4)	**0**

To directly compare L's cueing effect sizes to those of the control sample we used Crawford and Garthwaite's (2005) Revised Standardized Difference Test (RSDT). This test assesses whether the difference between L's RTs on valid and invalid trials is significantly larger than comparable differences obtained in our sample of non-synaesthetic controls. We assessed these differences for both visual and auditory cues, and applied the appropriate Bonferroni correction (alpha of .01/2 = .005). For the visual cues L showed significantly larger differences between valid and invalid RTs (cueing effects) than controls RSDT $t(7) = 5.00, p < .002$. She also showed larger cueing effects than controls with auditory cues RSDT $t(7) = 5.48, p < .001$.

Overall, the current findings in Experiment 1 are consistent with Smilek et al. (2007) who also used a cueing task and Price and Mentzoni (2008) who used the SNARC (non-cueing) task. Like Smilek et al., we showed strong synaesthetic cueing effects using visually presented month names. We extended this work by showing that aurally presented months names are also capable of directing a synaesthete's attention to locations in space. Most importantly, we empirically validated L's description of having different mental vantage points depending on whether she heard or saw the month names - both visually and aurally presented month names elicited strong cueing effects. Critically, the same month names yielded opposite cueing effects depending on whether they were seen or heard. Furthermore, the lack of cueing effects found for control participants reflects the absence of a spatial representation for months of the year. This is consistent with Price and Mentzoni (2008), who demonstrated month-SNARC effects for synaesthetes, but not for the eighteen controls that participated.

2.4. Experiment 2 (Hours)

The results from our first experiment clearly demonstrated that month names could direct L's spatial attention and guide her behaviour. For this synaesthete, the months of the year are allocated spatial locations that form an atypical spatial form (akin to a scoreboard 7). L also allocates hours of the day to spatial locations. Unlike her 7-shaped mental calendar, her spatial form for hours of the day is far from atypical. In fact, she herself describes it as a standard "clock face". For non-synaesthetes, the clock face represents a convention of how we can translate time units into space in an agreed upon manner. Despite the familiarity of the clock face's time-space mappings, L's clock face differs from the standard clock face in a number of key ways. First, L's clock face is lying horizontally rather than standing upright (see Fig. 1.1b). Second, what is unique about her clock face is how vivid this representation is for her. Third, and most importantly for this study, is her propensity to view this clock face from different mental vantage points depending on whether she *sees* a time unit, or *hears* a time unit. Unlike non-synaesthetes, for whom there is a canonical representation of a clock face (as though it is viewed from directly in front), for L seeing and hearing hour names leads her to view her clock face from completely different vantage points. Specifically, seeing the hours of the day (e.g., 3 AM) leads her to mentally view her clock face from a vantage point that is closest to the 6, farthest from the 12 (standard clock face), whereas hearing hours of the day (e.g., the spoken words "three AM") leads her to mentally view her clock from the opposite vantage point (closest to the 12, farthest from the 6). In fact, she prefers to view her mental clock from this auditory vantage point (upside down), and uses it even when just thinking about the hours of the day.

The purpose of Experiment 2 is twofold. First, we sought to replicate L's vantage-point-dependent cueing effects using hours of the day rather than months of the year. Second, we sought to assess whether non-synaesthetes would show cueing effects from visually and aurally presented hour units. Here, our rationale was that since the clock face is arguably the one standard manner in which time units are allocated to spatial locations for those without synaesthesia, then the non-synaesthetes might also show hour-name cueing effects. That is, the nighttime hours of 2 A.M., 3A.M., and 4 A.M., should cue attention to the right and the daylight hours of 8A.M., 9A.M., and 10 A.M., should cue attention to the left.[2] L's multiple vantage points for viewing her mental clock, as well as the fact that a clock face is presumably the manner in which non-synaesthetes would likely map time units to space, affords a number of interesting predictions related to L and to time-space synaesthesia in general. If hour names can trigger shifts of L's visual attention, then L should be quicker at detecting targets that fall in the synaesthetically cued location versus the opposite (invalid) side of space. One salient attribute that appears to differentiate

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[2] The terms 'nighttime' and 'daylight' are only being used here to aid in understanding of the two categories used (cue left versus cue right). L's attention is triggered by the positions of the hours around the clock face. Thus, our predictions would not change if we were to instead cue her with the hours 2 P.M., 3 P.M., and 4 P.M.

synaesthetes' experience of spatial forms from non-synaesthetes' spatial forms (e.g., the standard number line, the clock face) is that synaesthetes spatial forms are more vivid and intense than their non-synaesthetic counterparts. If so, this should influence the *magnitude* of cueing effects. In other words, if the spatial forms of time-space synaesthetes were more vivid than non-synaesthetic spatial forms (such as the standard clock face), then we would expect larger cueing effects for the synaesthete compared to the non-synaesthetes.

Critically, if it is also true that L's vantage point changes when she hears the hours names instead of seeing them, those same daylight hours that cued her to her left side of space when visually presented should now orient her attention to her right side of space, when these hours are aurally presented. In sum, if the visual and aural inducers lead to different vantage points we should find a three-way interaction between the type of inducer (visual and aural), the hour cues (daylight hours versus nighttime hours) and side of target (left and right) - the same triple interaction that we showed in Experiment 1. Finally, we expect that even if non-synaesthetes do show cueing effects, because of a canonical representation of the standard clock face, these effects will be the same for auditory and visual presentations of the time units (i.e., they will NOT show vantage point shifts) and will fail to show a significant three-way interaction.

2.5. Methods

Participants

The same participants that took part in Experiment 1 participated in Experiment 2.

Materials

The design was the same as Experiment 1, except the six time cues were the hours of the day (2 A.M., 3 A.M., 4 A.M., 8 A.M., 9 A.M., 10 A.M.). In one condition the hours were presented visually in the center of the display, and in another condition they were broadcast aurally over a built-in computer speaker.

Procedure

The procedure was identical to that of Experiment 1. Participants were to respond as quickly as possible once targets were detected, and to withhold responses on catch trials when no targets were presented.

2.6. Results and Discussion

L made few errors on 'catch' trials (98% correct). Again, only participants that scored above 80% on catch trials were included in the analysis, which resulted in two being excluded. Observations that were +/- 2.5 SDs from that individuals' cell mean were considered outliers. This resulted in 5.2% trials being discarded from the synaesthete and an average of 6.01% from the controls. We used the same 3-factor ANOVA as that used in Experiment 1, with the Bonferroni correction (alpha level of .005) to control type-I error rates for multiple tests. As predicted, L showed a significant 3-way interaction between type of inducer, hour cues, and side of target ($F(1, 904) = 28.75, p < .0001$). The separate analyses for each of the controls failed to show this interaction (F-statistics of the controls ranged from .01 to 3.14 – values whose probability failed to be below our Bonferroni corrected alpha level of $p < .005$).

Planned comparisons revealed the source of the 3-way interaction for L, and can be seen by the solid and dotted lines connecting the key pairs of means in Fig. 1.4 (the error bars represent the 95% confidence intervals). We predicted that when visually presented with the daytime hours (8 A.M., 9 A.M., 10 A.M), L's attention would be cued to the left. Supporting our prediction, L detected left targets ($M = 235$ msec) faster than right targets ($M = 415$ msec) following daylight hour presentations - shown with the positively sloped solid line in Fig. 1.4A. As well, we predicted that the nighttime hours (2 A.M., 3 A.M., 4 A.M.) should cue her attention to the right. Following nighttime hour presentations, right targets ($M = 240$ msec) were detected faster than left targets ($M = 421$ msec) – see the negatively sloped dotted line in Fig. 1.4A.

For the aural cues (shown in Fig. 1.4B), we predicted the opposite pattern of cueing. Namely, daytime hours (8 A.M., 9 A.M., 10 A.M) should now cue attention to the right. Supporting our prediction, after daytime hour presentations right targets (*M* = 238 msec) were detected faster than left targets (*M* = 393 msec) – see the sloped solid line in Fig. 1.4B. Likewise, we predicted that nighttime hours (2 A.M., 3 A.M., 4 A.M.) should now cue attention to the left. Following nighttime hours presentations, left targets were detected faster (*M* = 237 msec) than right (*M* = 365 msec) - see the positively sloped dotted line in Fig. 1.4B. For these planned comparisons all $\underline{t}$ values > 20.0, and all $\underline{p}$ values < .0001.

These findings parallel those found for the months in Experiment 1, and further show that L's synaesthetic representations of the hours of the day can bias her spatial attention to those locations. L also showed a change in vantage point according to whether she saw or heard the hours presented, replicating the vantage point change found with the months (Experiment 1).

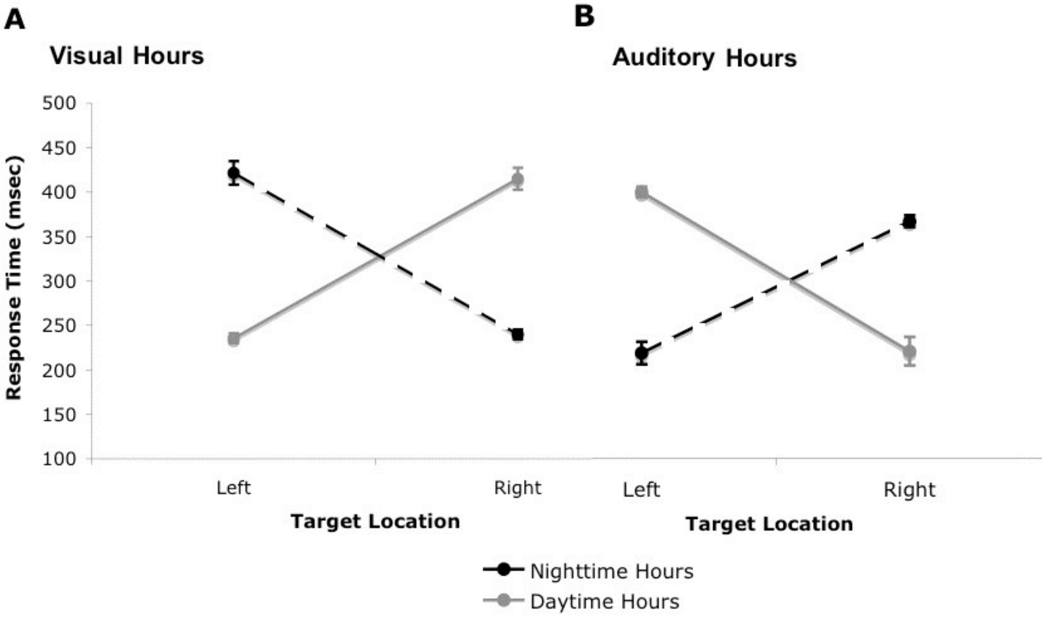

Figure 1.4: **Mean response times of the synaesthete (L) for Experiment 2 (Hours) across the two conditions: visual (Panel *A*) and auditory (Panel *B*).** Note "nighttime" hours refer to the hour cues 2 AM, 3 AM, and 4 AM, while the "daytime" hours refer to 8 AM, 9 AM, and 10 AM. The error bars represent the 95% confidence intervals.

Fig. 1.5 illustrates the mean response times of the control participants, with bars around the means reflecting the 95% confidence intervals. The asterisks denote L's mean response times. As shown in Fig. 1.5, L's means lie within the range of control means for synaesthetically cued (valid) trials, but outside of the range of controls for invalid trials. As expected, controls failed to show the triple interaction that L did. Contrary to our expectations, controls as a group also failed to show the two-way interaction where daylight hour cues would facilitate right target detection, and nighttime hour cues would facilitate left target detection (*F*(1, 56) = .177, *n.s.*). Even on an individual level, none of the controls showed this predicted interaction (largest *F*-value among the controls being *F*(1, 896) = 5.49, *n.s.* following Bonferonni correction).

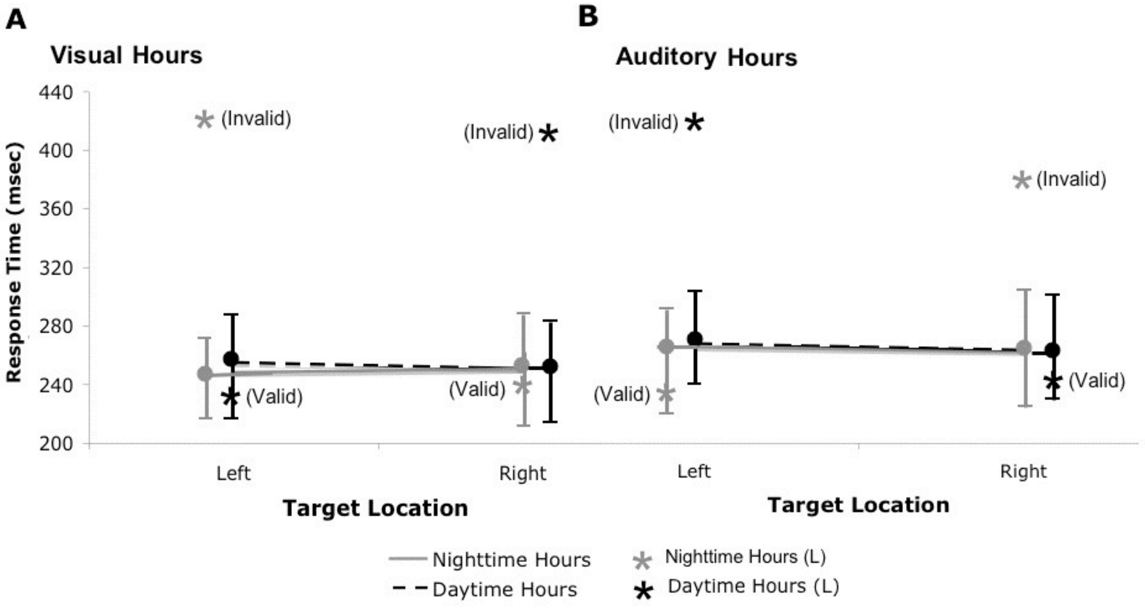

***Figure 1.5:* Mean response times of the Controls for Experiment 2 (Hours) across the two inducer conditions: visual (Panel *A*) and auditory (Panel *B*).** The error bars represent the 95% confidence intervals of participant means. The asterisks represent L's data, showing that her means fall inside the range of Controls during the valid trials (*valid*), while she is an outlier during invalid trials (*invalid*). "Nighttime" hours refer to the hour cues 2 AM, 3 AM, and 4 AM, while the "daytime" hours refer to 8 AM, 9 AM, and 10 AM.

