

RUNNING HEADER: Automaticity in sequence-space synaesthesia



NOTICE: this is the author's version of a work that was accepted for publication in *Cortex*. A definitive version was subsequently published in *Cortex* 49: 1165-1186. doi: <http://dx.doi.org/10.1016/j.cortex.2012.10.013>

Automaticity in sequence-space synaesthesia: A critical appraisal of the evidence.

Mark C. Price^a and Jason B. Mattingley^b

^aPsychology Faculty, University of Bergen, Norway.

^bQueensland Brain Institute & School of Psychology, The University of Queensland, Australia.

Correspondence should be addressed to:

Mark C. Price, Psychology Faculty, University of Bergen, Christiesgt. 12, 5015 Bergen, Norway.

Tlf: +47 55 58 31 87

Fax: +47 55 58 98 79

E-mail: mark.price@psysp.uib.no

Abstract

For many people, thinking about certain types of common sequence – for example calendar units or numerals – elicits a vivid experience that the sequence members occupy spatial locations which are in turn part of a larger spatial pattern of sequence members. Recent research on these visuospatial experiences has usually considered them to be a variety of synaesthesia, and many studies have argued that this *sequence-space synaesthesia* is an automatic process, consistent with a traditional view that automaticity is a key property of synaesthesia. In this review we present a critical discussion of data from the three main paradigms that have been used to argue for automaticity in sequence-space synaesthesia, namely SNARC-like effects (Spatial-Numerical-Association-of-Response-Codes), spatial cueing, and perceptual incongruity effects. We suggest that previous studies have been too imprecise in specifying which type of automaticity is implicated. Moreover, mirroring previous challenges to automaticity in other types of synaesthesia, we conclude that existing data are at best ambiguous regarding the automaticity of sequence-space synaesthesia, and may even be more consistent with the effects of controlled (i.e., non-automatic) processes. This lack of strong evidence for automaticity reduces the temptation to seek explanations of sequence-space synaesthesia in terms of processes mediated by qualitatively abnormal brain organisation or mechanisms. Instead, more parsimonious explanations in terms of extensively rehearsed associations, established for example via normal processes of visuospatial imagery, are convergent with arguments that synaesthetic phenomena are on a continuum with normal cognition.

Key Words: sequence-space (spatial form) synaesthesia, automaticity, visuospatial imagery, spatial cueing, SNARC effect

1. Introduction

A significant minority of healthy people experience some form of synaesthesia, a condition in which specific perceptual stimuli such as sounds, smells, tastes or written graphemes, or even just the thought of such stimuli, trigger specific perceptual sensations over and above those that most people would experience in a similar situation. The study of synaesthesia has generated considerable scientific and media interest in the last couple of decades (Mattingley, 2009), attracting journal special issues (e.g. *Cortex*, 2006, 2009; *Journal of Neuropsychology*, 2011) as well as other scholarly reviews (e.g., Grossenbacher and Lovelace, 2001; Hubbard and Ramchandran, 2005; Hubbard et al., 2011; Simner, 2007; Rich and Mattingley, 2002; Ward and Mattingley, 2006) edited volumes and popular accounts (e.g., Cytowic, 2002; Cytowic and Eagleman, 2009; Hubbard and Simner, in press; Robertson and Sagiv, 2005; Ward, 2008, in press). Grapheme-colour synaesthesia, in which letters or digits induce precise colour sensations, is the best known and most studied variety, but a wide range of often cross-modal associations between triggering stimuli (*synaesthetic inducers*) and elicited experiences (*synaesthetic concurrents*) have been recorded (Day, 2005). What these extra dimensions to everyday perceptual experience have typically been argued to share, in addition to their personal salience, is their apparently involuntarily nature, their lifelong presence arising in early childhood, and their consistency over time for any given individual (Rich et al., 2005; Mattingley, 2009), although consistency is now questioned as a necessary hallmark (Simner, 2012).

Here we provide a critical appraisal of recent studies of a phenomenon referred to as *sequence-space synaesthesia* (Eagleman, 2009; Simner 2009). This is the experience that members of common sequences such as numbers and calendar units (days, months, years etc.) occupy distinct loci in imaginal, peripersonal or extrapersonal space which are in turn part of a larger spatially extended pattern of sequence members (Price, 2009a; Simner, 2009). The spatial pattern is sometimes referred to as a *synaesthetic spatial form* (Price, 2009a; Price and Mentzoni, 2008). We focus on the widely held view that these

spatial forms are generated automatically, without the need for cognitive control, and challenge the empirical evidence that has been offered in support of this view.

Automaticity has often been taken as one of the behavioural gold standards for synaesthesia. We would suggest that the historical assumption underlying this creed is that apparently automatic behavioural effects – which distinguish synaesthetes from controls – are explicitly or implicitly taken as consistent with the proposed existence of special brain mechanisms that have been prominently suggested to underlie synaesthesia. These special mechanisms, such as atypical brain wiring that mediates excessive cross-activation between neighbouring cortical areas (the cross-activation theory: e.g., Hubbard and Ramachandran, 2005; Hubbard et al., 2011; Rouw and Scholte, 2007; see Rouw et al., 2011 for a review), or impaired inhibition of normal feedback between cortical areas (the disinhibited feedback theory: e.g., Grossenbacher and Lovelace, 2001; Cohen Kadosh et al., 2009), are in turn taken to legitimize synaesthesia as a topic for scientific investigation. However, even though synaesthetic experiences are typically reported to have an involuntary feel, characterizing their automaticity at a more technical level has proven controversial.

Central to this controversy is the fact that automaticity is not a unitary construct, but, as argued by Pashler (1998) in his widely cited book on attention, it is a grouping of dissociable properties that mental processes may develop if they are practiced intensively over a prolonged period. This folk psychological doctrine that practice may lead to automatic processing has a long history; indeed, Pashler quotes William James' dictum that "habit diminishes the conscious attention with which our acts are performed" (1890/1950, p.114).

More specifically, it is widely held that, with sufficient practice, certain cognitive processes that were initially under voluntary control will not only be performed more quickly and accurately, but may also undergo some fundamental qualitative changes. One key element of these changes is that mental operations may no longer be capacity limited and may therefore no longer interfere with ongoing tasks or themselves be affected by the demands of other tasks. Another key change is that highly practiced processes may eventually be triggered in the absence of voluntary control. Thus, provided a relevant set of stimulus inputs arises within an appropriate context, cognitive processing will proceed

to completion regardless of whether or not the individual intends for this to occur. Pashler (1998) also lists two other elements of automaticity that have been considered important by various theorists. One is that automatic processes are able to proceed without conscious awareness. The other is that automatic processes require little or no mental effort, consistent with the idea noted above that highly practiced processes that become automatic are no longer subject to capacity limits.

As mentioned above, however, automaticity might not be a unitary property. For example, a person who produces a rapid and involuntary response to a stimulus, implying automatic processing, might nevertheless be susceptible to interference from a concurrent task in his response to the same stimulus. In this respect it makes sense to refer to degrees of automaticity, with more strongly automatic processes displaying more of the key hallmarks of automaticity than weakly automatic processes. Furthermore, as suggested by Pashler (1998), the transition from controlled to automatic processing may be gradual. During this transition, controlled processing could eventually be largely replaced by automatic processing (MacLeod & Dunbar, 1988), or automatic processes may develop as an entirely separate type of cognitive operation that ends up co-existing with the more controlled process from which they developed.

Claims for the automaticity of synaesthesia are placed in stark relief by Pashler's (1998) conclusion that across a range of cognitive domains, from search tasks to Stroop-like phenomena, the evidence for automaticity is actually fairly weak. A detailed consideration of his arguments against automaticity as a widespread cognitive phenomenon is beyond the scope of the present paper. Nevertheless this conclusion is strikingly consistent with a detailed critique of the notion of automaticity in grapheme-colour synaesthesia. In an insightful analysis of research on this 'flagship' variety of synaesthesia, Treisman (2005) concurs with the view that automaticity is not a unitary construct. She then argues that grapheme-colour synaesthesia only qualifies as automatic in a narrow subset of the separable ways in which a mental process can be said to be automatic. In similar vein, Mattingley (2009) has reviewed many of the standard paradigms used in research on grapheme-colour synaesthesia, and concluded that synaesthetic colour does not unequivocally show the same kind of automatic effects as the early sensory processing of real colours. For example, these two reviews argue that

grapheme-colour synaesthesia fails to qualify as an early automatic effect because: (1) It does not appear to occur without conscious awareness of the evoking stimuli, (2) it is not immune to concurrent task interference, and (3) it does not occur in parallel across a stimulus array in the same manner that real colour can pop-out during visual search (see also Nijboer et al., 2011; Ward et al., 2010). It is only in the narrow sense of being *involuntary* that grapheme-colour may qualify as automatic (Treisman, 2005), but even here the involuntariness may be context specific and manifest most strongly when the synaesthete is already focused on colour processing (Mattingley, 2009).

Despite these challenges to the automaticity of grapheme-colour synaesthesia, an emphasis on obtaining evidence for automaticity has dominated much of the recent resurgence of scientific interest in sequence-space synaesthesia. In this paper we first provide a brief description of this variety of synaesthesia (Section 2) and its assumed automaticity (Section 3). We then review and critique the three main behavioural paradigms that have been used to argue that sequence-space synaesthesia has some degree of automaticity – namely SNARC-like effects (Spatial-Numerical-Association-of-Response-Codes; Section 4), spatial cueing effects (Section 5), and spatial incongruity effects (Section 6). Given that the studies we review have been central to establishing the reality of sequence-space synaesthesia, we also hope that our discussion will provide a useful synthesis of research to date in this area.

From the outset, we wish to make it clear that we do not challenge the reality of the experience of spatial forms, nor do we wish to diminish the valuable contributions of recent studies of the phenomenon. However, we will argue that evidence for automaticity is not as strong as has been claimed and that use of the concept of automaticity has been insufficiently precise.

We also stress that in our opinion the evidence against the automaticity of sequence-space synaesthesia, or other synaesthesias, does not detract from their scientific interest. To the extent that synaesthesia is mediated by processes under some degree of cognitive control, the phenomenon makes contact with normal cognition and becomes informative of graded individual differences in normal cognition. A critical and analytical appraisal of automaticity in synaesthesia is therefore convergent with recent arguments that continuity between synaesthesia and normal cognition is a more fruitful (as well as more

parsimonious) avenue for exploration than the search for special mechanisms (e.g., Ward et al., 2006, 2007). In this vein we will conclude that it is premature to invoke special brain mechanisms to explain the behavioural correlates of sequence-space synaesthesia (Section 7). Instead, such experiences can be seen as lying on a continuum with more controlled processes of normal cognition such as voluntary visuospatial imagery. The study of sequence-space synaesthesia may therefore be more informative of *normal* cognition than *abnormal* cognition. Additionally, sequence-space synaesthesia may be seen to converge with – rather than challenge – Pashler’s view that evidence for automaticity in cognitive domains is weak.

2. What is sequence-space synaesthesia?

Like other varieties of synaesthesia, sequence-space synaesthesia is an extra dimension to sensory experience. In this case the experience is of spatial location superimposed onto the more usual abstract and verbal representation of ordinal sequences. Cytowic and Eagleman (2009) provide an overview of the phenomenon (see also Jonas and Jarick, in press; Price and Mentzoni, 2008; Price, 2009a; Simner, 2009). Commonly described characteristics of the experience are a feeling that it is involuntary, that it is salient and personally important, that it dates back to childhood and has “always been this way”, that the spatial associations are precise and stable across time, and that sequence-space synaesthetes find it perplexing that others do not share their experience. It is these common features that have encouraged the inclusion of spatial forms into the growing and heterogeneous family of synaesthesias. The experience of spatial forms can be considered as an example of a *conceptual* synaesthesia (Grossenbacher and Lovelace, 2001) or *higher* synaesthesia (Ramachandran and Hubbard, 2001), because the synaesthetic experience can typically be triggered by thinking about the synaesthetic inducer (a sequence member) as well as by seeing or hearing its verbal label, rather than being triggered only by specific perceptual inducers (Ward et al., 2007). Estimates of the population incidence of sequence-space synaesthesia vary considerably, but indicate that spatial forms are far from uncommon experiences. For example, for calendar forms, which appear to be the most common variant, estimates range from 20% (Sagiv et al.,

2006) through approximately 11% (Phillips, 1897), to a more conservative 2% (Brang et al., 2010).

In addition to their core common characteristics, spatial forms vary in many ways between individuals. They range from simple, regular, 2-dimensional patterns such as a circle of the months, to complex, irregular, idiosyncratic 3-dimensional patterns such as a twisting number line or a looping figure of eight for the months of the year (e.g., see Figure 1 for examples of some simpler forms for calendar months). Within any given spatial form (e.g., a month circle), some sequence members (e.g., months) may be more spatially extended than others. The spatial forms may be experienced in imaginal space or projected in front or around the head or torso. They can be viewed from external egocentric perspectives (e.g., the whole form is experienced in front of one's head) or people may report a viewing position that is inside their spatial form (e.g., one feels one's viewpoint to be located on or in a particular month, with other months around one). The forms may be static but, for some people, shifting which sequence member is attended may elicit a feeling that the form moves relative to the viewer, or that the viewer moves within the form. For example, calendar forms for months of the year or days of the week may express this type of relative movement as calendar time progresses. People also often report that they can 'zoom into' part of a spatial form. Spatial forms may include some colour, especially when they co-occur with grapheme-colour synaesthesia, but (by personal observation during interviews with synaesthetes) they are usually uncoloured.

INSERT FIGURE 1 APPROXIMATELY HERE

Following a flurry of descriptive papers on spatial forms at the end of the nineteenth century (Galton, 1880a, 1880b, 1881; Phillips, 1897) the phenomenon was more or less ignored by psychological science until a resurgence of interest in the last decade, culminating in a dedicated special issue of the journal *Cortex* in 2009. The majority of these recent studies have focused on behavioural validations of the existence, consistency and automaticity of the spatial associations claimed by sequence-space synaesthetes (e.g., Brang et al. 2010; Gertner et al., 2009; Hubbard et al. 2009; Jarrick et al., 2009a, 2009b, 2011a, 2011b; Jonas et al., 2011; Piazza et al., 2006; Price and Mentzoni, 2008; Sagiv et

al., 2006; Smilek et al., 2007). It has also been shown, however, that sequence-space synaesthesia is associated with stronger self-reported visual imagery (Price, 2009a), above-average performance on behavioural tests of visuospatial working memory and imagery (Simner et al., 2009; although see Rizza and Price, 2012) and on tests of sequence representation (Mann et al. 2009), unusually good memory for personal or historical dates (Simner et al., 2009), and marginally slower performance on some types of mental arithmetic (Ward et al., 2009). Much of this work was reviewed by Simner (2009).

Various speculative explanations of sequence-space synaesthesia have been proposed. Galton (1880a, 1881) suggested number forms were a residue of childhood visuospatial strategies to help encode abstract verbal sequences (see also Jonas et al., 2011). A popular contemporary suggestion is that explicit spatial forms are an exaggeration and distortion of the normally implicit overlap between spatial and magnitude representation in the parietal lobes that has been extensively documented in the literature on numerical cognition (Hubbard et al., 2005b; Hubbard et al., 2011; Tang et al., 2008; Simner, 2009). This suggestion is analogous to the widely held view that grapheme-colour synaesthesia arises from additional cross-connectivity between proximal cortical colour and language processing areas (e.g., Hubbard and Ramachandran, 2005; Nunn et al., 2002; Rouw and Scholte, 2007), or that this cross connectivity is at least one crucial component of a distributed network of functional and structural brain abnormalities in synaesthetes (Hubbard et al., 2011; Hupe et al., 2012; Rouw et al., 2011). In a variation of this argument, Eagleman (2009) has proposed that spatial forms may arise from abnormal cross-connections between the right middle temporal gyrus of the cortex, which he argues plays an important role in mediating sequence representations, and ventral stream object representations in nearby inferior temporal cortex. Consistent with this proposal, Eagleman also argues that spatial forms are visually depicted object representations, rather than spatial representations mediated by parietal cortex.