A recent study by Dodd, Van der Stigchel, Leghari, Fung, and Kingstone (2008) demonstrated that the cueing task only works for numbers, and not for other ordinal sequences like months or letters in non-synaesthetes. Thus, our failure to find cueing effects in our non-synaesthetes appears to be in line with their findings. The cueing effect sizes for L and each of the controls are presented in Table 2. The left side of the table shows the RTs for the valid and invalid trials and the magnitude of the cueing effect for visual hour cues. Once again "valid" trials are valid from the synaesthete's perspective; for visual presentations nighttime hours followed by targets on the right and daylight hours followed by targets on the left comprise valid trials (the same mappings occur for controls using the standard clock face). For the auditory cues, "valid" trials for the synaesthete are opposite to controls (so to calculate controls' cueing effect sizes keep the magnitude and merely reverse the sign). As can be seen in Table 2, the cueing effect sizes are much larger for the synaesthete L, than for any of the controls for both the visual and auditory presentations. To directly compare L's cueing effect sizes to those of the control sample we again used Crawford and Garthwaite's (2005) Revised Standardized Difference Test (RSDT). For the visual cues L showed significantly larger differences between valid and invalid RTs (cueing effects) than controls RSDT $t(7) = 17.93$, $p < .0001$. She also showed larger cueing effects than controls with auditory cues RSDT $t(7) = 24.89$, $p < .0001$.

2.7. Overall Conclusions

The results of these experiments replicate those found by Smilek et al. (2007). Like Smilek et al., we showed that time units (months and hours) can direct the attention of a time-space synaesthete independent of her intention. Even though L was aware that the time cues were not predictive of the target location, she could not process the time unit without it biasing her attention to the corresponding location in space. In both experiments, when the target fell in the location cued by the time cue, she was significantly faster than when the target fell in the opposite location. We also extended the work of Smilek et al. by showing

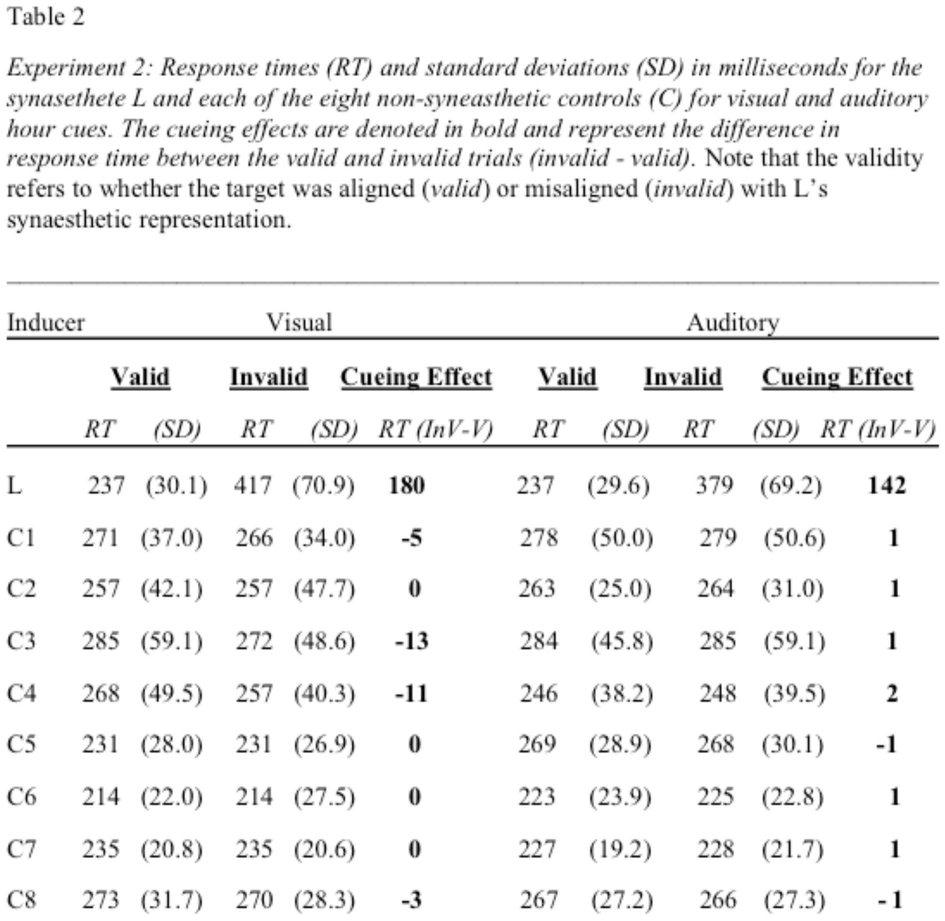

Table 2

Experiment 2: Response times (RT) and standard deviations (SD) in milliseconds for the synasethete L and each of the eight non-syneasthetic controls (C) for visual and auditory hour cues. The cueing effects are denoted in bold and represent the difference in response time between the valid and invalid trials (invalid - valid). Note that the validity refers to whether the target was aligned (*valid*) or misaligned (*invalid*) with L's synaesthetic representation.

Inducer	Visual					Auditory				
	Valid		**Invalid**		**Cueing Effect**	**Valid**		**Invalid**		**Cueing Effect**
	RT	*(SD)*	*RT*	*(SD)*	*RT (InV-V)*	*RT*	*(SD)*	*RT*	*(SD)*	*RT (InV-V)*
L	237	(30.1)	417	(70.9)	**180**	237	(29.6)	379	(69.2)	**142**
C1	271	(37.0)	266	(34.0)	**-5**	278	(50.0)	279	(50.6)	**1**
C2	257	(42.1)	257	(47.7)	**0**	263	(25.0)	264	(31.0)	**1**
C3	285	(59.1)	272	(48.6)	**-13**	284	(45.8)	285	(59.1)	**1**
C4	268	(49.5)	257	(40.3)	**-11**	246	(38.2)	248	(39.5)	**2**
C5	231	(28.0)	231	(26.9)	**0**	269	(28.9)	268	(30.1)	**-1**
C6	214	(22.0)	214	(27.5)	**0**	223	(23.9)	225	(22.8)	**1**
C7	235	(20.8)	235	(20.6)	**0**	227	(19.2)	228	(21.7)	**1**
C8	273	(31.7)	270	(28.3)	**-3**	267	(27.2)	266	(27.3)	**- 1**

that time-space associations could be dependent on the modality of the inducer (visual or auditory). This was the case for L who demonstrated opposite cueing patterns between the auditory and visual conditions (Fig.'s 1.2 and 1.4). For instance, when visually presented with the months *January, February,* or *March*, she was significantly faster to detect targets located to her left side of space (consistent with her synaesthetic locations of these months), whereas when these exact same months were presented aurally the reverse pattern emerged; she was faster to respond to targets on her right side (consistent with the synaesthetic location of the months from her auditory vantage point). This was also true for the hours of the day in Experiment 2. Therefore, our results provide objective evidence consistent with L's subjective reports of her modality-dependent mental vantage point changes. They also conclusively show that these synaesthetic representations are real spatial experiences that do indeed direct her spatial attention and can influence her behaviour.

Although our research (as well as Smilek et al., 2007 and Price and Mentzoni, 2008) clearly demonstrates the robustness of these time-space pairings for individuals with time-space synaesthesia, there is much evidence that ordinal sequences (like months, days of the week, letters, and numbers) are spatially coded in non-synaesthetes as well (Dehaene et al., 1993; Fischer et al., 2003; Gevers, Reynvoet, and Fias, 2003, 2004). For example, Gevers at al. (2003) used a SNARC-type (non-cueing) task and had participants make temporal order judgments concerning the months January to April and September to December by identifying whether a month came before or after the month of July (order-relevant task). They found that earlier months were responded to faster with the left hand and later months faster with the right hand, leading the authors to conclude that the ordinal representation of time was spatially defined. Yet, in a second experiment, Gevers et al. introduced an order-irrelevant task (i.e., does the month end in the letter R or not?) and also found a SNARC effect, albeit of a significantly smaller effect size than the effect size for the order-relevant task. The finding that even a small SNARC effect was present in a task that only required superficial analysis of the month name without having to refer to any sort of spatial reference, suggested that the spatial component of the time unit could be activated into a sequence automatically. It should be noted however, that Gevers et al.'s results were not replicated in a recent study conducted by Price and Mentzoni (2008), demonstrating just how variable these cognitive effects are across participants and tasks.

In the Gevers et al. (2003) task, the goal was to make before/after judgments about the presented month names (non-cueing task), whereas in the present study the goal of the task was to detect simple targets (cueing task). Participants were expressly told that the month names were essentially superfluous (i.e., that they did not predict target locations). The failure to show any cueing effects for month names among the control participants in the present study indicates that for non-synaesthetes any associations between months and spatial locations are far from robust, and do not lead to cueing effects in a simple target detection task. It has been suggested by Galfano, Rusconi, and Umiltá (2006) that the passive viewing of a cue might not be sufficient to bias attention to a particular location in space that otherwise would occur if the cue was actively processed. For instance, just presenting a meaningless number or month name on a computer screen is likely not strong enough to activate a mental calendar or number line and allow retrieval of the month's position in a sequence. For non-synaesthetes, this might account for the variability across studies that attempt to provide objective evidence that the spatial mappings of numbers and time units influences overt behaviour. In general for non-synaesthetes, the magnitude of effect sizes might be influenced by the type of judgment made (it seems that ordinal information might lead to smaller effects than magnitude information, but see Tang, Ward, and Butterworth, 2008), and cueing effects appear to be less robust and reliable than when stimuli are actively processed (as in the SNARC-type tasks). Thus, given the fact that (1) non-synaesthetes have only an implicit mapping between months and spatial locations, and (2) month cues need not be processed to do this simple target detection task - it is not surprising that non-synaesthetes showed no cueing effects in the month cueing task.

We were somewhat surprised that in Experiment 2, for the non-synaesthetes hour names (e.g., 3 AM) failed to activate the hour-space mappings of the standard clock face to a point where they influenced behaviour. No cueing effects were observed either at the group or the single subject level. Ristic et al. (2006) did show cueing effects of numbers when participants were told to *imagine* that the numbers represented the hours on a clock. Likewise, Bächtold et al. (1998) showed SNARC effects using a non-cueing task that corresponded to different mental reference frames that were induced by asking participants to imagine numbers on a ruler versus a clock face (also see Price, 2009). In the current study, no such instructions were given to participants. This supports the argument that at least for non-synaesthetes cueing effects will arise only through active processing of the cue (e.g., imagining the hour positioned on a clock face). The cueing effects found by Ristic et al. might have also been enhanced by telling participants to imagine a clock face, and including four possible target locations (left, right, top, and bottom) that correspond more to the clock face than the two target locations (right and left), used in Experiment 2. Essentially, based on our failure to show any cueing effects in the hour cueing experiment, we conclude that the mappings between time-units and space are far from robust in non-synaesthetes, and whether or not these mappings can be empirically demonstrated in cognitive tasks depends on the specifics of the experimental design. Specifically, we propose that in order to show such behavioural effects in a reliable, robust manner, at minimum the empirical design must ensure that the cues are actively processed.

In contrast to the null effects with the non-synaesthetes, the mappings between time and space for the synaesthete (L) were both strong and reliable even using a cueing task where the time-units did not have to be processed to complete the required task. Given that under these conditions, L still showed very robust cuing effects, we conclude that L's time-space mappings are far more vivid than those possessed by any of the controls. Here the findings involving the standard clock face are particularly relevant. Despite the potential for the clock face to instill time-space mappings in the non-synaesthetes, no cueing effects were noted – a finding that stands in direct contrast to the strong cueing effects noted for L using these same cues. The findings of Experiment 2 support the subjective claims of synaesthetes who propose that being presented with a time unit triggers a vivid, conscious experience of a spatial map in which the time units are arrayed.

Arguably what is most fascinating and unique regarding L's time-space pairings was the complete reversal in response time patterns for heard months (and hours) compared to seen months (and hours). These opposing patterns support her subjective claim that she views her spatial forms from opposite mental vantage points for seen versus heard inputs - essentially reversing her outlook on time! It is interesting to speculate why L might have developed these different mental vantage points within her spatial representation of time units. L reports that she prefers to view her time units from an auditory vantage point and does so even when thinking about the time units. One may speculate that when L was a child, she first learned the names of the months by hearing them. To aid in her month learning, she mapped the month names to arbitrary sequential locations in space (with January, on her right, April in front of her, July on her left and subsequent months extending away from her). These right-to-left mappings, and the L shaped space that formed early on in her pre-school years were essentially unconstrained by cultural influences. When she attended school however, the month names in addition to being presented aurally would also be presented visually by the teacher. Here cultural influences would dictate that January would be in the leftmost position followed by February, March, April, extending in a rightward direction (for a recent review of how culture can dictate and influence the development of imagined space for numbers and time units see Hubbard et al., 2009). These visual depictions of (culturally defined) left-to-right months shown by her teachers, would conflict with L's right-to-left sequencing of the months. One way of resolving the conflict of these visually presented left-to-right months with her idiosyncratic representation of right-to-left months (at least for the early months), was to maintain her L shaped space, but mentally view it from a different (opposite) location (from the crux of the 7). By viewing the space from this new location, January, February, March, would run from left to right (as she was shown in school), but now the tail of her space would run behind her rather than away from her (see Figure 1.1). A similar logic might explain her clock face mappings. Although this speculation is admittedly post-hoc, Jarick, Stewart, Smilek and Dixon (in prep) are currently investigating this possibility.

The present findings are in some ways reminiscent of the classic study by Bisiach and Luzzatti (1978) who asked two left neglect patients to imagine and describe landmarks of the Piazza del Duomo in Milan (a familiar location to both patients). Patients mentally viewed the square first looking from the steps of the Cathedral onto the square. From this vantage point they described only those landmarks that appeared on the right side of the square and ignored all those on the left side. However, when they changed their mental vantage point to the opposite side of the square (now facing the Cathedral), the patients described the buildings and landmarks that they had previously ignored. This study showed that neglect following stroke influenced the experience not only of the external world, but also the internal representations of that world. It also showed that just as we can change our vantage point by changing locations in the physical world, we could mentally change our vantage point within an internal representation of that world. In the current study, we conceptually replicated these general principles. We showed that changing mental vantage point had a profound effect on attention using a cueing paradigm. We presented month or hour names that were associated with a particular vantage point, and biased attention to a particular side of space. We then showed that changing mental vantage point (by presenting the same month or hour names in a modality associated with a different vantage point) biased attention to the previously unbiased side of space. Thus, while the neglect patients used changes in mental vantage point to name previously neglected locations, L used changes in mental vantage point to bias her attention to formerly unbiased locations in space.