The suggestion that spatial forms are more visual than spatial in nature, at least for some individuals, has also been made by Price (2009a, 2009b). However Price (2009a) cautioned that spatial forms might be mediated by similar processes to general intentional imagery rather than by unusual synaesthetic connectivity. In support of this position,

Price (2009a) reported data showing that people with spatial forms seem to have a strong experience of general visual imagery that is above average (consistent with some of the data of Simner et al (2009) showing behavioural advantages on visuospatial working memory and imagery tasks). Price (ibid.) also showed that at least some of the behavioural correlates of sequence-space synaesthesia can be mimicked in non-synaesthetes merely by giving mental imagery instructions (see below).

Obviously not all these views are mutually exclusive. Additionally, as with other types of synaesthesia where heterogeneity has been stressed, it should be kept in mind that spatial forms may fall into different categories which may even have different behavioural correlates.

3. The assumed automaticity of sequence-space synaesthesia

A salient aspect of the literature on sequence-space synaesthesia is that spatial forms are almost always described as experiences that arise automatically. Early empirical investigations such as those of Piazza et al. (2006), Smilek et al. (2007), and Price and Mentzoni (2008) all characterized the phenomenon as automatic and claimed to provide empirical support for this automaticity. This apparent automaticity is in turn typically used as part of the justification for classifying the phenomenon as a variety of synaesthesia. In the *Cortex* (2009) special issue on sequence-space synaesthesia, 4 out of 6 papers, plus the editorial, characterized spatial forms variously as involuntary, automatically elicited, arising ‘early’, and having unintentional or automatic effects on behaviour. The tendency to argue explicitly for the automaticity of spatial forms, or to at least take it for granted, has continued in more recent empirical studies (e.g., Brang et al. 2010; Diesendruck et al, 2010; Gertner et al., 2009; Jarrick et al., 2009a, 2009b, 2011a, 2011b; Makioka, 2009, Mann et al., 2009).

However, as for grapheme-colour synaesthesia, there has typically been a failure to define or analyse precisely in what manner spatial forms might be automatically elicited. Following the kind of helpful breakdown offered by Pashler (1998) and Treisman (2005), we can ask whether they are triggered involuntarily, whether their activation by-passes serial processing bottlenecks, whether they are immune from dual task interference, and

whether they can be triggered without attention to, or perhaps even without conscious awareness of, the inducer. In fact the evidence presented to date concentrates only on the first of these dissociable characteristics of an automatic process; i.e., Are the spatial associations that constitute a spatial form activated in a reflexive manner in the absence of goal-directed control, or do they arise voluntarily as a function of task-relevant strategies or even from experimental demand characteristics? We question whether the evidence to date provides strong evidence even for this narrower sense of what we might mean by automaticity.

Findings on this issue have largely been derived from three experimental paradigms: (1) variations on the spatial stimulus-response congruity effect, known as the SNARC effect (Spatial Numerical Association of Response Codes; Dehaene et al., 1993); (2) variations on the spatial cueing paradigm introduced by Posner and Snyder (Posner et al., 1980); and (3) findings that relative magnitude judgements and distance effects, involving visually-displayed sequence members, are influenced when their spatial layout is perceptually incongruent with a person's spatial form. In the remainder of this paper we evaluate the strength of evidence, from each of these paradigms, for the involuntary (and hence 'automatic') nature of synaesthetic associations. For each paradigm we focus largely on specific characteristics of task performance that are conventionally taken, within circumscribed research on that paradigm, to indicate some degree of involuntary performance. We first extend the critique of the evidence from SNARC effects presented by Price (2009a). We then raise similar concerns about the evidence from spatial cueing experiments and perceptual incongruency effects.

4. Are SNARC-like effects from spatial forms really automatic?

4.1 The classic SNARC effect

The classic SNARC effect (Spatial-Numerical-Association-of-Response-Codes) occurs when normal experimental participants make simple binary reaction time (*RT*) decisions about numerals (e.g., from 1-9) presented one by one, centrally on a display in random order (Dehaene et al., 1993). The task can be a simple magnitude comparison, in

which participants press a left- or a right-hand key if a target number is larger or smaller than a reference number (Dehaene et al., 1990). A central aspect of the experimental procedure is that the instructed stimulus–response mapping – i.e., which hand is used to indicate which of the two possible response alternatives – is reversed for different trial blocks. This permits the average left versus right-hand response time (*RT*) to be calculated for each stimulus. For participants whose written language runs left to right, the key finding is that small numbers (e.g., 1-4) are responded to relatively faster with the left hand than the right, whereas larger numbers (e.g., 6-9) are responded to relatively faster with the right hand than the left. A similar effect of response hand is also found when the magnitude of the stimuli is seemingly irrelevant to the categorization task, such as a parity judgement task in which participants classify each stimulus as odd or even (Dehaene et al., 1993). The general finding that relatively smaller numbers are responded to faster with the left hand and larger numbers with the right hand is taken to reflect an automatic behavioural influence of implicit analog spatial representations of number magnitude, usually as a horizontal line from left to right¹. This in turn has been argued to be convergent with a whole body of data from behavioural, neuro-imaging and neuropsychological studies which indicate that the representation of ordinal sequence information and space are fundamentally interrelated, even in the non-synaesthete population (e.g., Hubbard et al., 2005b)

INSERT FOOTNOTE 1 APPROXIMATELY HERE

4.2 Applying the SNARC effect to spatial forms

Although it was initially argued that this type of spatial stimulus-response congruity effect is confined to Arabic numerals (Dehaene et al., 1993), subsequent studies found that the printed names of calendar months or weekdays, and the letters of the alphabet, can also induce SNARC-like effects (Gevers et al., 2003; 2004). For example Gevers et al. (2003) found that *RT* to decide if a month falls in the first or second half of the year, or *RT* to decide whether it ends with a particular target letter, is relatively faster with the left than the right hand for early months and vice versa for late months.

Using a similar procedure, Price and Mentzoni (2008) later failed to obtain a SNARC effect with months as stimuli and early/late month judgement as the task, although a small effect was found when the task was a type of parity judgement where months were classified as odd or even numbered (see Price, 2009a). However, crucially for the current discussion, Price and Mentzoni compared these data from non-synaesthetes with results from a small group of participants who experienced spatial forms for months. These forms were all roughly circular (seen in a clockwise order by some individuals, and in an anticlockwise order by others) and experienced as being oriented in the vertical plane such that early and late months always fell on opposite sides of the egocentric vertical midline. Regardless of whether the response task was early/late judgement or parity judgement, the participants with spatial forms showed a SNARC-like effect. Two of these participants had early months on their left and two had early months on their right. The polarity of the SNARC effects reversed accordingly, with two participants showing a relative left-hand advantage for early months and two showing a right-hand advantage for early months. In addition, the magnitude of the SNARC effect was greater for sequence-space synaesthetes than controls, at least when the task was early/late judgement (i.e., a magnitude comparison) (see Price, 2009a).

Price and Mentzoni (2008) argued that their data provided an objective behavioural verification of the synaesthetes' claimed spatial associations for the months. Additionally they argued that these associations appeared to be induced automatically because they modulate SNARC-like effects even in a parity task, where the spatial and categorical dichotomization of the calendar into early versus late months may appear irrelevant to judging the months as odd or even. To put this more precisely, if the spatial associations are activated when they are irrelevant, they might by implication appear to be *involuntarily* triggered, thus fulfilling one possible criterion for automaticity.

Subsequent studies have continued to use SNARC-like effects as behavioural markers of sequence-space synaesthesia. Jarick et al. (2009a) tested one participant with a number form where small numbers from 1-10 ran vertically upwards before the line continued in a horizontal left-right direction. Using numerals from the vertical component of their number line as stimuli, and parity judgements as the experimental task, a SNARC-like stimulus-response congruity effect between response hand and number was found when

the 2 response keys were aligned vertically, but not when they were aligned horizontally. By contrast a group of controls showed no effect with vertically-aligned keys but showed the usual SNARC effect when using horizontal keys.

Another single case study by Hubbard et al. (2009) also tested for SNARC effects from numerals that lay in a vertical component of their participant's number line. Their participant, DG, is a spatial form virtuoso who reports up to 58 different spatial forms. However results with DG were less clean-cut. They found some indication of the predicted vertical SNARC effect from vertically aligned response keys when using a magnitude comparison task but not when using a parity task (unlike Jarick et al., 2009a). Controls again showed no effect of response hand with vertically aligned keys but gave standard effects in both tasks when using horizontal keys.