Moreover, the current work also informs us about the correspondence between real world space and imagined space. In the real world, we often view spaces from different vantage points. In the neglect study, presumably, the patients had physically experienced the Piazza Del Duomo from different vantage points (facing the church versus sitting on the church steps). In the current study, profound effects of vantage point emerged in a space that the synaesthete *had never actually experienced* in the physical world. Her calendar space is entirely mentally generated. As such, one might imagine that there would only be a single canonical perspective for viewing this space. However, the current results conclusively show that for this mentally generated space (that has no real-world equivalent), different mental vantage points are both possible, and are systematically employed by the synaesthete. The current findings suggest, therefore, that the characteristics that govern external spaces (the fact that we can explore a space from multiple vantage points) appear to also govern internal spaces. This interpretation maps on to the subjective descriptions of a number of synaesthetes who report being able to navigate through their mental calendars, which like L, they have never physically experienced. In addition, this study shows that the vantage point from which this internal space is viewed can have dramatic influences on detecting targets *in external space*. That is, while January is on her left in this mentally created *internal* space, it influences her ability to detect targets on the left side of a computer screen, presented in real-world *external* space.

The precise mechanisms underlying these profound differences observed between L and the controls in our cueing tasks is currently being examined. However, there is growing evidence indicating that the parietal lobe is the main area responsible not only for providing connections between numbers and space, but also ordinal sequences and space, as well as aspects of spatial attention (Tang et al., 2008; also see Hubbard et al., 2005, 2009 for reviews). Tang et al. (2008) used functional magnetic resonance imaging (fMRI) to study which brain areas were dedicated to cardinal versus ordinal properties of number forms. Their findings showed distinct but partially overlapping neural networks in the intraparietal sulcus (IPS), which suggests that the IPS is not only involved in numerical sequences, but in processing non-numerical ordinal concepts as well. In terms of spatial attention, the posterior IPS has been shown to be involved in activating different spatial reference frames, where the human homologue of the monkey lateral IPS codes for eye-centered reference frames (Ben Hamed, Duhamel, Bremmer, and Graf, 2001) and ventral IPS deals with head-centered reference frames (Duhamel, Bremmer, Ben Hamed, and Graf, 1997). Recent work on the SNARC effect has suggested that these spatial numerical associations are dependent on eye- and world centered reference frames (Hubbard et al., 2005, 2009; Wood, Nuerk, and Willmes, 2006). Therefore, it appears that certain areas in the posterior IPS are responsible for the cross-activation of ordinal sequences and space in synaesthetes as well as in non-synaesthetes. From our behavioural data here, we can only speculate that these connections might be stronger in synaesthetes than non-synaesthetes - a situation that would account for the more robust cueing effects in L compared to the non-synaesthetes. It is interesting to consider how a lifetime of experience consistently making associations between time units and space could modify (by possibly facilitating) the connectivity between spatial (human VIP and LIP) and ordinal (posterior IPS) areas within the parietal cortex.

A second, more recent hypothesis attempting to uncover the neural substrate associated with sequence-space synaesthesia was proposed by Eagleman (2009). Eagleman believed that the key characteristic underlying sequence-space synaesthesia was that it was triggered by the ordinality of the sequences (opposed to cardinality) and thus, we should find a stronger connection between brain areas that process ordinal categories and brain areas responsible for spatial processing. In support of this theory, an fMRI performed on sequence-space synaesthetes demonstrated a common region in the right hemisphere, an area located in the medial temporal gyrus (Pariyadath, Churchill, and Eagleman, 2008) in response to words related to ordinal sequences (e.g., letters, numbers, months, etc.), whereas words related to non-ordinal categories predominately activated areas in the left-hemisphere that are commonly believed to process language. Therefore, Eagleman (2009) proposed that the right medial temporal gyrus is the common substrate that underlies sequence-space synaesthesia. As a word of caution however, it is important to note that only one study to date has shown the activation of the medial temporal gyrus in synaesthesia, which was Pariyadath, Churchill, and Eagleman (2008).

In sum, this study makes six claims. First, visually presented month names can bias the spatial attention of time-space synaesthetes. Second, aurally presented month names can also bias the spatial attention of individuals with spatial forms for time units. Third, aural and visual presentations of the time units can elicit different mental vantage points from which L can view her spatial forms. Fourth, the ability of time units to bias attention appears to be stronger for synaesthetes than non-synaesthetes, even when the time units under consideration are similar for synaesthetes and non-synaesthetes (i.e., the standard clock face). Fifth, mental space such as L's 7 (or L) - shaped mental calendar, which has no real-world correspondence, nevertheless adheres to the characteristics of real-world spaces. Specifically, just as we can experience real world external spaces from different vantage points, L can experience this purely internal space from different vantage points. Sixth, the cueing effects reveal that vantage point changes within an internal space can influence the ability to attend to and detect objects in external space. Such a finding highlights that although real world experience may help us to mentally view a given space from different vantage points, real-world experience of the space is not necessary – strong vantage point effects can be demonstrated even in a mental space without any real world correspondence. Most importantly, these vantage point effects pertaining to internal space can influence the detection of objects out there in the real world.

In closing, a unifying feature described in the self-reports of time-space synaesthetes is that they find their spatial calendars cognitively useful. Indeed, Simner, Mayo, and Spillar (2009) showed that synaesthetes outperform non-synaesthetes on a variety of temporal and spatial tasks. However, spatially localizing to-be-remembered items is also a well-known mnemonic technique (method of loci) that non-synaesthetes can learn to employ. This study shows that spatial forms (that might aid in memory retrieval) can be accompanied by highly distinct vantage points, which auditory and visual stimuli can differentially activate. By understanding the relationship between spatial forms and these mental vantage points, we can hope to gain a better understanding ultimately of how spatial forms may prove useful for synaesthetes and non-synaesthetes alike.

3: The Ups and Downs (and Lefts and Rights) of Synaesthetic Number-forms[3]

Validation from spatial cueing and SNARC-type tasks

With the growing evidence suggesting that the general population represents 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), tasks have been developed to demonstrate how numbers can direct spatial attention to locations along this mental number line (Dehaene et al., 1993; Fischer et al., 2003; Salillas, Yagoubi, and Semenza, 2008), as well as investigating whether the mental number line can influence behaviours, such as counting and arithmetic calculations (Seron et al., 1992; Ward, Sagiv, and Butterworth, 2009). Dehaene et al. (1993) was the first to empirically demonstrate the link between the mental number line and behaviour using a parity judgment task (SNARC effect). To recap, the SNARC task requires participants make odd/even judgments regarding a centrally presented digit. Participants in this task are typically faster at making the judgment when the response button is compatible with the location of the digit along the mental number line. For instance, participants are faster to make left-handed responses for small numbers versus large numbers. Due to the magnitude of the results, the SNARC effect has been used repeatedly to demonstrate the influence of the mental number line on behaviour (e.g., Daar and Pratt, 2008; Müller and Schwartz, 2007; Notebaert, Gevers, Verguts, and Fias, 2006; Schwartz and Keus, 2004; Ito and Hatta, 2004; Shaki and Fischer, 2008; Wood, Nuerk, and Willmes, 1993).

In addition to the SNARC type paradigms, cueing paradigms have demonstrated that numbers can influence spatial attention. Fisher et al. (2003) showed that attention could be automatically directed to the left or right visual field by simply being presented with a small or large digit. In this cueing paradigm, the digits 1, 2, 8, or 9 are centrally presented on a

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[3] A version of the chapter was originally published in *Cortex, 45,* pp. 1190-1199.

computer screen, followed by a target (circle) to the left or right of fixation. Participants are required to detect the presence of the target circle as quickly as possible by pressing a central button on the keyboard. Fischer at 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 location. Recent electrophysiological evidence provides support for Fischer et al. (2003)'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, Dehaene, Piazza, and Hubbard, 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 to 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). These atypically strong number-space associations (*number forms*) are now considered a variant of synaesthesia (Hubbard et al., 2005; Piazza, Pinel, and Dehaene, 2006; Sagiv et al., 2006; Tang et al., 2008). Synaesthetic number forms seem to *involuntarily* and *automatically* trigger the conscious experience of the location occupied by that number (Seron et al., 1992). That is, whenever a number is seen, heard, or thought of, the synaesthete cannot (through an act of will) prevent experiencing the associated spatial location (Sagiv et al., 2006; Seron et al., 1992). This is one of the first studies to explore the behavioural effects associated with having number-form synaesthesia.

Mentioned briefly in Chapter 2, Tang et al. (2008) conducted an fMRI study to investigate the brain areas underlying the number forms of synaesthetes versus the brain areas supporting the more ubiquitous left-to-right mental number lines. They selected synaesthetes whose number forms ran from left to right, and compared them to controls who presumably had the standard, left to right mental 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 likely a spatial representation of the sequential (as opposed to magnitude) aspects of numbers (Sagiv et al., 2006). This sequential interpretation of this form of synaesthesia may extend to other forms of synaesthesia as well, such as time-space synaesthesia.

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. For both L and B, the numbers 1 through 10 rise vertically from bottom to top, and the numbers 10 to 20 extend horizontally from left to right (see Fig. 2.1 for a "birds eye" view of L's representation). For L, after 20 her numbers run from right to left as shown in the figure. For B, after 20 the numbers extend rightward and away from her.

We first sought to empirically evaluate these 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 horizontal than vertical responses consistent with their standard left-to-right mental number lines (although for some non-synaesthetes, vertical SNARC effects may be present; Gevers et al., 2006; Schwarz & Keus, 2004). 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.

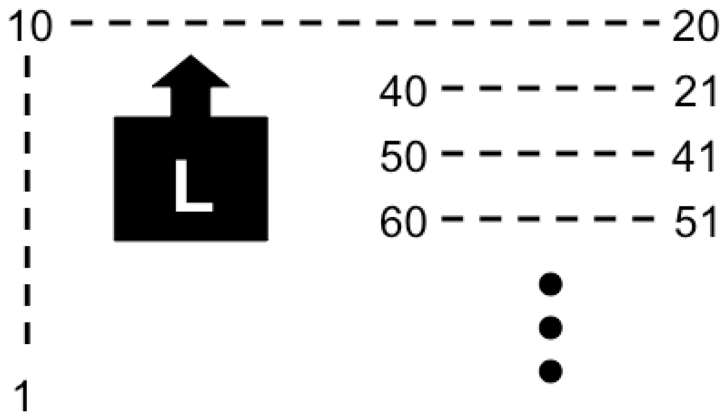

Figure 2.1: **A schematic depiction of the idiosyncratic number-forms experienced by a Number-Form Synaesthete (L).** Her numbers from 1-10 bottom to top in the vertical dimension, while her numbers 10-20 run from left to right in the horizontal dimension.

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 cueing 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 for both L and B the digits

10 to 20 run horizontally from left to right. While L took part in both the SNARC and cueing tasks, B could only participate in the cueing task (Experiments 2 and 3) due to wrist injury that interfered with her making the repetitive movements required during the SNARC task.

3.1. Experiment 3

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.

3.2. Methods

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 the synaesthete(s) 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.

Materials

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 0.6°.

We conducted the different response-mapping conditions in two sessions: a horizontal session (left button "odd" and right button "even") and a vertical session (top button "odd" and bottom button "even"). All participants were given these same response options. For the horizontal session, we classified the correct responses of 1-left (odd) and 8-right (even) as SNARC *compatible* (following the terminology in the SNARC effect literature). Thus, 2-right (even) and 9-left (odd) were classified as SNARC *incompatible*. This classification is in accordance with the left-to-right mental number line. For the vertical directions, we classified 1-down (odd) and 8-up (even) as SNARC compatible, and in turn 2-up (even) and 9-down (odd) were SNARC incompatible (following Gevers et al., 2006). This response classification was determined in accordance with L's number-forms. Note that counterbalancing the buttons was not necessary due to both low and high digits being responded to with both the left or bottom (odd) and right or top (even) buttons.

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. Participants completed the horizontal session first and the vertical session second. Each session contained 20 practice trials (10 compatible, 10 incompatible), followed by two blocks of 160 randomized trials (separated by a self-paced break). 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.

3.3. Results and Discussion

Correct responses for L and the controls were submitted to an outlier analysis in which observations +/- 3 SDs were discarded. This resulted in 0.61% 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 ANOVA, with response direction (horizontal or vertical), and compatibility (SNARC compatible versus incompatible) as factors. We also 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.

Figure 2.2A illustrates the mean response times for L in the horizontal and vertical response directions (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, $t(313) = -0.81$, *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.

In terms of errors, L showed no effect of compatibility for horizontal responses. She made six errors on compatible trials and seven errors on incompatible trials, $\chi^2 = .08, p >$

.05. However, L showed strong compatibility effects for vertical responses. She made four errors on compatible trials, but 21 errors on incompatible trials, $\chi^2 = 12.51$, $p < .001$ (see bracketed values in Fig. 2.2A). 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.

Figure 2.2B 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 (aligned with the mental number line), $t(13) = -5.7$, $p < .0001$. Their compatible and incompatible responses in the vertical dimension (misaligned with the mental number line) 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. 2.2B). 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*].

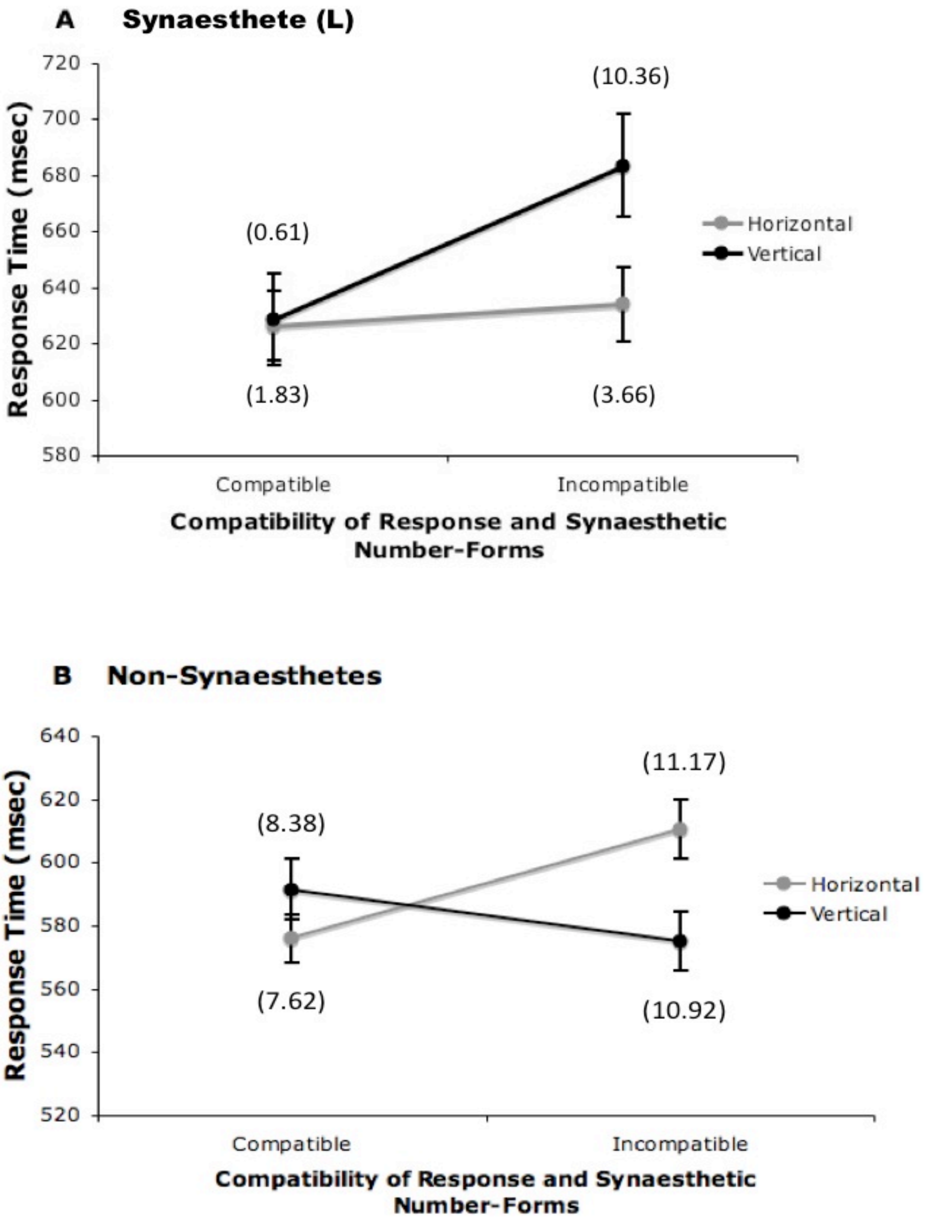

Figure 2.2: **Mean response times for the synaesthete L and non-synaesthetic controls pertaining to the SNARC task in Experiment 3.** The horizontal response condition (left-right button presses) was *misaligned* with L's number-forms, while the vertical response condition (up-down button presses) was *aligned*. Error bars represent the 95% confidence intervals and the bracketed values are the percentage of errors made in each condition.

In 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 SNARC effect when making responses in the vertical dimension (up/down), whereas non-synaesthetes demonstrated a SNARC effect when making responses in the horizontal dimension (left/right). While the SNARC effect results are a positive first step, it is crucial when conducting 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.

3.4. Experiment 4

In this experiment, our primary aim was to provide converging evidence for L's unusual number forms using the cueing task. As with the SNARC task, we ran versions of the cueing task that were either aligned (congruent) or misaligned (incongruent) with L's number-form. We also sought to replicate any synaesthetically triggered effects in a different synaesthete B who happened to have a similarly shaped number form. For both synaesthetes 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.

3.5. Methods

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 who conveyed to us that she spatially representing her numbers in an idiosyncratic manner. Like L, B's number-form extended vertically from 1 at the bottom to 10 at the top. Also like L, her number form then turned rightward and extended horizontally until 20. After that, B reports the numbers swirling out in space in a structure that she cannot explain. Unlike L who projects her numbers out in the space around her, B reports viewing her number-form in her "minds' eye". Twelve of the fourteen non-synaesthetes (three males; *M* = 24 years old) that served as a control group in Exp 3 participated in Exp 4. They were compensated with an honorarium. The University of Waterloo Office of Research Ethics approved all procedures and participants gave written consent before participating.

Materials

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 (~0.1°) 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 (~0.7°) appeared inside one of the boxes that served as the target stimulus.

Procedure

Participants were seated unrestrained approx. 57 cm 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. Following Fischer et al. (2003), after one of six variable delays (SOA's of 350, 400, 500, 600, 700 or 800 msec) following the offset of the digit, a target (white circle) would appear in one of the boxes until the participant responded or 1000 ms 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 10 practice trials (2 valid, 2 invalid, 2 catch) 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.

3.6. Results and Discussion

L and B both performed perfectly on ‘catch’ trials withholding responses on 100% of the trials. Control participants all performed above 80% on catch trials. Correct response times were trimmed for outliers using a +/- 2.5 SD cut-off. This resulted in 0.58% of trials being discarded for L, 1.94% discarded for B, and an average of 4.38% for controls. Separate 3-factor ANOVA’s involving direction (vertical versus horizontal), Validity (valid or invalid), and cue-target SOA (350, 400, 500, 600, 700, or 800 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 ANOVA’s 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. 2.3 for both horizontal (panel A) and vertical (panel B) conditions. For both synaesthetes the ANOVA’s revealed a significant main effect of cue-target SOA 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 Direction 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. 2.3). 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. 2.3 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 SOA (the variable foreperiod effect), $F(5, 24) = 67.39, p < .001$, and a main effect of direction, $F(1, 24) = 10.4, p < .01$, caused by faster responses to horizontal as opposed to vertical cues. Unlike the two synaesthetes, no validity x 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. 2.3, 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) Revised Standardized Difference Test (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 $t(11) = 0.25$]. Non-significant differences were also found for B [RSDT $t(11) = 0.26$ for B, *n.s.*]. However, when the targets were placed vertically (aligned with the synaesthetes' number forms), 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 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 direction interactions.

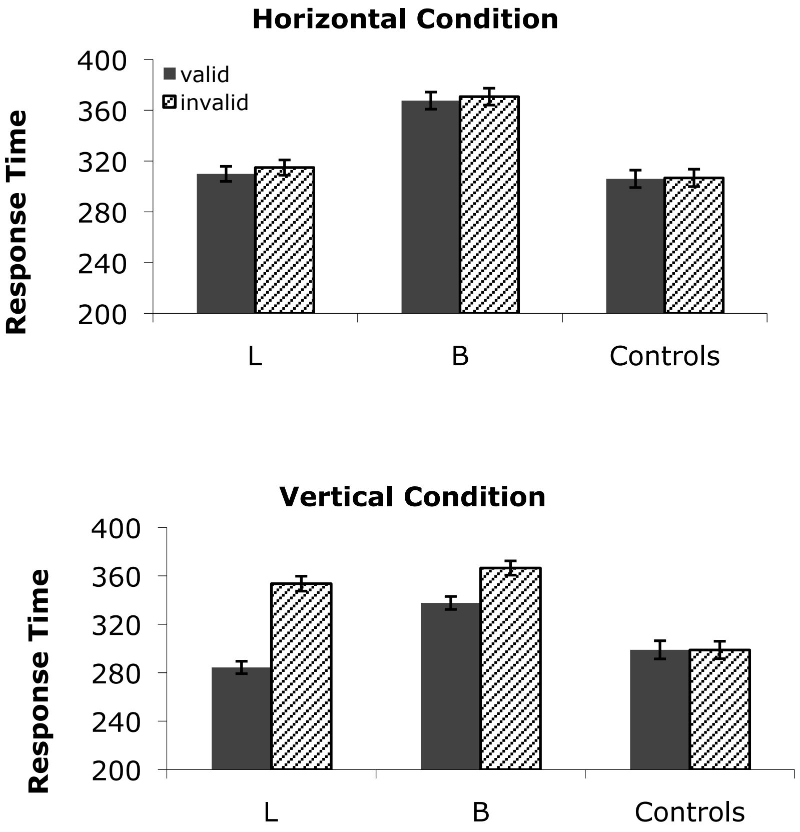

Figure 2.3: **Mean response times for the synaesthetes (L and B) and non-synaesthetic controls, for the horizontal (panel A) and vertical condition (panel B) of the spatial cueing task in Experiment 4.** The number cues were the low digits (1, 2) and the high digits (8, 9). Targets appeared to the left or right of fixation for the horizontal condition and validity was in reference 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 "correct" locations were considered valid trials and "incorrect" locations were invalid trials. Error bars represent the 95% confidence intervals.

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 SOA than Fisher et al. - hence our results cannot be considered an exact replication. It could be argued that by having far more trials, we increased the likelihood that controls did not attend to the numbers since they were irrelevant to target detection. 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 cueing task was misaligned with their number forms, they demonstrated significant 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 3.

3.7. Experiment 5

The spatial cueing task provided converging evidence for the SNARC effects shown in Experiment 3. Only when the targets were aligned with the synaesthetes' number forms, were significant cueing effects observed. The cueing task has an advantage over the SNARC task in that two digit numbers can be used in the cueing 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. 2.1). In Experiment 5, we modified the spatial cueing 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, to 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.

3.8. Methods

Participants

The same number-form synaesthetes (L and B) and twelve non-synaesthetic controls (five took part in Exp's 3 and 4; 7 males; *M* = 22.2 years old) participated for an honorarium.

Materials

The design was similar to Experiment 4, 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).

Procedure

The procedure was identical to Experiment 4.

3.9. 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 +/- 2.5 SDs were removed. This resulted in 0.88% 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 ANOVA's, involving Validity (valid or invalid), and cue-target SOA (350, 400, 500, 600, 700, or 800 msec). Mean response times are illustrated in Figure 2.4. 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 (2005) Revised Standardized Difference Test (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*]. B did not demonstrate significantly larger cueing effects than controls using this procedure [RSDT t(11) = 1.04, *n.s.*]. In sum, both synaesthetes showed significant cueing effects consistent with their subjective reports, and L's cueing effects were significantly larger than controls. Once again, our results provide empirical support for the synaesthetes' contention that the segment of their number forms containing the numbers 10 to 20 run from left to right. Thus, our findings extend the results of Experiment 4 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.

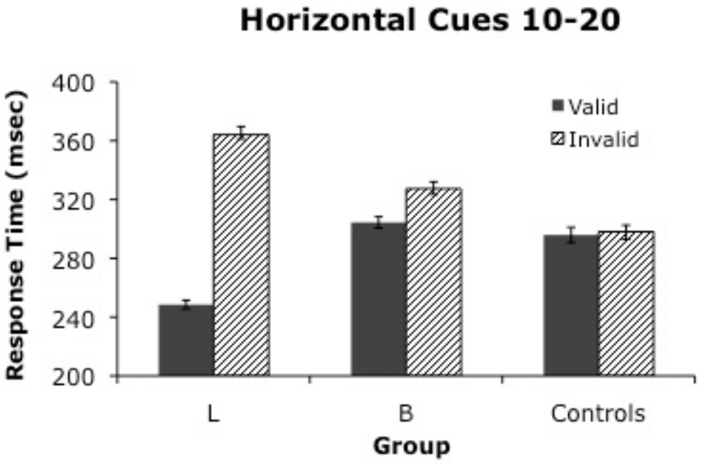

Figure 2.4: **Mean response times for the synaesthetes (L and B) and non-synaesthetic controls during the spatial cueing task in Experiment 5.** The number cues were low digits (10, 11) and high digits (19, 20). Validity was in reference with the synaesthetes number-forms. Error bars represent the 95% confidence intervals.

3.10. Overall Conclusions

This series of experiments provides empirical confirmation of synaesthetic number forms using two types of tasks: the SNARC task (Dehaene at 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. 2.1). In our first experiment using a variation of the SNARC task, our findings confirmed these differences between non-synaesthetes and synaesthetes (Fig. 2.2).

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 direction. 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 (i.e., an excel or SPSS spreadsheet), 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.

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), Sagiv et al. (2006), and Gertner, Henik, and Kadosh (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, importantly they 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 for a recent 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.

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) were 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 low and high numbers are positioned on the clock face (low numbers on the right higher numbers on the left). Similar findings have also been reported by Galfano et al. (2006) and Price (2009). These results highlight how cueing effects may depend 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, Michielin, Zorzi, and Umiltà (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, Ranzini, et al. (2009) 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.

Spatial Cueing, numbers, and Synaesthesia

Importantly, we replicated and extended our SNARC findings with the spatial cueing 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 to 10 rose vertically and 10 to 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 spatial cueing results in the present study provide converging evidence for similar cueing effects with months and hours using a similar spatial cueing paradigm (Chapter 2 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, Ranzini et al. (2009) who also demonstrated interference effects specific to DG's synaesthetic spatial-forms.

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 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 to 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, Foley, Hill, and Ryan, 1999; Dehaene et al., 1993), these two synaesthetes are unswerving in their contention that the numbers 1 to 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.

4 : 9 is Always on Top[4]

Assessing the automaticity of synaesthetic number-forms

One aspect of number-form synaesthesia that has not yet been empirically demonstrated, but has been alluded to in the literature, is the automaticity with which number-forms are experienced and affect behaviour (Gertner et al., 2009; Seron et al., 1992; Smilek et al., 2007). The underlying assumption is that digits automatically trigger a conscious experience of a specific spatial location. However, a plausible alternative that has yet to be ruled out is that these number space mappings are voluntarily produced via top-down processes.

Synaesthetes frequently report that when they perceive a digit, they cannot inhibit themselves from also experiencing the corresponding spatial location that the particular digit synaesthetically occupies. To date, researchers have taken the first steps to: (a) objectively confirm whether or not number-form synaesthetes do indeed experience particular spatial locations upon seeing particular digits (i.e., confirm the reality of number form synaesthesia; Chapter 3, Hubbard, Ranzini et al., 2009; Piazza et al., 2006; Seron et al., 1992), (b) examine whether number-forms affect arithmetic (Ward et al., 2009), and (c) explore where in the brain number-forms might arise (Tang et al., 2008).