In summary, a number of studies have demonstrated congruity effects between the rough spatial layout of stimuli in participants' spatial forms and the spatial layout of response keys, and in at least some studies this has been shown with parity tasks that are assumed to reflect automatic spatial associations (for this assumption see e.g., Dehaene et al., 1993; Jarick et al., 2009a).

4.3 Concerns with the evidence from SNARC effects: Automatic spatial codes or intentional strategies?

Unfortunately for studies of SNARC-like effects in sequence-space synaesthesia, it has been increasingly argued that spatial stimulus-response congruity effects, such as the SNARC effect, may reflect intentional, short-term and task-specific spatial associations, which may even be verbally mediated, rather than reflect the detailed layout of persistent automatised spatial associations (Caessens et al., 2005; Fischer, 2006; Fischer et al., 2009, 2010; Gevers et al., 2006; Shaki and Fischer, 2008; Proctor and Vu, 2002; van Dijck et al., 2009).

First, SNARC effects may only be a very gross reflection of the fine structure of underlying spatial associations. Early research on the number-SNARC effect with normal participants found that the influence of response hand increased in a continuous manner as stimuli approached the ends of the numeral sequence being used (Dehaene et al.,

1993). This was taken to imply that their spatial representations were progressively more lateralized, in turn supporting the notion of continuous spatial representations of the number sequence – the so-called *mental number line*. However this interpretation of the details of obtained SNARC effects has been questioned (Cohen Kadosh et al., 2008; Santens and Gevers, 2008). Instead SNARC effects might just derive from a simple, binary, task-oriented categorization of stimuli. This may include, but is not restricted to, spatial categorizations such as left/right or up/down (Gevers et al., 2006; Notebaert et al., 2006; Proctor and Cho, 2006). Evidence from interference tasks shows that these categorizations may sometimes be visuospatially mediated – for example during magnitude judgement (Herrera et al., 2008) – but can also be mediated as verbal conceptual representations – for example during parity judgement (van Dijck et al., 2009). In these respects it is noteworthy that the only study to examine whether detailed geometrical distance within spatial forms is reflected in the magnitude of SNARC effects (Price and Mentzoni, 2008) found this not to be the case; SNARC effects indeed reflected only a crude left/right distinction between stimuli.

Second, even to the extent that non-verbal spatial representations are involved in the SNARC effect, these appear to be highly flexible and context sensitive (e.g., Fischer et al., 2010; Fischer et al., 2009; Shaki and Fischer, 2008). They may also be mediated by standard processes of visuospatial imagery. For example, it is known that SNARC effects are reduced in children with visuospatial impairments (Bachot et al., 2005) and also that simple mental imagery instructions, such as imagining the numbers 1-12 laid out on a clock face, can reverse the direction of standard number-SNARC effects in normal adults (Bächtold et al., 1998). The relevance to studies of sequence-space synaesthesia is that, as mentioned above, people with spatial forms appear to have a stronger general experience of visual imagery in everyday life (Price, 2009a) and also perform better on some behavioural tests of visuospatial imagery (Simner et al., 2009). It is therefore possible that the unusual SNARC effects shown by people with spatial forms are related to their tendency and aptitude for using mental imagery in a goal directed manner. Similar suggestions, that imagery-based strategies may contribute to behavioural differences between synaesthetes and controls, have already been made in the literature on grapheme-colour synaesthesia (Yaro and Ward, 2007).

Price (2009a) tested the plausibility of this suggestion by asking normal non-synaesthete participants to visually image the months of the year in various spatial layouts before using left versus right key presses to classify month names as either (a) occurring in the first or second half of the year (a magnitude comparison task), or (b) corresponding to odd or even numbered months (a parity task). In both tasks, month-SNARC effects were obtained which were congruent with the spatial layout of the instructed images; i.e., imagining early months on the left of a horizontal left-to-right month line induced a left-hand advantage for early months, whereas imagining early months on the right side of a clockwise circle of months induced a right-hand advantage for early months. Moreover, the opposing SNARC effects associated with these different imagery instructions were of similar magnitude² to the opposing month-SNARC effects that Price and Mentzoni (2008) previously reported for different sequence-space synaesthetes who experienced early months either on the left or right of their circular forms. It is especially significant that mental imagery in non-synaesthetes can simulate both the direction and magnitude of ‘synaesthetic’ SNARC effects in a *parity* task. The past assumption has been that spatially represented ordinal sequences must influence parity judgements in an automatic manner because the spatial representations are irrelevant to this type of odd/even categorisation (Dehaene et al., 1993; Jarick et al., 2009a). But if intentional spatial representations *can* influence parity judgments, this assumption is counterfactually challenged.

INSERT FOOTNOTE 2 APPROXIMATELY HERE

A central method of synaesthesia research has been to demonstrate that particular groups of experimental participants are behaviourally unique in some manner. The fact that imagery instructions are sufficient to emulate a behavioural correlate of the spatial form experience challenges this uniqueness and challenges the extent to which it is necessary to invoke special explanatory mechanisms. While the SNARC effects obtained from people with spatial forms might, in the behaviourist tradition, provide objective corroboration of these participants’ verbally reported spatial associations, it is hard to see what they add to verbal reports in terms of evidence for the automaticity of the

associations. Parsimony would instead suggest that the SNARC data in these synaesthetes can be accounted for by the kinds of controlled short-term associations which are already implicated in SNARC effects in non-synaesthetes (Fischer et al., 2010), including visuospatial associations which are continuous with imagery skills found in the normal population,

A further aspect of the data from SNARC studies of sequence-space synaesthesia would seem to support this account. First, the *magnitude* of the unusual SNARC effects obtained from people with spatial forms – in terms of the *RT* difference between congruent and incongruent trials – have never been shown to be outliers from the range of effects obtained in control participants. Second, the magnitude of these SNARC effects is not even always shown to differ significantly from that of the control group as a whole. For example, the data from the month-SNARC study by Price and Mentzoni (2008) show that although 4 sequence-space synaesthetes had larger SNARC-effects than control participants during a magnitude comparison task, SNARC-effects from the spatial associations of the months were not larger than for controls during a parity judgement task (see Price, 2009a); the group difference here lay only in the unusual *direction* of the observed effects. In the aforementioned single case studies of number lines presented by Jarick et al. (2009a) and Hubbard et al. (2009), unusual vertical SNARC-effects were elicited by numerals from vertical components of participants' number lines when response keys were vertically arranged. Yet the magnitudes of these effects were never directly compared with the more routine horizontal SNARC effects elicited by control participants using the standard horizontal layout for response keys. In the Hubbard et al. study, where a significant vertical SNARC-effect was found for magnitude comparison, it is not even clear that this individual effect was significantly larger than the group null effect from control participants using the same arrangement of vertical keys.

To summarise, although the *layout* of the spatial associations adopted by sequence-space synaesthetes in these experiments are sometimes unusual, the processes mediating the associations may not themselves be unusual or particularly automatic.

4.4 SNARC effects are also unreliable and inconsistent across studies

A further problem is that synaesthetic SNARC effects in parity judgement – which is the task used to argue for automaticity – are not even reliably obtained across participants in different studies. This reflects the unreliability of normal SNARC effects in the non-synaesthete population (Wood et al., 2006). Although Price & Mentzoni (2009a) reported a month-SNARC effect in their 4 participants when using either magnitude comparison or parity judgement, and Jarick et al. (2009a) reported a number-SNARC effect from the vertical number line of their single-case study when using parity judgement, failures to obtain synaesthetic number-SNARC effects with parity judgement were reported in the single-case studies of both Piazza et al. (2006) and Hubbard et al. (2009; but this study did find an effect for magnitude comparison). The failure to observe an effect in some participants weakens the evidence that the synaesthetic associations are automatically elicited, at least among all participants, and is consistent with data suggesting that non-synaesthete SNARC effects in parity judgement are mediated by transient verbal codes (van Dijck et al., 2009) rather than permanent visuospatial representations.