A number of authors have indicated that automaticity is a hallmark of various types of synaesthesia (Dixon et al., 2000; Mattingly, Rich, Yelland, & Bradshaw, 2001). In grapheme-colour synaesthesia, researchers have used cognitive tasks such as a variant of the Stroop task to show that synaesthetes cannot prevent synaesthetic colours from occurring, and cannot ignore these colours once they are produced (e.g., Cohen Kadosh and Henik, 2007; Cohen Kadosh, Tzelgov, and Henik, 2008). In order to see if automaticity is also a hallmark of number-form synaesthesia, researchers would have to show that (1) numbers involuntarily cause synaesthetes to attend to specific spatial locations, and (2) that this process is very rapid, and does not require cognitive resources.

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[4] A version of this chapter has been submitted to *Brain and Cognition*.

The involuntary aspect of synaesthetic number-forms has recently been discussed in Gertner et al. (2009). These authors tested number-form synaesthetes and non-synaesthetes on a numerical comparison task (e.g., determining which of two digits is larger). In this task, two digits were either aligned horizontally (beside one another) or vertically (on top of one another) and participants were required to choose the number that was the largest in magnitude. All of the synaesthetes showed a significant distance effect, such that response times increased as the distance between the digits decreased, but *only* when the digits appeared in the orientation consistent with their number-forms. Non-synaesthetes, on the other hand, showed considerable flexibility in their assigning of numbers to space – they showed the distance effect for both orientations. When considering the distance effect, the fact that the spatial orientation of the presented digits seemed to matter to the synaesthetes, but was irrelevant for the non-synaesthetes suggested to Gertner et al., that for the synaesthetes, the presented numbers were automatically activating a conscious experience of space – when the presented digits were aligned with this space it exacerbated the distance effect, when they were misaligned it disrupted the distance effect. Gertner et al. (2009) highlighted the fundamental difference between synaesthetes and non-synaesthetes: namely the "conscious experience" of spatial locations in response to numbers. Specifically, number-space associations for non-synaesthetes appear to be controlled by strategic processes which allow them to flexibly assign different spatial locations to numbers when it is advantageous to do so (low numbers on the left as in the number line, versus low numbers on the right as in the standard clock face) depending on the task demands (Bächtold et al., 1998; Ristic et al., 2006). By contrast number-form synaesthetes seem unable to ignore their number-space associations even in situations when there is either no benefit to the individual, or even a cost.

The current research aims to provide further evidence that automaticity is a hallmark of number-form synaesthesia by showing that numbers elicit the experience of spatial locations very quickly and even for a task that requires no numerical processing at all. We once again studied the number-form synaesthete L, as her number-form for the digits 1 through 9 are orthogonal to the standard left-to-right "mental number line". As a reminder, L's numbers ascend upwards from 1 at the bottom to 9 at the top, and turn right at 10 with the numbers 10-20 running horizontally from left to right. In Chapter 3, we empirically confirmed the atypical structure of L's number-forms in two tasks: a SNARC-type task and spatial cueing task. Whereas non-synaesthetes showed significant effects when the stimuli or response were aligned horizontally (consistent with the mental number line) but not vertically, the synaesthete L demonstrated significant effects when the stimuli or response were aligned vertically (corresponding with her number-forms) but not horizontally. A potentially important difference to note between L and controls during the spatial cueing task, was that L showed significant cueing-effects even at the shortest SOA of 350 ms between cue and target. By contrast, the results of Fischer et al. (2003) suggest that cueing effects for non-synaesthetes begin to emerge only after a cue-target SOA of 700 ms or longer. In spatial cueing tasks, there is an important distinction between strategic or controlled processing and *automatic* processing. Controlled processing involves strategically using the cue to optimize target detection (e.g., voluntarily moving attention to a location where the target is likely to fall). Automatic (or reflexive) orienting involves the obligatory directing of attention to specific locations despite the participant's intentions. That is, reflexive orienting is resistant to top-down influences, such as strategy use. To demonstrate automatic or reflexive orienting of gaze cues, Friesen and Kingstone (1998) and Kuhn and Kingstone (2009) have typically used a cue-target SOA of less than 200 ms, which is said to be the cut-off value below which volitional control of spatial orienting is thought to be impossible. Although our value of 350 ms approached this cut-off, the fact that it was above 300 ms leaves open the possibility that L's cueing effects might have been the result of strategic (as opposed to automatic) directing of spatial attention.

The current experiments modified the previous cueing task to assess the involuntary and automatic nature of L's number-forms. In this task, one of four digits (1, 2, 8, or 9) was centrally presented on the computer screen flanked by two empty boxes, either at the top and bottom of the display (*aligned* orientation) or to the left and to the right (*misaligned* orientation). Following a variable delay (150 or 500 ms), a target (white circle) appeared in the left or right box and participants were instructed to respond to the targets' appearance as quickly as possible by pressing a button on a keypad. The SOA between the cue and target was either long (500 ms) or extremely short (150 ms) – a value below the acknowledged 200 ms cut-off at which strategic influences are precluded. Thus, if it is the case that L's number-forms still influence her spatial attention within this very short time window, then numbers **must** direct her attention to locations specified by her number-forms rapidly. To further reduce the potential of strategic effects from influencing L's response times, we had targets fall in synaesthetically "correct" (valid) locations very rarely (only 14.2% of trials). On the vast majority of trials (85.8%) targets fell in her synaesthetically "incorrect" (invalid) locations. Therefore, if L were to use a strategy to optimize her performance it would benefit her to direct her attention to a location in space that was *opposite* to the synaesthetic location cued by her numbers. Concretely, upon seeing a low number in our design, targets were six times as likely to occur at the top of the screen (in the synaesthetically *invalid* location) compared to the valid location. Thus if it were possible, the best strategy would be to prevent her attention from being directed to her synaesthetically-cued location, and to direct her attention to the top of the screen when seeing a low number, and the bottom of the screen when seeing a high number. As such, by loading up on invalid trials we sought to assess whether automatic cueing effects would still emerge in the face of strategic demands to orient her attention to locations that were opposite to the synaesthetic locations cued by the numbers.

4.1. Experiment 6

4.2. Methods

Participants

A healthy 22-year-old female number-form synaesthete and 12 non-synaesthetic, age-matched University of Waterloo students (9 females; mean age of 20.5 years) volunteered to participate for an honorarium. All participants reported having normal or corrected-to-normal vision and were right-handed. The University of Waterloo Office for Research Ethics approved all experimental procedures and participants gave written consent before participating.

Materials

Stimuli were presented on a LG 17” LCD flatscreen computer display controlled by a Mac mini. We used the same stimuli as in Chapter 3. The fixation was a central dot (diameter 0.1° of visual angle) flanked by two hollow boxes (1° in width and height) that were 10° in eccentricity (approx. 5° from central fixation). For the horizontal condition the boxes appeared to the left and right of the display, whereas for the vertical condition they were situated at the bottom and top of the display. The cues were the digits 1, 2, 8, and 9 in Arial font (subtending 2°). The target was a white circle (0.7°) that appeared inside one of the two boxes. All stimuli were white presented on a black background. Manual button-presses were made on a response pad equipped to record response times with millisecond accuracy (Cedrus RB 530). SuperLab 4.0 was used to present the stimuli and record the response times of each participant.

Procedure

Participants were seated comfortably at a distance of 57 cm in front of the computer monitor and response pad. Typical trial events were as follows: fixation for 500 ms, replaced by a cue (either 1, 2, 8, or 9) for 150 ms, followed by a target. Targets were either presented immediately after the cue (150 ms SOA), or after 350 ms (500 ms cue-target SOA). Targets remained on screen until the participant responded or 3500 ms elapsed. On “catch” trials, no target was presented and the boxes remained empty for 3500 ms. Participants were asked to focus centrally on the fixation dot and the digit cue for the duration of the experiment. They were instructed to detect the target circle that appeared in one of the boxes as quickly as possible by pressing the central button on the response pad, and to withhold their responses on trials when no target appeared (catch trials). These “catch” trials were inserted to make sure that participants were performing the task accurately - waiting until targets appeared prior to making a response rather than anticipating target appearances.

All participants completed the horizontal (*misaligned for L*) condition first followed by the vertical (*aligned*) condition second, (yoked to the order in which L was tested). In each condition participants were given 10 practice trials (4 valid, 4 invalid, 2 catch) followed by 6 blocks of experimental trials with a one-minute break in between. Each block contained 16 valid trials (2 repetitions of each digit at each SOA), 96 invalid trials (12 repetitions of each digit at each SOA), and 16 catch trials (4 repetitions of each digit with no target). Thus, in terms of the overall experiment the proportion of invalid trials amounted to 85.8% compared to only 14.2% valid trials, allowing the cues in this design to be *predictive* of the target location on 85.8% of the trials (but note for the synaesthete, they were predictive of the "wrong" location). In addition to the experimental trials, we included 12.5% catch trials. All trials were randomized within each block. Overall participants completed a total of 768 trials for each condition (horizontal and vertical), with the entire experiment lasting approximately 50 minutes in duration.

4.3. Results and Discussion

L's performance on the 'catch' trials was nearly perfect (99% accurate). Only control participants that performed greater than 80% catch trials were included (mean of controls was 93.5%), which excluded 4 participants. In trimming the response time data for outliers we were cognizant of the fact that there were far more invalid than valid responses. Accordingly all response times were submitted to a non-recursive outlier rejection procedure that adjusts the cut-off criterion for an outlier depending on the number of observations (Van Selst and Jolicoeur, 1994). Thus, observations greater than +/- 2.5 SDs were removed for the invalid trials (n = 288) and observations greater than +/- 2.47 SDs were removed for the valid trials (n = 48). This procedure resulted in few trials being discarded for L (0.31% valid, 0.06% invalid) and controls (0.76% valid, 0.09% invalid). The remaining response times for L and the group of controls were submitted to a 3-way ANOVA involving orientation (horizontal or vertical), SOA (150 or 500 msec), and validity (valid or invalid). The mean response times for L and controls can be seen in Figure 3.1 (horizontal condition) and Figure 3.2 (vertical condition). For both orientations, L and controls showed a significant main effect of delay (both *p-values* < .01), where response times decreased as the delay between cue and target increased. This finding is common with a variety of SOAs and is known to reflect the Variable Foreperiod effect described in Vallesi et al. (2007), where response times have been shown to decrease as time to prepare for the upcoming target increases.

For the horizontal (*misaligned*) condition, high digits predicted the target to appear on the left and low digits predicted targets to appear on the right (i.e., 85.8% invalid locations, with validity referring to the mental number line). For the vertical (*aligned*) condition, high digits predicted the target to appear on the bottom and low digits predicted targets to appear on the top (i.e., 85.8% invalid locations, with validity being relative to L's number-forms). If L were to use a strategy for this task she should use the same one as controls, and thus show a similar pattern of response times as controls regardless of orientation. Given the predictive nature of the cues (85.8% invalid, 14.2% valid), the best strategy for L and controls would be to direct attention to the "invalid" target locations: left/bottom following high digits (8,9) or right/top following low digits (1,2). The ANOVA for L revealed a significant 2-way interaction between orientation and validity, $F(1, 1258) = 78.08$, $p < .001$. L showed no validity effects in the horizontal condition. In the vertical condition despite the fact that strategy dictated moving attention to the invalid location, L still showed strong cueing effects that ran counter to this strategy. As in all previous experiments for these vertical alignments, she showed faster RTs for valid targets compared to invalid targets (for both 150 and 500 msec SOAs, *p's* < .0001). As for the non-synaesthetic controls, no significant main effects or interactions involving validity and condition were found (all *p's* > .05).

To more directly compare L's cueing-effects to those of controls, we performed the Revised Standardized Difference Test (RSDT; Crawford and Garthwaite, 2005). We used this test to assess whether L shows differences between conditions (valid vs. invalid) that are larger than the differences shown by a control sample. We performed this analysis for the long and short SOAs for both the vertical and horizontal orientations and applied the appropriate Bonferroni correction (alpha of .05/4 = .0125). For the horizontal (misaligned) targets, L's response time differences between valid and invalid targets for both SOAs were not significantly different from controls (all *p-values* > .05). However for the vertical (aligned) targets, L's cueing effects (invalid minus valid RTs) at the 150 ms SOA condition were significantly larger than those of controls, RSDT $t(7) = -5.08$, $p = .0014$. Moreover, these same cueing effects were even larger for L at the 500 ms SOA, RSDT $t(7) = -6.76$, $p = .0003$. Recall that if L were applying a performance optimization strategy, rather than these standard cueing effects where valid trials are responded to faster than invalid trials, L should have shown faster performance on *invalid* trials.

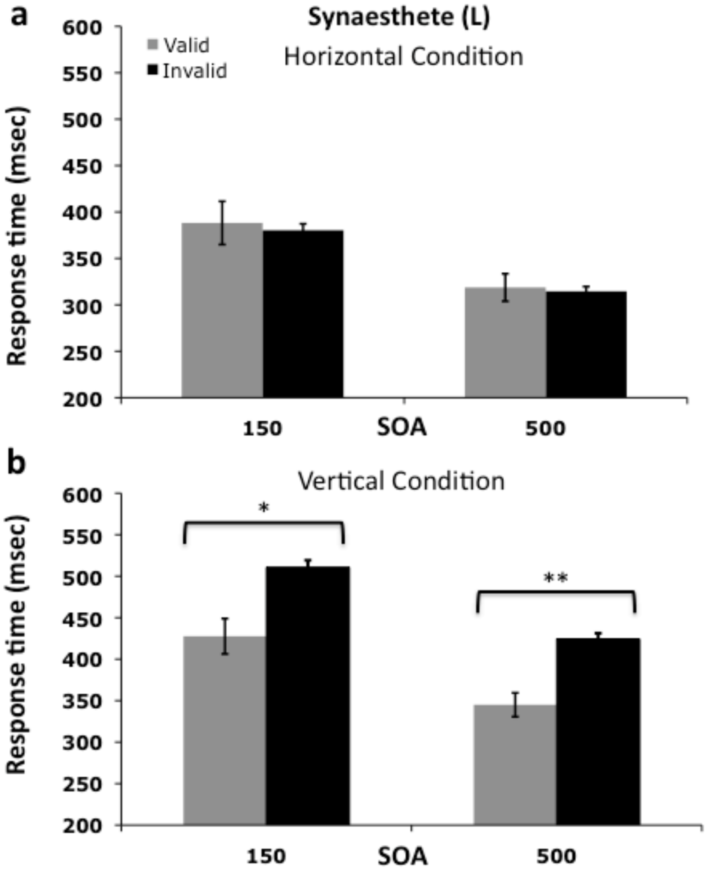

Figure 3.1: **Number-form synaesthete (L)'s response times to detect targets for the horizontal (*misaligned*) condition (a) and vertical (*aligned*) condition (b) in Experiment 6.** The error bars represent confidence intervals and the asterisks symbolize significance less than .01. Note: * $p < .01$ and ** $p < .001$.