4.5 Summary

The use of SNARC effects as a tool to demonstrate the psychological reality of stable, detailed and automatic synaesthetic spatial forms is compromised by arguments that, in non-synaesthetes, SNARC effects are not an unequivocal signature of long term spatial coding for numerical or other sequences. Instead they may reflect strategic short-term visuospatial or verbal representations. Further, SNARC effects from spatial forms appear to be quite unreliable. Even when present, the magnitude of any effect is within the range obtained from non-synaesthetic controls and does not always differ significantly between synaesthetes and controls at the group level. There is also evidence that the effects can be simulated by giving mental imagery instructions to non-synaesthetes, even with minimal training, and even with tasks that have been assumed to reflect automatic associations. Arguments that SNARC effects support any variety of automaticity of sequence-space synaesthesia therefore seem at best premature.

5. Are spatial cueing effects from spatial forms really automatic?

5.1 Standard varieties of spatial cueing effect

The ubiquitous spatial cueing paradigm is another procedure that has been employed to argue for the automaticity of sequence-space synaesthesia. The basic paradigm, as used with non-synaesthetes, is to have people perform speeded detection or identification of visual targets at unpredictable spatial locations to either side of the visual fixation point (for an extensive review, see Wright and Ward 2008). The key finding is that participants are faster (and sometimes more accurate) in responding to targets that are preceded by a cue that brings the focus of attention to the location of an upcoming target (valid trials), compared with targets preceded by cues that shift attention to other locations in the visual field (invalid trials). The assumption is that perceptual processing is enhanced at attended locations, so that target stimuli falling close to the current focus of attention are processed more rapidly than those elsewhere.

It is usual to distinguish between different varieties of spatial cueing effect and we summarise these briefly because the distinctions are highly relevant to the discussion that follows.

1) *Exogenous cueing from direct cues*: A basic distinction can be made between so-called *direct* cues, and *symbolic* cues (Wright and Ward, 2008). Direct cues are physical transients (e.g., a briefly flashed stimulus) which are displayed away from fixation and which speed the processing of subsequent targets when these are presented in close spatial proximity to the cue location. This type of stimulus-driven attentional capture is referred to as *exogenous* cueing. Although it can be enhanced or attenuated by voluntary processes, it is traditionally considered to reflect some core properties of automatic processes. These include being relatively immune to dual task interference, and showing an inflexible and involuntary character because the cueing persists even if the cues are on average non-predictive of target location. The rapid time course exhibited by this type of cueing is considered an additional hallmark of automaticity. Typically, maximal cueing is obtained when the cue-target onset asynchrony (CTOA) is around 100 *msecs* (Cheal and Lyon, 1991; Frischen et al., 2007). Beyond this interval, facilitatory processing at the

cued location tends to fall off rapidly and may be replaced with inhibitory processing at around 500 *msecs* (so-called *inhibition of return*, Klein, 2000; Posner and Cohen, 1984).

2) *Endogenous cueing from symbolic cues*: By contrast, symbolic cues carry some symbolic representation of the target's likely location (e.g., an arrowhead pointing left or right), and are usually presented centrally at fixation, rather than at target locations. Symbolic cueing effects can in turn be subdivided into two broad categories. The first of these is standard voluntary, top down, or *endogenous* cueing, which reveals the influence of control processes on the spatial allocation of attention. This is often elicited using cues that correctly predict target location on the majority of trials (so-called *predictive cues*). Compared with exogenous cueing, the facilitatory influence of endogenous cueing evolves at longer CTOAs, persists as CTOA is extended rather than showing inhibition of return, and is attenuated if the cues are voluntarily ignored.

3) *Involuntary cueing from symbolic cues*: Symbolic cues can also induce a more automatic type of cueing whose properties appear to be a mixture of the properties of exogenous and endogenous cueing (Wright and Ward, 2008, pp. 232-243). Like exogenous effects, this type of cueing has rapid onset, and seems involuntary because it can occur when cues are non-predictive or even counter-predictive. However, like endogenous effects, it persists over longer CTOAs and does not show inhibition of return. This hybrid variety of cueing was first reported for central cues consisting of schematic faces in which the eyes look to the left or right, and which appear to cue attention involuntarily in the direction of gaze (Friesen and Kingstone, 1998). Subsequently, similar cueing effects at a behavioural level have also been shown with non-predictive arrow cues, questioning the special status that was initially accorded to eye gaze as a variety of attentional cue (for an overview see Frischen et al., 2007; Kuhn and Kingstone, 2009).

4) *Cueing from centrally presented numerals*: Of particular relevance to the current discussion, Fischer et al. (2003) found that central symbolic cues consisting of numerals from 1-9 can cue attention to targets presented 700 *msecs* after cue onset, even if the numeral cues are non-predictive. Specifically, it was found that *RTs* to detect visual targets on the left of fixation are faster following relatively smaller number cues, whereas *RTs* to right side targets are faster following larger number cues. We will return to discuss

how this numerical congruency effect might relate to the three preceding categories of cueing effect. For the moment, we simply note that the effect has been taken as convergent support for the notion that people (at least in cultures whose writing runs left to right) generally possess an implicit left-to-right spatial representation of number magnitude. It has also provided the inspiration for studies of cueing in sequence-space synaesthetes.

5.2 Applying spatial cueing to study spatial forms

Using a similar procedure to the numeral cueing study of Fischer et al. (2003), Smilek et al. (2007) compared people with spatial forms for the calendar months with control participants, now employing one of 6 different month names as non-predictive central cues. On each trial the month name preceded a lateralized visual target that had to be detected as fast as possible using a go/no-go procedure. Smilek et al. found significant cueing effects in 3 of 4 sequence-space synaesthetes who reported month forms in which early months were positioned on one side of body-centered space and late months on the other. Specifically, the synaesthetes showed a cueing benefit when targets were preceded by a month name whose left or right location in their spatial-forms corresponded with the left or right location of the target stimulus, compared to when the location was incongruent with the target. No cueing effects were found for control participants.

Further recent studies have continued to explore cueing effects arising from written names of various types of sequence member, including months for participants with month forms, numerals for participants with number lines, weekdays for a participant with a weekday form, clock times for a participant with a vivid involuntary image of a clock face, and letters for participants with forms for the alphabet sequence (Hubbard et al., 2009; Jarick et al., 2009a, 2009b; 2011a; 2011b; Jonas et al., 2011; Teuscher et al., 2010). The cueing effects observed in these participants again differed from those of control participants, and seem to reflect the relative left-to-right or bottom-to-top locations of sequence members in the synaesthetes' reported forms. These studies have varied in their procedural details, such as the range of CTOAs over which cueing effects were tested, and whether cues were non-predictive or counter-predictive (see Table 1).

Additionally, studies that focused on number forms have tested both horizontally aligned portions of synaesthetes' number lines (using left versus right targets and horizontally arranged response keys) or, sometimes in the same participant, tested vertically aligned portions of number lines (using lower versus upper targets and response keys).

It is notable that usually only one to two synaesthetes have been tested per study, and these participants have tended to be rather exceptional in some respect. For example, Hubbard et al. (2009) tested numeral cueing in relation to the number line of DG, the spatial form virtuoso with 58 forms who was also tested for SNARC effects (see above). The many studies by Jarick and colleagues have focused almost exclusively on synaesthete L who is unusual because, as further discussed below, visual versus aural cues induce different egocentric viewpoints on her month and clock-time forms.

What is common to most of these studies is that synaesthetes' spatial cueing effects have been interpreted as automatically mediated, rather than as an example of voluntary endogenous cueing. Exactly what the authors of these studies mean by *automatic* is, however, left unspecified. In some studies, the implicit assumption is that the cueing effects resemble those usually observed with direct cues, as opposed to the endogenous cueing effects typically found with symbolic cues. For others (e.g., Jarick et al, 2011a), more explicit parallels are drawn between synaesthetes' cueing effects and the type of involuntary cueing from symbolic cues that is associated with gaze cues. However, in the following sections we consider the procedures and data from these studies in detail and offer a critique of their conclusions. What we suggest is that current data fail to rule out the possibility that observed cueing effects are endogenously mediated, and that many aspects of the results in fact favour this interpretation.