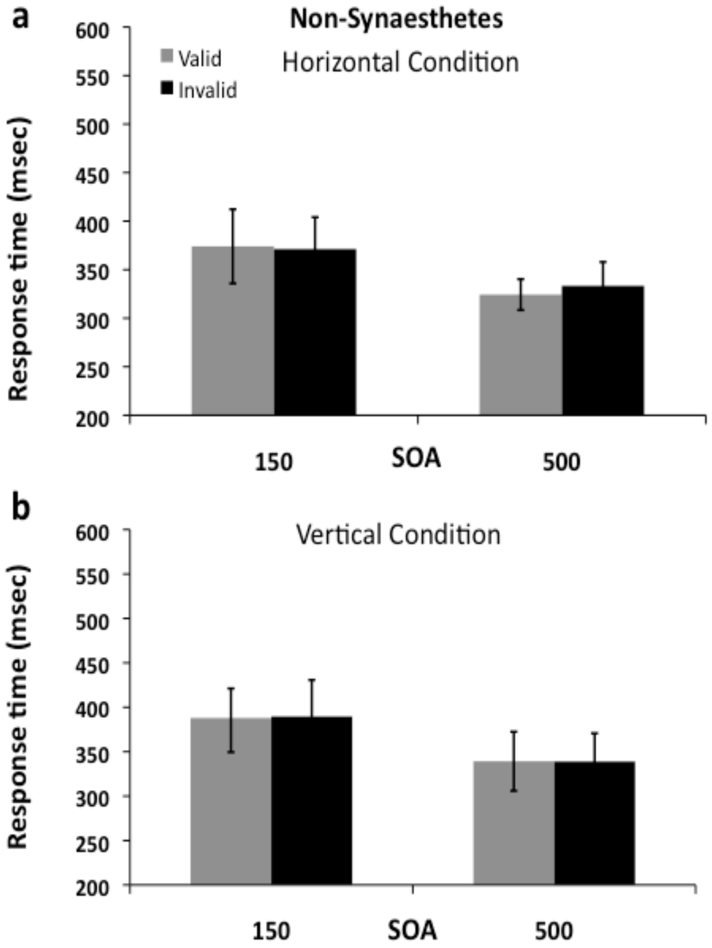

Figure 3.2: **Average response times of the non-synaesthetic controls to detect targets for the horizontal condition (a) and vertical condition (b) in Experiment 6.** The error bars represent confidence intervals.

What our data suggest is that neither L nor the controls employed the optimal strategy, or in fact any strategy at all. That is, even though the ANOVA revealed a significant cueing-effect for L in the vertical condition, it was not in the optimal direction that would improve her performance. Rather L continued to respond with reference to her number-form, such that she was much quicker to detect targets in their synaesthetically valid locations (14.2% of the trials) than invalid locations (85.8% of the trials). Furthermore, the absence of an interaction between SOA and validity and the significant RSDT results shows that this validity effect occurred at both short (150 ms) and long (500 ms) SOAs between cue and target. Earlier we mentioned that if L were to use a strategy for detecting the targets in the vertical condition, she *should* orient her attention to the top when cued by a low digit and to the bottom when cued by a high digit (opposite to her synaesthetic number-space). Our findings suggest that L did not (or could not) use this strategy and her number-forms continued to bias her attention to the synaesthetically valid locations.

These finding are consistent with our previous results (Chapter 3) using a non-predictive design (50% valid, 50% invalid targets). As in that study, L demonstrated cueing-effects only when the targets were aligned with her number-forms (*vertical condition*) and showed no cueing effects when target locations were misaligned (*horizontal condition*). Importantly, despite the fact that we loaded up on invalid trials (so that moving her attention to her synaesthetic location would yield a performance cost on the vast majority of trials), L still responded in accordance with her synaesthesia. Critically, not only did L show cueing-effects with the SOA of 500 ms, but she showed cueing-effects with only 150 ms between cue and target onset as well. Since 150 ms is generally acknowledged to be too quick to implement a strategy, our findings indicate that L's number-forms must direct her attention *automatically*.

4.4. Experiment 7

What is evident from Experiment 6 is that L's number-forms occur automatically and can influence her attention very quickly (within 150 ms). This was shown in the vertical condition where she responded significantly faster to detect the targets when they appeared in her synaesthetically valid locations at the shortest SOA of 150 msec. However, it was unclear whether or not L *could* (through top-down control) implement a strategy that would conflict with her number-forms in the vertical domain. Therefore, we conducted a follow up experiment where we e*xplicitly instructed* L to use a performance optimization strategy that was based on the fact that for the vast majority of trials, one could correctly predict where the target would be located based on the identity of the digit (e.g., in the vertical condition, low numbers predict targets on the top and high numbers predict targets on the bottom of the screen). As in the previous experiment, this strategy if implemented would be in direct contrast with the organization of L's number-forms. In order to use the appropriate strategy, L would have to direct her attention to her synaesthetically *invalid* locations. There are only two ways in which she could accomplish this: (1) by suppressing her number-forms and focusing on the predictability of the cue, or (2) allow the cues to direct her attention towards the valid locations, and then re-direct her attention to the invalid locations. Both of these processes should take time and require cognitive effort.

Therefore, if L's number-forms are experienced automatically (as suggested by Experiment 6), then her synaesthesia should still influence her attention at the shortest SOA of 150 ms in the vertical condition. Thus, she should continue to respond fastest to the synaesthetically valid targets in this short amount of time. At long SOAs of 800 ms however, L should have ample time to employ the performance optimization strategy that we instructed her to use, allowing her to respond faster in the reverse direction of her synaesthesia (i.e., faster for invalidly cued targets). In essence, this second experiment was designed to pit automatic effects against strategic effects.

Lastly, L should not show any automatic cueing effects in the horizontal condition since her number-forms are misaligned with the target locations. She might, however, be able to use the strategy at the 800 ms SOA. This pattern of results should also be observed for the group of non-synaesthetic controls.

4.5. Methods

Participants

The same number-form synaesthete (L) and 18 non-synaesthetic University of Waterloo students (10 female; average age of 21.2 years) volunteered to participate for an honorarium. All participants reported having normal or corrected-to-normal vision, were right-handed, and were native English speakers. The University of Waterloo Office for

Research Ethics approved all experimental procedures and participants gave written consent before participating.

Materials

We used the same stimuli and design as Experiment 6, except that we used a longer SOA of 800 ms with the short SOA of 150 ms between cue and target.

Procedure

The procedure was identical to that of Experiment 6, but with different (explicit) instructions. Instead of the participants being naïve to the experimental design, we explicitly informed L and controls of the disproportional trial types in both orientation conditions. For example, we informed participants in the horizontal orientation that "85.8% the targets will fall on the left following a low digit (1 or 2) and on the right following a high digit (8 or 9)". We further encouraged them to use that strategy to improve their performance during the experiment.

4.6. Results and Discussion

L performed perfectly (100% accurate in both conditions) on the catch trials and we included only those control participants that performed greater than 80% or better on these trials (two controls were excluded on this basis). Controls' catch trial means were 97.4% for the horizontal condition and 95.7% for the vertical condition. All response times were submitted to the observation weighted non-recursive outlier procedure (Van Selst and Jolicoeur, 1994). Thus, observations greater than +/- 2.47 SDs were removed for the valid trials (n = 48) and observations greater than +/- 2.5 SDs were removed for invalid trials (n = 288). This procedure resulted in few trials being discarded for L (0.62% valid, 0.04% invalid) and controls (0.88% valid, 0.08% invalid). The remaining response times for L and the group of controls were submitted to a 3-way ANOVA involving orientation (horizontal or vertical), SOA (150 or 800 ms), and validity (valid or invalid). The mean response times for L and controls across the two SOAs can be seen in Figure 3.3 (horizontal condition) and

Figure 3.4 (vertical condition). Like the previous experiment, both L and controls showed the Variable Foreperiod effect with a main effect of SOA for both conditions, $F(1, 1298) = 216.38$, $p. < .0001$ and $F(1, 15) = 16.44$, $p < .001$, respectively. Controls showed no other main effects or interactions involving either condition or validity (all *p-values* > .05).

The ANOVA for L revealed a significant 2-way interaction between orientation and validity $F(1, 1298) = 149.77$, $p < .001$. As can be seen in Figure 3.3, when the targets were aligned horizontally, she was able to take advantage of the strategy that was given to her; targets in "invalid" locations (with respect to the standard number line) were responded to faster than targets in "valid" locations. This pattern occurred both at short and long SOAs. By contrast, in the vertical condition when targets locations were aligned with her number forms (i.e., presented either on the top or the bottom of the screen), but were presented mostly (85.8% of the time) in invalid locations, she was unable to take advantage of the strategy. Indeed at the long SOA she showed no difference between valid and invalid trials, and at the short SOA she showed faster valid than invalid trials – a data pattern that is opposite to the strategy, but consistent with the hypothesis that numbers automatically direct her attention to specific spatial locations dictated by her synaesthetic number-form.

To directly compare L to controls, we again performed the Revised Standardized Difference Test (RSDT) for both orientations. The RSDT for vertical targets (aligned with her number form) revealed that L's cueing effects were significantly greater than controls at the shortest SOA of 150 ms, RSDT $t(15) = -3.0$, $p = .0089$, but not at the longer SOA of 800 ms, RSDT $t(15) = -0.68$, *n.s.* Thus, as predicted L's response times were quicker for the synaesthetically valid targets than invalid targets when the SOA was too quick to implement a strategy (within 150 ms). In other words, when the targets were *aligned* with her number-forms and the SOA was too rapid for her to use a strategy, L was quicker to detect targets that fell in the synaesthetically valid locations than the invalid locations. This finding replicates the validity effect shown in Experiment 6. It confirms that L's number-forms are elicited automatically despite her deliberate intentions to use the strategy provided. The fact that she was attempting to use the strategy can be seen by her performance in the 800 msec SOA condition. In contrast to the previous experiment, (where she showed a significant cueing effect) in this experiment, her attempts to use the strategy abolished any cueing effects. Thus, one must assume that in the vertical condition, she adopted a set where she attempted to use the strategy on all trials. With enough time to implement the strategy (in the 800 ms condition) she was able to overcome her synaesthetic number-space mappings and abolish any cueing effects. Without enough time to implement the strategy, her performance in the 150 msec SOA condition was dictated by the automatic cueing of her attention by the numbers to their synaesthetically valid locations.

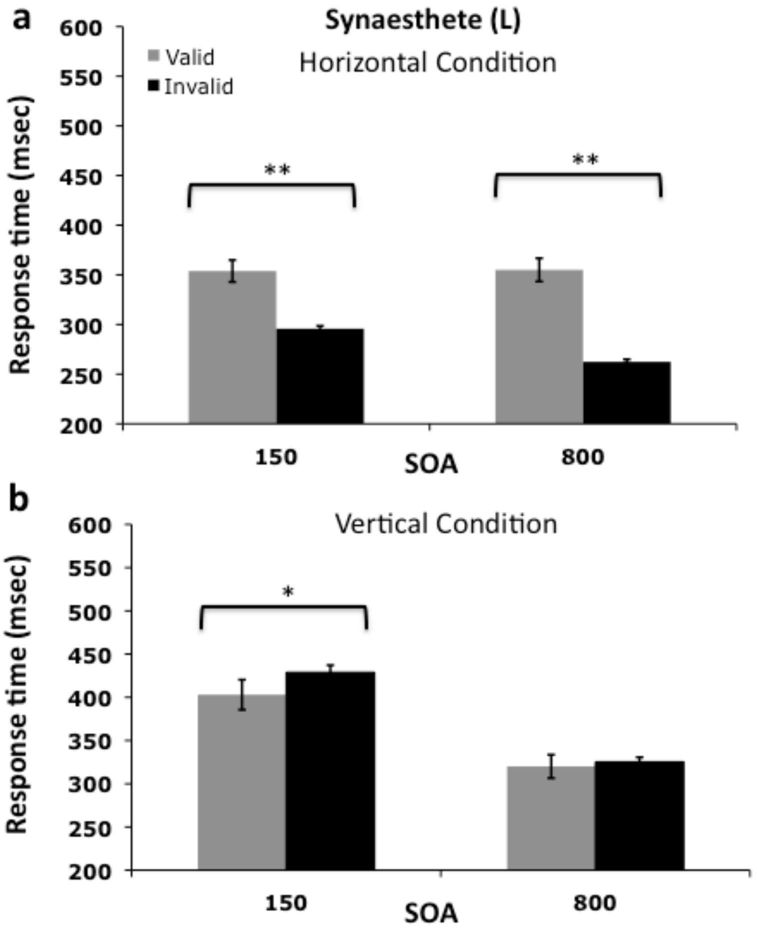

Figure 3.3: **Number-form synaesthete (L)'s response times to detect targets for the horizontal (*misaligned*) condition (a) and vertical (*aligned*) condition (b) in Experiment 7.** The error bars represent confidence intervals and the asterisks symbolize significance less than .01. Note: * $p < .01$ and ** $p < .0001$.