In our discussion we will also attempt to relate empirical findings from cueing experiments to three separable issues that do not appear to have been adequately disentangled in the literature so far, namely: (a) Whether observed effects support any of the proposed characteristics of automaticity and, if so, which ones; (b) Whether observed effects support the notion that spatial forms cue attention in the same manner as (real) perceptual stimuli; and (c) Whether observed effects support the suggestion that spatial forms are mediated by special mental processes.

To facilitate our discussion, Table 1 summarises procedural aspects and data from those studies that have attempted to argue for automatic spatial cueing in sequence-space synaesthetes. Each of the 14 rows in the table presents one participant's performance from one study, in relation to their performance for one type of spatial form (e.g., months or numbers), and with one type of cue-target contingency (e.g., non-predictive or counter-predictive) and one type of target / response key layout (e.g., horizontally or vertically arranged).

INSERT TABLE 1 APPROXIMATELY HERE

To support our arguments and provide a detailed overview of the available literature, the following discussion is necessarily lengthy. However, it is structured so that readers can choose to follow summaries of our main conclusions by reading just the last paragraph in each of sections 5.3 to 5.6, along with section 5.7 which presents our overall conclusions from cueing studies.

5.3 The time course of cueing effects indicates they are dissimilar to standard exogenous shifts of attention induced by direct cues

As summarised by Wright and Ward (2008), exogenous cueing from direct cues is characterised by fast, involuntary and inflexible attentional capture which typically peaks by CTOAs of 100 *msecs*, beyond which facilitatory processing at the cued location tends to fall off rapidly and is replaced by inhibition of return. As can be seen from Table 1, most studies of spatial cueing in sequence-space synaesthetes have used CTOAs much longer than 100 *msecs*. Admittedly, three studies have obtained significant cueing effects at CTOAs of 150 *msecs* and have argued that this is a short enough interval to rule out endogenous cueing (Smilek et al. 2007; Jarick 2011a, 2011b). However even a CTOA of 150 *msecs* is already too long to be conclusively diagnostic of an automatic attention shift. At this timing interval, where exogenous capture is likely to be on the decline and endogenous shifts are beginning to take effect, the influence of each of the two processes may be roughly equivalent (e.g., see Wright and Ward, 2008, Fig 2.9).

Moreover, if the cueing effects are similar to the exogenous effects of direct cues, they should decline at longer CTOAs. Studies with synaesthetes in fact show little evidence of a decline in cueing as CTOA increases well beyond the range normally associated with exogenous cueing. All but one of the studies listed in Table 1 measured cueing at more than one CTOA. Of those studies, most reported that the size of the cueing effect was unaffected by CTOA, and all observed significant cueing at CTOAs of at least 500 *msecs*, with some studies showing it even at 800 *msecs* (Jarick et al., 2009b) or 900 *msecs* (Hubbard et al., 2009). Only one study found that cueing disappeared at a longer CTOA – of 800 *msecs* – but this occurred for a synaesthete who had taken part in several cueing studies, and who was therefore highly practiced. This synaesthete was also given unusually specific instructions to attend to cues that were counter-predictive (Jarick et al., 2011a). Some authors have explicitly stated that the lack of influence of CTOA on cueing is an argument for automatic effects (e.g., Hubbard et al, 2009). However, across the range of CTOAs used in these studies, we would argue that this lack of influence actually rules out an automatic cueing effect that is similar to the usual exogenous effects of direct cues.

Consistent with our view, one recent study of synaesthetic cueing effects, not listed in Table 1, specifically failed to obtain significant cueing effects at short CTOAs (Jonas et al., 2011). This study differed from those discussed so far in that it tested a group of 13 people with spatial forms for the alphabet, using letters as cues, and the dependent variable was *RT* to initiate saccades to lateralized targets (rather than a key press). While a cueing effect on saccade latency was observed with 600 *msec* CTOAs, effects at 150 *msecs* failed to reach significance and were not formally shown to differ from the performance of controls. Jonas et al. therefore concluded their cueing effects were *not* strongly automatic, although they suggested that this might result from lack of practice with using alphabet forms as compared to calendar forms.

Two further chronometric aspects of published studies also argue against exogenous cueing. First, the *RTs* reported are rather long given that the task in most instances involved onset detection of targets. Mean *RT* on incongruent trials over the 14 participant/condition samples summarised in Table 1 is 451 *msecs* (median 391 *msecs*), based on *RTs* obtained for the *shortest* CTOA used for any given participant. The range is

from 304 *msecs* to 1070 *msecs* (participant PD from Smilek et al., 2007). Especially at the longest end of this range, observed *RTs* are suggestive of strategically mediated responses. There is an additional point here. Since the visual targets were not masked and remained visible on the display until response, long *RTs* extend the period available for cues to exert their influence on target processing. Of the 6 participant/condition samples from Table 1 for whom the smallest CTOA was 150 *msecs*, mean *RT* for incongruent trials at that CTOA was over 400 *msecs* for all but one sample (JK at 320 *msecs*). The time window for cues to influence *RT* was therefore usually at least 550 *msecs*, rather than 150 *msecs*, giving participants ample time to initiate a voluntary (endogenous) shift of attention.

Second, the size of the obtained cueing effects has often been much larger than is usual for exogenous cueing. From Table 1, the mean cueing effect over the 14 participant/condition samples, based on the average cueing effect across all CTOAs used in each sample, was 93 *msecs* (median 62 *msecs*) and ranged from 17 *msecs* to 368 *msecs*. Indeed the mean cueing effect is comparable to cueing effects from a study which deliberately set out to measure the influence of *endogenous* cueing in sequence-space synaesthetes: Using 12 participants with month forms, and a more complex response task involving target identification, Teuscher et al. (2010) reported a mean cueing effect of 62 *msecs* from month names which were now 75% predictive of target location, were presented at a 500 *msecs* CTOA, and were revealed by event related potentials to influence target processing at a post-perceptual stage.

Summing up, the time course of obtained cueing effects in spatial attention studies seems inconsistent with the notion that the names of sequence members induce a synaesthetic spatial representation that can cue attention in the same manner as real physical transients in space. Studies to date have used CTOAs that were too long, have failed to observe a decline in cueing as CTOA increased, and have reported *RTs* and cueing effects that were uncharacteristically large for exogenous cueing. In these respects the synaesthetic experience of the sequence member is not functionally equivalent to a bottom-up percept.

5.4 Could observed cueing effects be endogenously mediated?

As argued above, the fact that cueing effects in sequence-space synaesthetes exhibit long *RTs* and large cueing effects that persist over a wide range of CTOAs is suggestive of endogenous rather than exogenous cueing. However, in a series of studies on the sequence-space synaesthete L, Jarick et al. (2009b, 2011a, 2011b) present arguments against the proposal that synaesthetes' cueing is mediated by controlled response strategies.

In addition to her number line, L reports spatial forms for the weekdays and clock-times for which her egocentric viewpoint changes depending whether she reads or hears the name of the sequence member. Specifically, some weekdays or times are reported to be situated to the *right* side of space when the inducer name is *heard*, but are experienced to the *left* side of space when the inducer name is *read*, and vice versa. To validate L's claim, Jarick et al. (2009b) showed that centrally presented weekday or clock-time names yielded spatial cueing effects whose left versus right direction indeed depended on whether they were presented visually at fixation or (in separate blocks) aurally. Acknowledging that the 600 *msecs* CTOA used in that study was too long to rule out endogenous cueing, Jarick et al. (2011b) replicated L's modality-dependent cueing effect for months in a second study where visual and aural cues were now randomly intermixed within blocks of trials. It was argued that this precluded endogenous cueing because it would have been impossible for L to rapidly alternate these mental vantage points from trial to trial in a top down voluntary manner.

Although this second study provides further elegant confirmation of L's shifting mental vantage points on her spatial forms, we nevertheless disagree with the authors' conclusion that their procedure ruled out endogenous cueing. The combination of a 600 *msecs* CTOA and long *RTs* (of around half a second on incongruent trials) gave L sufficient time of over a second to register the modality of the cue, activate one of her two well-rehearsed spatial models for that type of sequence, and make her response. Suspicion that endogenous cueing might have occurred is also supported by the large size of the obtained cueing effects. For visual cues, the cueing effect was 138 *msecs*. Moreover, this was considerably larger than the 34 *msecs* cueing effect from visual cues that was obtained at the same CTOA in the previous study (Jarick et al., 2009b) where

visual cues were blocked on their own rather than intermixed with aural cues. This large increase in cueing is more consistent with the view that cueing was mediated by controlled strategies, rather than by automatic processes which one would assume to be relatively context independent.