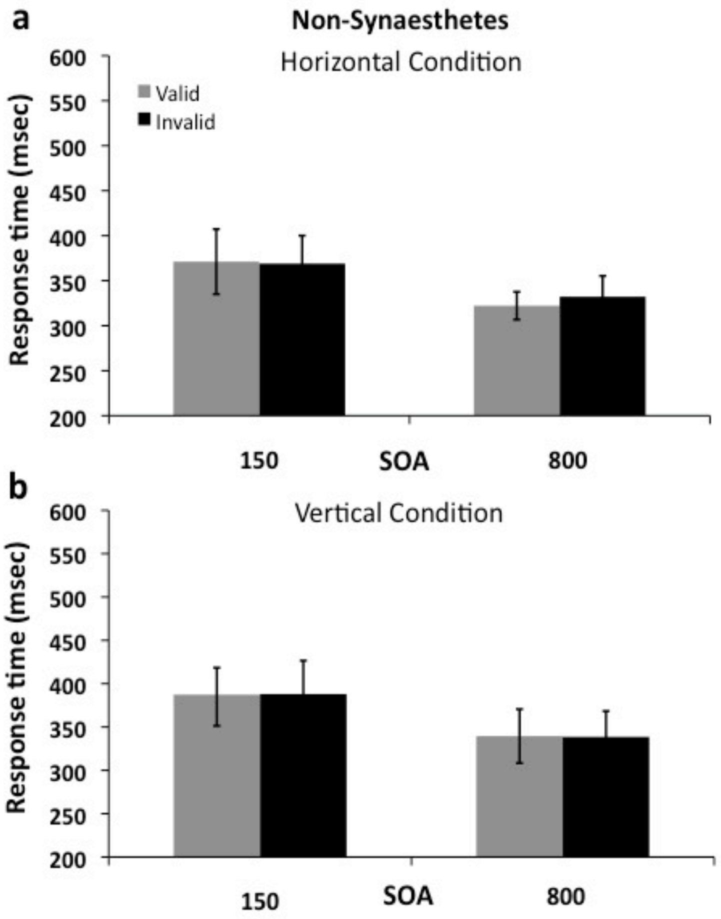

Figure 3.4: **Average response times of the non-synaesthetic controls to detect targets for the horizontal condition (a) and vertical condition (b) in Experiment 7.** The error bars represent confidence intervals.

Contrary to our predictions, the RSDT for the horizontal (misaligned) condition revealed significantly larger cueing effects for L compared to controls for both the 800 ms SOA, $t(15) = -5.83$, $p < .0001$ and for the 150 ms SOA, $t(15) = -7.84$, $p < .0001$. Particularly surprising was the significantly faster responses to the invalid trials compared to valid trials **at the shortest SOA**. Since this SOA is too short to implement a performance optimization strategy, another explanation must be sought. Previous research with L showed a remarkable ability to change the mental vantage point (MVP) with which she views her synaesthetic forms (Chapter 2). Regarding her number forms, L claims that although her typical mental vantage point is in front of the number 1, so that the numbers 1 to 9 rise up in front of her as shown in Figure 3.5, she reports that she can move around in her number-space taking on a variety of MVPs. In fact, she reports that she has had to do this many times throughout her education, where the numbers are typically represented horizontally from left to right. Thus, given the instruction that high digits would most often be followed by leftward targets, and low digits by rightward targets, one way in which L could align her bottom-up number form to this particular spatial arrangement is by mentally viewing her number form from the left side with the number 5 in front of her (the "revised" MVP in Fig. 3.5). Note that from this mental vantage point, her bottom up number form becomes a right to left number-form (aligned to the specific instructions). Viewed from this new mental vantage point, low numbers would **automatically** cue her attention to her right, and high numbers to her left[5].

As such, with this new mental vantage point, what we have called invalid locations (for the standard left-to-right number line) would be synaesthetically valid locations for L – a situation that could account for the large cueing effects shown by L at this very short cue-target SOA. This explanation presumes that while she can adopt certain MVPs others may be too difficult, especially when incompatible with her preferred MVP (in front of the digit 1 in Fig. 3.5). Thus, while she can view her rising number-form from the side via a 90 degree change in her MVP (the revised MVP in Fig. 3.5 that creates a right to left form from a vertical one), she cannot completely reverse her MVP by 180 degrees and look at her rising number form from the top so that high numbers are on the bottom, and low numbers are on the top (likely due to resulting numbers being upsidedown). Perhaps there are constraints on her potential MVPs whereby she can tolerate looking at a vertical form from the side (but not a 180-degree perturbation), which would be directly opposite to her habitual (or "canonical") mental vantage point for viewing this form.

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[5] This 90° change in MVP only occurred when L consciously altered her strategy. Because there was no explicit strategy in the previous experiments, there was no need for L to change MVP in those cases.

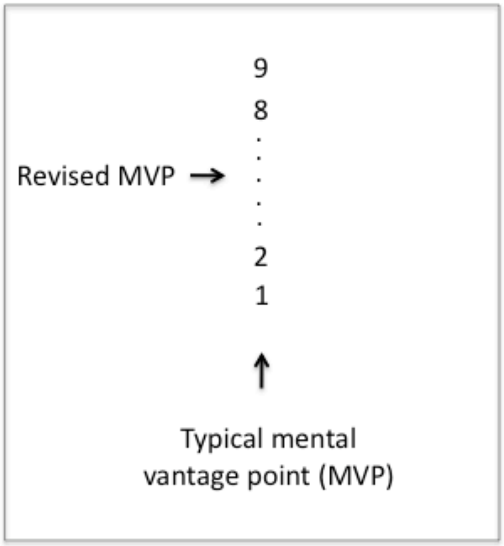

Figure 3.5: Schematic "birds-eye" view of L's preferred mental vantage point (MVP) at the bottom and L's revised MVP once she was explicitly instructed to use a strategy with high digits cueing her to the left and low digits cueing her to the right (Experiment 7).

4.7. Overall Conclusions

This study examined whether synaesthetic number-forms are elicited rapidly (i.e., automatically), despite any type of strategic influences imposed on by the task. To investigate this, we used a spatial-cueing paradigm whereby we (1) decreased the SOA to 150 ms, and (2) increased the proportion of invalid trials (85.8%) compared to valid trials (14.2%). Research has repeatedly shown that 150 ms is too quick for participants to employ any type of strategy during a cueing task. Thus, if L's number-forms were elicited without voluntary control, then the digit cues should trigger shifts in her visual attention to the synaesthetically valid target locations even at the shortest SOA of 150 ms. This was true in Experiment 6, where L demonstrated cueing-effects consistent with her synaesthetic number-form (faster RTs for valid trials) at both the 150 and 500 ms SOAs when the targets were aligned vertically. Even when L was explicitly told about the uneven trial proportions

(85.8% invalid) in Experiment 7, she still responded according to her vertically rising number-form – she was faster to detect targets in the synaesthetically cued locations than at the uncued locations in the 150 ms condition, providing the strongest evidence of automaticity. At the longer SOA of 800 ms, however, it is evident that L was trying to implement some control over her attention but only enough to diminish the cueing-effects found in the 150 ms SOA. That is, once L had ample time between cue and target onset it seemed as though she was able to exert some control over where her attention was allocated, either by suppressing her synaesthetic number-forms from directing her attention to the cued locations, or by re-direct her attention from the cued (valid) locations to the invalid locations on at least half of the trials.

Although it is unclear what strategy L was using to diminish the vertical cueing-effects at the 800 ms SOA in Experiment 7, what is clear from our data is that L's unique number-form can influence her attention rapidly (within 150 ms). These findings support Gertner et al. (2009) who argued that number-forms are involuntarily activated in synaesthetes, yet our data suggests that this is only the case at very short time intervals, or if not instructed to use a strategy. Moreover, this activation of number-forms occurred even when the task did not explicitly require any numerical processing (unlike the number comparison task in Gertner et al., 2009). Here in Exp. 7, we showed that L could flexibly utilize different vantage points to improve her performance in the horizontal condition. By changing her mental vantage point, she could view her number form from a vantage point that aligned with the given strategy. Our data suggests that L was able to turn a vertical number form into a right to left number form by changing her mental vantage point. With this new mental vantage point, L showed that low numbers automatically cued rightward spatial locations and high numbers leftward locations. That number-forms orient attention automatically is supported by the fact that cueing effects emerged at a very short SOA, even when the synaesthete would have performed better not having their number-form. Thus, where Gertner et al. (2009) argue that synaesthetes have very concrete forms in which encountering visual numbers causes their unique forms to "pop out" (pg. 372) in an inflexible manner, we would suggest that although the number forms may be inflexible – they may be mentally viewed from different vantage points. While there may be some flexibility with which these mental vantage points can be viewed, not all mental vantage points appear to be possible – L could not adopt a vantage point that directly conflicted with her preferred vantage point.

It is important to keep in mind that synaesthetes not only differ significantly from non-synaesthetes in terms of their number-form structure; they also differ from one another in terms of their experience. From multiple interviews with synaesthetes, one can observe qualitative differences from one synaesthete to the next. Individual differences across synaesthetes has been empirically shown by Dixon et al. (2004), where they made the distinction between synaesthetes that project their experience out into space (termed *projectors*), and synaesthetes whose experience is contained within their "minds eye" (termed *associators*). With such differences between synaesthetes, it is no wonder why some studies could find no differences between synaesthetes and controls (e.g., Piazza et al., 2006), while others have found strong differences between the two groups (e.g., Chapter 3, Hubbard, Ranzini, et al., 2009; Simner et al., 2009). In fact, Smilek et al. (2004) highlights this individual variation among time-space synaesthetes, showing effects in only three of the four. A question that remains in the literature is the proportion of synaesthetes that can flexibly modify their mental vantage point within their spatial forms, and whether this navigation-like behaviour is akin to a mental rotation or translation of the spatial-form or the individual (Sagiv et al., 2006). Indeed Simner et al. (2009) suggest that it is likely akin to mental rotation since synaesthetes seem to perform superiorly to nonsynaesthetes on mental rotation tasks. While these questions require examining multiple synaesthetes, it is important that group studies control for individual differences in order for synaesthesia to advance with an accurate understanding of the phenomenon.

In this study, we focused on one synaesthete (L) who has reported that she "projects" the numbers out in the space around her. Thus, she perceptually experiences numbers in very specific spatial locations that unlike non-synaesthetes, is a very vivid and conscious experience for her. Previously, we confirmed L's subjective reports of her number-forms using two objective tasks: SNARC-effect and spatial cueing tasks (Chapter 2). Here we extend those findings to show that L's number-forms are not only highly consistent and strong enough to influence her attention, but they occur extremely quickly. In addition, even when attempting to use a strategy that dictates redirecting attention to precisely the opposite spatial locations to those dictated by her synaesthesia, she still shows cueing effects that are consistent with her number-forms. This fast, involuntary directing of attention bears the key attributes of automatic processing. Here we provide the first empirical evidence to support the contention that automaticity is a potential attribute of number-form synaesthesia.

5

: General Discussion

Since Galtons' reports of number-forms in 1880, there has been little empirical research to investigate and support the authenticity of his claims. Most of the research on numerical cognition has focused on discovering the ways in which the general population represents numbers, with very few studies concerned about the extraordinary number-forms that Galton described. Over the past decade, however, researchers have come to realize the importance of studying individual differences in the manner by which people represent numbers. Recently a number of investigations have been devoted to exploring individuals who possess extraordinary spatial representations, such as number-forms or time-space associations - today referred to as time-space and number-form synaesthesia. In fact, *Cortex* recently published a special issue focused on visuo-spatial forms and synaesthesia, which included the results from Chapter 2 and 3 of this thesis. The overall goal of the current thesis was to empirically verify the authenticity of synaesthetic spatial forms, while at the same time provide data that would convincingly demonstrate how time-space and number form synaesthetes differ from the general population.

5.1. *Importance of the current findings*

Smilek et al. (2007) were the first to use empirical methods to verify that time-space representations were consistent over time[6], involuntarily activated, and could automatically direct spatial attention. In Chapter 2, we replicated this work by demonstrating that L's time-space was highly consistent over test-retest sessions, even three years apart. We adopted the same synaesthetic cueing task from Smilek et al., and showed that L was faster

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[6] Sagiv et al. (2006) were the first to show that synaesthetic illustrations were consistent over time.

to respond to validly cued targets than invalidly cued targets. For the first time, we showed that aurally presented month or hour cues could direct this synaesthetes attention. Chapter 2 extended Smilek et al.'s work, showing that L's mental vantage point could change depending on whether the time units were seen or heard. For example, when L saw the word *January*, she reported experiencing January on her left side, however when she heard the word *"January"* she experienced the month on her right side. We found that L was faster at detecting targets in validly cued locations relative to invalidly cued locations, for both visually presented cues (January orients her attention to the left) and aurally presented cues (January orients her attention to the right). We replicated these vantage-point dependent effects in L using the hours of day as well.

Even though all of the non-synaesthetic control groups in our studies did not show any hint of a spatial representation for months (or hours, surprisingly; consistent with Price & Mentzoni, 2008 and Smilek et al., 2007), other researchers (e.g., Gevers et al., 2003, 2004) have argued that months of the year and days of the week could be spatially represented to some extent in the general population. This finding has not yet been replicated, but still remains a possibility. What will likely not be found in the general population however, is L's conscious and vivid ability to mentally navigate within and around an internally generated time-space, being able to take on a variety of mental vantage points. Not only can L view her space from at least two different mental vantage points (i.e., auditory and visual), we have recently shown in a follow-up study that her time-space representation arise automatically (within 150 msec), allowing her to rapidly switch from one vantage point to the next on a trial-by-trial bases (Jarick, Jensen, Dixon, and Smilek, under review). Thus, even if future research does happen to show that time-space representations are inherent in all of us, it is doubtful that they would resemble the extraordinary spatial forms experienced by synaesthetes such as L.

To further contrast synaesthetes from non-synaesthetes, in Chapter 3 we compared the number-form synaesthetes (L and B) to a group of non-synaesthetes in two numerical cognition tasks that have been repeatedly used to demonstrate the spatial associations of numbers in the general population: spatial-cueing and SNARC-type tasks. Both of these tasks confirmed the authenticity of the atypicality of the synaesthetes' number-forms (i.e., rising vertically from 1 to 9, then left-to-right from 10-20). Whereas controls showed the classic SNARC effect for left-to-right responses, L and B showed SNARC effects consistent with the arrangement of their number-forms - in the vertical orientation. These findings were mirrored in the cueing paradigm, where L and B only showed cueing effects (i.e., faster RTs for validly cued targets) when the targets were aligned with their number-forms (top and bottom for the digits 1-9, Exp. 4; left and right for digits 10-20, Exp. 5). Interestingly, controls however, failed to show any cueing effects even when the targets were consistent with the mental number line (i.e., on the left and right; failing to replicate Fischer et al., 2003). This finding, coupled with the fact that L and B showed significantly larger number cueing effects than the controls alludes to one of the hallmarks of number-form synaesthesia, namely the vividness of the number forms. Further research will be needed to ascertain whether it is the vividness of these number forms, or the fact that numbers appear to trigger a conscious experience of space in the synaesthetes, that underlies the more pronounced directing of spatial attention in these individuals.

While the differences in performance between synaesthetes and non-synaesthetes could be attributed to a number of factors, one possibility put forth by Gheri, Chopping, and Morgan (2009) is that synaesthetes might be aware of their unique condition and essentially perform in such a way to show off their unique 'talent'. This possibility was reconciled in Chapter 3. We used the same cueing paradigm and modified it so that the number cues were now predictive of target location 85% of the time. The difficulty for the synaesthete (L) was that the cues predicted the target location that was in the *opposite* direction to the location of where the numbers were located in her synaesthetes number form. Thus, if L were to use a strategy to perform well on this task, she would need to orient her attention to the opposing location cued by the presented number. To make matters worse for L, in one condition we also reduced the cue-target SOA to 150 msec, which is commonly used to reflect automatic processing (e.g., Kuhn and Kingstone, 2009). In the face of these drastic measures to bias L against showing synaesthetic validity effects, validity effects were still observed. That is, despite the fact that targets fell in the synaesthetically cued locations only 15% of the trials, L was still significantly faster to detect these targets, compared to those that fell in the opposite location. The fact that strategy dictated the opposite pattern of results (faster invalid than valid), and that the validity effects emerged with only 150 msec SOA between cues and targets, suggest that numbers *automatically* (or reflexively) directed L's attention to their synaesthetic locations.

In the above experiment, we let the extreme imbalance in invalid relative to valid trials dictate the implementation of strategy – we did not explicitly inform L about this imbalance. In a follow-up experiment we used the same extreme imbalance, but explicitly informed L about the uneven trial proportions. In this experiment, we specifically told her to use a performance optimization strategy that was in direct contrast to her number-forms. At the longer SOA of 800 ms, it was evident that L was attempting to implement the strategy, because she abolished the strong synaesthetic cueing effects. At the short SOA, however she still responded according to her vertically rising number-form – low numbers directed her attention to the bottom of the screen, and high numbers to the top - resulting in the relatively rare valid trials still being responded to faster than the more frequent invalid trials. The findings of this experiment arguably provided the strongest evidence of automaticity, and suggested that L's performance in all of these cueing tasks was involuntary and in no way influenced by experimenter demands.

Overall, this series of studies convincingly demonstrated the reality of time-space and number-form synaesthesia. Although most people could successfully imagine time units and numbers arranged in a spatial structure, individuals with these forms of synaesthesia experience something that is extremely vivid and truly unique. Their synaesthetic experiences are characterized by consistency, automaticity, and permanence.

5.2. *Synaesthesia: all or none?*

Although the claims made in this thesis are heavily reliant on one case-study, we strongly believe that this one case (L) is representative of individuals who belong on the extreme end of the sequence-space continuum. That said, there are likely many individuals who fall in the middle of this continuum - some of whom might have synaesthesia (i.e., associators) and others who might not. At the opposing end of the continuum would presumably be individuals who have absolutely no spatial arrangement for sequences.

Support for such a continuum comes from Brang, Teuscher, Ramachandran, and Coulson (2010) who conducted a large-scale study of time-space synaesthesia in an attempt to meticulously characterize the phenomenon and they discovered that out of 183 “potential” synaesthetes, only 2.2% of them passed their consistency test. Furthermore, those synaesthetes that did pass (“verified” synaesthetes) were significantly less variable in their spatial arrangements (three quarters were circular). However, Brang et al. (2010) noted that it was extremely difficult for some synaesthetes to project their 3D representation onto a 2D platform, and that the month often encompassed a region of space and not a particular point. (This is a common limitation in studies of sequence-space synaesthesia). Thus, although the authors estimate that 2.2% of their sample were verified synaesthetes, this estimate might be considered quite conservative. Nonetheless, their study indicates that those with vivid sequence-space associations (at the extreme end of the continuum) are quite rare.

Consistent with the idea that sequence-space representations lie on a continuum from no spatial representation to a very lucid one, the non-synaesthetes reported by Brang et al. (2010) did not find the task of placing months in spatial arrangements that foreign. Those individuals that described no spatial array for months were able to place the months in non-random locations during their consistency test. Thus, even though the participants could not visualize a spatial array of months, they could (through culture, education, etc.) nonetheless assign months to spatial patterns in a non-arbitrary fashion. Interestingly, the non-synaesthetic representations were likely to be simple linear or rectangle mappings. Brang et al. (2010) speculated that while sequence-space representations might be inherent in all of us to some degree, for non-synaesthetes those spatial representations tend to follow conventional standard (i.e., horizontal or vertical lines), whereas the spatial arrangements experienced by synaesthetes are typically idiosyncratic (e.g., spirals, ovals, ‘scoreboard 7’s’, etc.)

In addition to the differences in spatial structures between ‘potential’ and ‘verified’ synaesthetes, Brang et al. (2010) found critical behavioural differences in a cued recall task pertaining to novel spatial arrangements. That is, synaesthetes outperformed non-synaesthetes when having to learn a spatial calendar in direct opposition to their own. The general learning advantage of synaesthetes over non-synaesthetes suggests that synaesthetes could have superior spatial memory abilities (Simner et al., 2009). This would not be surprising given the amount of experience synaesthetes have viewing their own spatial calendars. Furthermore, it could also be the case that brains of synaesthetes contain direct connections between the sequence and spatial representation regions of their parietal cortex that facilitates the formation of sequence-space relationships. As there are no fMRI studies on sequence-space synaesthesia to date (apart from Tang et al., 2008 that exclusively studied number-forms), the flexibility with which L and other synaesthetes appear to be able to manipulate their spatial forms, is a phenomenon that needs further enquiry.

Extensive informal interviews with a variety of time-space synaesthetes, lead one to speculate that there are classifiable differences among them. For instance, just as there are 'associators' and projectors' among grapheme-colour synaesthetes (Dixon et al., 2004), this distinction is likely true of sequence-space synaesthetes as well. Although this would be difficult to empirically test, the subjective reports of time-space synaesthetes appear to map on to the projector/associator distinction in that some only visualize their spatial calendar in their "minds eye", while others definitely "project" the calendar out in the space in front of them. Likewise, the classification of being a "higher" or "lower" synaesthete might also apply to time-space synaesthetes (Ramachandran and Hubbard, 2001b). It may well be that for some individuals the explicit awareness of a spatial location might only be elicited by the month name itself (e.g., actually seeing the word *January* – 'lower'). For others ('higher' synaesthetes) activating the concept of the time unit may be enough to activate the spatial location. Researchers have come to recognize the importance of adequately discriminating synaesthetes from non-synaesthetes, and of correctly subtyping different experiences. Brang et al. (2010) has taken an important initial step in differentiating synaesthetes from non-synaesthetes using a standard consistency task and a cognitive measure. An ongoing challenge to researchers will be to find ways to empirically differentiate between the different subtypes of synaesthetes suggested by their self-reports. We hypothesize that once such objective measures are available we will be able to show that like their grapheme-colour counterparts, not all time-space synaesthetes are created equal. Our belief is that by correctly subtyping different types of synaesthetes, we will then ultimately be able to place them on a continuum that ranges from non-synaesthetic (effortful assignment of time units to space), to extreme synaesthetic (effortless, automatic assignments of time units to space).

5.3. *Why study synaesthesia?*

Besides being an intriguing phenomenon within itself, synaesthesia also can inform us about mechanisms in the non-synaesthetic mind. The study of synaesthesia can help us understand psychological processes, such as perception, consciousness, memory, development, and so on. Synaesthetes possess experiences that are outside the normal ken of the experiences of non-synaesthetes. For instance, although non-synaesthetes may experience a spatial representation of numbers in the form of the 'mental number line' this representation appears to only be activated on an implicit level. Number-forms, however, have been demonstrated in synaesthetes to be a more explicit phenomenon (e.g., presenting a number leads to an explicit experience of space). Thus, while there are some obvious similarities between synaesthetes and non-synaesthetes, the key lies in their differences. A key question is what is happening in the synaesthetic brain that allows these conscious spatial structures to emerge? The answer to this question could provide clues regarding the mechanisms underlying consciousness and/or spatial perception in the average brain as well. Moreover, the degree to which spatial forms are brought into consciousness might be the critical element detailing where individuals would fall along the non-synaesthetic – synaesthetic continuum (Cohen Kadosh and Henik, 2007).

Researchers in different laboratories have revealed that synaesthetes have specialized cognitive abilities that may confer a cognitive advantage over non-synaesthetes (Simner et al., 2009; Price, 2009, Mann et al., 2009; Brang et al., 2010). For example Brang et al. (2010) and Simner et al. (2009) have reported superior memory advantages associated with synaesthetic number-forms and time-space associations when compared to non-synaesthetes. One important question pertaining to these cognitive advantages involves the chicken or the egg scenario – which came first? Did the skill lead to the synaesthesia or did the synaesthesia lead to the skill? One possibility is that individuals with superior visuo-spatial and memory abilities use these abilities to develop conscious associations between sequences and space (the skill leads to synaesthesia). Alternatively having time-space synaesthesia could provide an additional memory cue (much like the method of Loci) that confers a cognitive advantage over those without vivid time-space mappings (synaesthesia leads to the skill). Conclusively adjudicating between these alternatives remains a challenge for cognitive neuroscience, but either way one can see how investigating the cognitive advantages associated with synaesthesia could highlight the relationship between spatial abilities and abilities like memory in the general population.

The research specifically detailed in this thesis could have implications for theories on numerical cognition, spatial representations, and automaticity. Findings from the numerical cognition literature firmly suggests that we represent numbers in an ordinal, linear manner, with small numbers on the far left side of the line and larger numbers on the right. This linear number line has been demonstrated using a variety of tasks, including the SNARC effect, spatial cueing tasks, number comparison tasks, size congruity, and the distance effect. Our results with L and B challenge this assumption, showing that the number line for some individuals can be vertical, with small numbers on the bottom and larger numbers at the top. Number-form synaesthesia research in general contradicts the notion of a linear mental number line, showing that many number-forms often take on an idiosyncratic structure (e.g., spirals, ovals, staircases, rectangles, etc.). Not only are number-forms atypical from the standard mental number line, it is common for synaesthetes (like L) to actually "see" the numbers explicitly out in space. Evidence for this implicit-explicit difference can be observed in Chapter 3 when one compares both the pattern of results, and the magnitude of the effect sizes, between synaesthetes and non-synaesthetes. In terms of task, we found effects congruent with the horizontal mental number line in controls and the vertical number-forms in the synaesthetes when they performed the SNARC-type task, but controls failed to show any hint of the mental number line during the spatial cueing task. This inconsistency with controls is likely due to the task demands. The SNARC task requires participants to actively process the number ("is the digit odd or even?), which in turn appears to be demanding enough to activate the implicit number line. In the cueing task, there are no requirements to process the number - the participants only concern was where the target was going to appear, causing the number to be irrelevant for non-synaesthetes. A crucial difference between the *implicit* mental number line and *explicit* number-forms is the automaticity with which they arise. For the mental number line to have an effect, it seems as though one needs to actively process the number, just seeing numbers is not sufficient. In number-form synaesthetes however, just seeing (or hearing) a number is enough to automatically activate the synaesthetic spatial location associated with that number, and thus is easily activated with passive tasks (i.e., spatial cueing).

Another central question in the numerical cognition literature is how we represent two-digit numbers. One theory suggests that numbers are represented as whole (*holistic model*), while the competing theory argues numbers are represented in single digits (*parallel model*). Research on number-forms (including our findings with L and B) supports the holistic model, since number-forms tend to form a continuous pattern from 1 to thousands and beyond. Each whole number (single, double, or triple digits) occupies a distinct spatial position along the number-form. Indeed, L reports that numbers are sometimes added or represent more space if they become significant. Therefore, research with synaesthesia supports a holistic model as opposed to a parallel model.

Almost every area in cognitive neuroscience at some point has questioned whether or not a certain perceptual, cognitive, or memory process is *automatic*. By automatic we mean an involuntary or reflexive operation, as opposed to a voluntary and controlled process. The distinction between the two systems could uncover the mechanisms underlying a cognitive process under question. Synaesthetes often report that their synaesthesia occurs involuntarily and that it is difficult to ignore or suppress. The evidence presented in Chapter 4 supports those claims and also suggests that at least for one number-form synaesthete the synaesthetic experience occurs rapidly (in less than 150 ms). These findings could be indicative of a specialized neuronal 'module' (Fodor, 1983) that is dedicated to synaesthetic number-forms. In support of such a module is the finding that under certain conditions L's associations between time and space and numbers and space are not susceptible to strategic manipulations. However, other elements of L's performance argue against a purely encapsulated module. An intriguing attribute of L is her ability to navigate within her internally generated number- and time-space. It seems as though the synaesthetic representations are initially activated following an inducer (e.g., month name), and remain active until they are not needed anymore. Thus, while the representations are active, L can manipulate her viewpoint as needed and rapidly take on a variety of mental vantage points. However, L does claims that it is more difficult to take vantage points that contradict her preferred vantage point[7]. Altogether, the results presented in Chapter 4 indicated that L's spatial representation are, (1) elicited rapidly, (2) obligatory, and (3) are not influenced by other processes, such as strategy use. It is these features that point to number-forms being automatic. Thus, studying the neural architecture underlying synaesthesia could ultimately help to uncover the mechanisms responsible for automatic processes.

While the knowledge gained from synaesthesia research is typically dedicated towards understanding synaesthesia exclusively, much of the knowledge acquired can also be applied to other realms of psychology. The study of synaesthesia arguably is the study of the outer edge of the cognitive envelope – it shows what is possible in a small extraordinary segment of the population. By understanding the edges of the envelope, one could perhaps further our understanding of spatial perception more generally.

In the words of Galton (1880, p. 252),

"*The various ways in which numerals are visualized is but a small subject, nevertheless it is one that is curious and complete in itself.*"

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[7] This claim in itself could have major implications for how we are able to process and manipulate spatial representations.

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