In a second set of manipulations to try and rule out endogenous cueing, two similar experiments tested L with cues consisting of the numerals 1, 2, 8, or 9 from the initial vertically ascending part of her spatial form for numbers (Jarick et al., 2011a), or once again with visual or aural month names which were now presented in separate rather than mixed blocks (Jarick et al., 2011b). As well as reducing CTOA to 150 *msecs*, both these experiments used an 85% predictive cueing contingency in which the direction of the contingency was arranged to *counter* the expected cueing effects from L's pre-existing spatial associations – i.e., the cues predicted that detection targets would usually appear opposite to the side of space associated with that numeral or month in L's spatial forms. In the experiment with numeral cues, where responses were made with a lower versus upper key press, smaller numbers nevertheless cued attention to the upper part of the display and larger numbers cued attention to the lower part of the display, despite the fact that this ran counter to the cues' predictive contingency (Jarick et al., 2011a). In the experiment with month cues, opposing cueing effects were again obtained from visual and aural cues, and the direction of these effects again followed L's spatial form rather than the cue-target contingency (Jarick et al., 2011b). Jarick et al. argued that their data strongly imply automatic cueing effects, both because cueing was present at 150 *msecs* CTOAs and because any strategic cueing would have followed the predictive contingencies.

We have already argued above, however, that CTOAs of 150 *msecs* are insufficiently short to rule out endogenous cueing effects, especially when targets remain visible until response and mean *RTs* are long (over 400 *msecs* in both studies). Moreover, the lack of influence of cue-target contingency is also inconclusive for two reasons. First, the ability to ignore cue-target contingency is a known property of endogenous cueing (Wright and Ward, 2008). Second, as a group, control participants did not show significant cueing effects in the above experimental conditions and were therefore not strongly influenced by the predictive contingency. In fact cueing effects in line with the 85% contingency

even failed to show a significant group effect in 12 control participants who were cued with numerals and tested with conventional horizontally aligned targets (Jarick et al., 2011a). This was despite now being *explicitly instructed* to use the contingency to optimize their performance, and despite the inclusion of a long 800 *msecs* CTOA which gave ample time for any strategic influences to manifest themselves. The potential influence of cue-target contingency appears, therefore, to have been rather weak in the context of these experiments. Without a successful manipulation check showing that the contingency was effective for control participants, there is little reason to expect that it should have influenced the synaesthete L, especially since her spatial forms are likely to have provided a more dominant strategic influence.

In conclusion, and counter to what has been previously claimed, evidence to date does not rule out endogenous influences on cueing effects in sequence-space synaesthetes. There are also some more positive reasons to suspect that endogenous cueing is involved.

First, it is notable that the initial description of a numeral cueing effect in non-synaesthetes (Fischer et al., 2003), which was the original inspiration for the synaesthetic cueing studies, was never claimed to be exogenously mediated and indeed was obtained at a long CTOA of 700 *msecs*. At least in non-synaesthetes, compelling evidence that numeral cueing effects can be modulated by controlled strategies comes from a study by Ristic et al. (2006) who reported that the standard leftward cueing effect for small numerals and rightward cueing effect for larger numerals can be reversed simply by asking participants to imagine a horizontal number line running from right to left. Ristic et al. also found that imaging numbers on a clock face gives rise to reversed cueing effects congruent with the numbers' clock face locations. They concluded that the cueing effects of numerals "are both fragile and flexible and depend critically on the top-down spatial mental sets adopted by individuals." (p. 862). Galfano et al. (2006) arrived at a similar conclusion after observing that the effect of number cues is modulated by instructions and by their predictiveness. Convergent evidence that standard numeral cueing is highly sensitive to mental set also comes from the fact that the cueing effect is not always observed. For example, in the synaesthetic cueing studies of both Jarick et al.

(2009a) and Hubbard et al. (2009), control participants did not show a horizontal cueing effect from numerals.

If *non-synaesthete* numeral cueing is mediated by mental set involving intentional visuospatial imagery, it is in principle possible that number cues, or other types of cue such as month and weekday cues, could also exert their effects in this manner among sequence-space synaesthetes. As suggested by Price (2009), this is made particularly likely by the synaesthetes' above-average tendency to experience visuospatial imagery and their skill in using it (Simner et al., 2009). We do not wish to imply here that synaesthetes are confabulating their spatial associations or that they necessarily apply a conscious strategy to shift attention in a particular manner on each trial of a cueing experiment. However, as stressed by Gheri et al. (2008), synaesthetes are usually exposed to considerable demand characteristics during behavioural studies. In addition to knowing they are special participants, they are aware that the experimenter is interested in their synaesthetic associations. Moreover there is increasing general evidence that participants' task-sets in experiments can be unconsciously activated (e.g., Lau and Passingham, 2007; Reuss et al., 2011). A combination of intentions, imagery skill and procedural context may therefore activate strategic associations between cues and areas of space that then mediate cueing effects in an endogenous manner.

Indeed one aspect of these cueing studies with sequence-space synaesthetes argues logically that cueing effects *must* result from symbolic associations that are established for the purposes of the experiment. These studies present detection targets in one of two possible locations to either side of fixation. But these locations on a two-dimensional screen are very unlikely to correspond closely to the synaesthetic location of any given sequence member for a given synaesthete, let alone correspond closely to all the various loci in peripersonal or imaginal space that are associated with the whole set of cues used in the experiment. Therefore, when 2-3 numerals or month names appear to cue attention to a particular target area on a screen, the mediating spatial association must to some extent have been constructed by the participant as a strategic response to the stimuli and response task. For example, deliberately or intuitively, a synaesthete may associate the leftmost target area with 3 month names from 3 different locations on the left of their spatial form. These associations may even be verbally mediated as has been suggested for

spatial associations that underlie some SNARC effects (see section 4.3). The extent to which these associations are task-specific creations rather than precise reflections of synaesthetes' natural spatial associations is likely to be greater for more complex spatial forms, such as when the most natural viewpoint on one's spatial form is from within the form rather than an external view which might translate more readily into a 2D screen layout. This appears to be the case for participant PD, from Smilek et al.'s (2007) cueing study of month forms, as described in her autobiographical account of her synaesthesia (Duffy, 2001).

Summing up, we would argue that: (1) Previous attempts to rule out endogenous cueing in a series of studies with synaesthete L are inconclusive; (2) Endogenous cueing is likely to have occurred, given the known susceptibility of numeral cueing effects to top down mental set, and given the visuospatial skills of sequence-space synaesthetes; (3) There are strong logical reasons to suspect that cueing effects are mediated by short term symbolic associations during cueing studies with synaesthetes.

5.5 Could observed cueing effects be a variety of involuntary cueing from symbolic cues?

An alternative interpretation of cueing in sequence-space synaesthetes, suggested by Jarick et al. (2011a), is that it is similar to the involuntary cueing effects observed from symbolic cues such as schematic diagrams of eye gaze (Frischen et al., 2007). If this were the case, then spatial forms could provide a useful supplement to gaze cues for the study of automatic cueing. Synaesthetic cueing indeed has many of the documented properties of gaze cueing, namely that it (a) occurs at short CTOAs but persists over longer CTOAs without inhibition of return, (b) occurs with non-predictive cues and (c) even persists when cues are counter-predictive (*i.e.*, similarly to when a leftward gaze cue usually predicts a right target). An obvious attraction of this interpretation is that it allows synaesthetic cueing, by analogy to gaze cueing, to be categorized as automatic in the sense of appearing to be involuntary. A second related attraction is that gaze cueing has been argued by some to be mediated by special (perhaps innate) processes linked to the biological significance of gaze, because gaze cueing appears to differ from both the exogenous cueing effects of direct cues and the conventional endogenous cueing effects

of symbolic cues (for discussion see Frischen et al., 2007). This would parallel arguments that sequence-space synaesthesia is mediated by special brain processes. However, as with arguments that synaesthetic cueing resembles exogenous cueing, this interpretation of synaesthetic cueing is premature for the following reasons.

First, it is still unclear how similar synaesthetic cueing and gaze cueing are in terms of their basic properties. We have already argued that the 150 *msecs* minimum CTOA used in studies of synaesthetic cueing may not be short enough to distinguish between endogenous and exogenous cueing effects. Similarly, it may not distinguish between endogenous cueing and the type of cueing elicited by gaze that already emerges at very short CTOAs of around 100 *msecs* (Kuhn and Kingstone, 2009). We have also already argued that the resilience of synaesthetic effects in the face of counter-predictive cues (Jarick et al., 2011a, 2011b) is inconclusive because the cue-target contingency in those studies was ineffective for control participants and could in any case have been ignored if cueing was endogenous. Additionally, whereas synaesthetic cueing with counter-predictive cues has usually persisted at long CTOAs of up to 800 *msecs* (Jarick et al., 2011a, 2011b), the immunity of gaze cues to a counter-predictive contingency has been reported to often fade at longer CTOAs (Frischen et al., 2007). Another consideration is that, as with exogenous cueing, the size of the cueing effect observed with gaze cues (e.g., 12 *msecs* in the seminal study by Friesen and Kingstone, 1998) is typically much smaller than effects observed with synaesthetic cueing.

Second, *even if* synaesthetic cueing were similar to gaze cueing, arguments for the automaticity of the cueing would still need to be qualified. Wright and Ward (2008) have argued that gaze cueing involves goal-driven processing because, unlike the effects of direct cues, it is context dependent and can be disrupted by frontal lobe damage (see also Vecera and Rizzo, 2004). They therefore propose that gaze cueing should not be considered as strongly automatic (or in their words, as “reflexive”) as exogenous cueing from direct cues. The effects of gaze on attentional shifts may instead be highly over-learned to the point where they end up being triggered involuntarily. In other words, of the various properties that could be attributed to an automatic process, gaze cueing shows only the property of involuntariness. This distinction between strongly automatic processes, and processes which show an acquired involuntariness, may also apply to the

cueing effects mediated by spatial forms. By analogy to gaze cueing, the involuntary spatial associations of the synaesthetes would be acquired by learning rather than result from special processes mediated, for example, by unusual brain connectivity.

Third, and consistent with the previous point, the status of gaze cueing as a unique and biologically specialized process has now been challenged by findings that similar behavioural effects are obtained with biologically irrelevant, symbolic cues such as centrally presented arrows that are non-predictive (for a review see Frischen et al., 2007). The behavioural similarity of arrow cues and gaze cues has even been found when the cues are counter-predictive (Kuhn and Kingstone, 2009), challenging previous suggestions that gaze cueing is more strongly automatic (or more “reflexive”) than cueing with arrows. If abstract symbols such as arrows can induce the same type of apparently automatic cueing as eye gaze, then any similarity between synaesthetic cueing and gaze cueing plausibly implies that synaesthetic cueing develops from top-down learning rather than from a biologically hard-wired process.

In summary, it has been suggested that synaesthetic cueing effects may be analogous to gaze cueing. The latter could be considered automatic – in the restricted sense of being involuntary – even though it appears to show fewer hallmarks of automaticity than direct cueing. However, suggestions that this weaker degree of automaticity could be acquired via normal learning processes are supported by observations that gaze cues show similar properties to learned symbolic cues. Under the analogy, this would obviate the need to posit special mechanisms to account for synaesthetic cueing. In any case the comparison between gaze and synaesthetic cueing is compromised by lack of evidence that synaesthetic cueing is as involuntary as gaze cueing, or has the same time course. Synaesthetic cueing also seems to show cueing effects that are larger than those typically observed for gaze cueing.

5.6 Apparent cueing effects might not be mediated by attention shifts at all

So far our discussion has assumed that observed cueing effects from spatial forms are mediated by the ability of the cues to redirect attention, even if the cueing is not as

reflexive as previously argued. However even this basic assumption is called into question by an anomaly in the cueing effects observed with sequence-space synaesthetes.

One characteristic of both exogenous cueing from direct cues and involuntary cueing from gaze cues is that they tend to derive primarily from *facilitatory* processing (faster *RT*) at the cued location (Friesen and Kingstone, 1998; Posner and Snyder, 1975). Endogenous cueing, on the other hand, tends to result in both facilitation at the cued location and *inhibition* (slower *RT*) at the uncued location. Unfortunately, cueing studies with sequence-space synaesthetes have never included trials with neutral cues to provide a baseline against which *RTs* on trials with congruent and incongruent cues can be compared. This prevents straightforward assessment of whether observed cueing effects, expressed simply as the difference between incongruent and congruent *RT*, are facilitatory, inhibitory or both. An assessment of this kind is also complicated by inconsistency across studies in whether synaesthetes (a) show slower *RTs* than controls on both congruent and incongruent trials (e.g., some participants in Smilek et al., 2007), or (b) show faster *RTs* than controls on both types of trial (e.g., Hubbard et al., 2009), or (c) show slower *RTs* than control participants on incongruent trials and show *RTs* within the control range on congruent trials (e.g., Jarick et al., 2009b, 2011a, 2011b). This variation may reflect individual differences in baseline *RT* and also reflect a tendency for some participants to show slowed overall performance in tasks where some kind of incongruency has to be overcome (see Jarick et al., 2009b).

There is nevertheless some evidence suggesting that the synaesthetic cueing effects are predominantly carried by inhibitory processing on incongruent trials, which is the *opposite* pattern to what would be predicted if exogenous or other involuntary cueing was involved. If we consider the 14 cases of synaesthetic cueing effects summarized in Table 1, the magnitude of observed cueing effects *increases with the magnitude of participants' RT on incongruent trials* rather than with their *RT* on congruent trials. In Figure 2, we show the cueing effect for each participant/condition plotted against both the *RT* for incongruent trials and the *RT* for congruent trials. The figure uses data for the shortest CTOA that was employed for the participant, and excludes the individual in row 1 of Table 1 whose extremely long *RTs* are outliers and thus unduly influence the overall

pattern. We find a significant correlation of $r = .58$ for incongruent *RTs* ($p = .04$, 2-tailed), but no indication of a correlation for congruent *RTs* ($r = .03$, $p = .91$).

INSERT FIGURE 2 APPROXIMATELY HERE

In conclusion, if cues exert their influence on performance by inducing attentional shifts, as is assumed in these studies, it is curious that incongruent *RT* is the primary driver of the cueing effects. A possible explanation is that the apparent cueing effects are partly or even wholly mediated by a variety of perceptual incongruity that slows *RT* on incongruent trials, but has no facilitatory effect on congruent trials. As we discuss further below, sequence-space synaesthetes are already known to make slower judgements about sequence members that are displayed in a layout that is incongruent with their spatial form, compared with a congruent layout. A similar generalized influence of incongruity perhaps arises when a visual target is displayed in a location that is different from the area of space that a synaesthete associates with a recently named sequence member. This account differs from a standard attentional cueing account in that responses to the target are slowed by perceived incongruity, rather than by slowed perceptual processing due to a diverted focus of visuospatial attention. Note that if this interpretation is correct, it might explain why apparent cueing effects are so large in sequence-space synaesthetes, and also why they seem relatively unaffected by CTOA.

We suggest that future studies of cueing effects in sequence-space synaesthesia should include neutral cues in order to resolve this issue.

5.7 Summary

Several studies have argued that, for sequence-space synaesthetes, the written (and sometimes heard) names of numbers, weekdays, months, clock-times or letters can induce a shift of visuospatial attention toward the side of space that is most strongly associated with these sequence members. However we have outlined a number of concerns with the prevailing interpretation of these data. In particular, we have argued

that characteristics of the cueing effects in synaesthetes have not yet, despite claims to the contrary, been convincingly shown to be due to an automatic shift of attention.

As they stand, the data do not rule out the possibility that the cueing effects are mediated by task-specific strategies, similar to the endogenous cueing that is usually associated with predictive symbolic cues. In some respects the data and cueing procedures positively favour this interpretation, for example in terms of the observations that response times are unaccountably long, cueing effects are large and persist over a wide range of CTOAs, and that the mapping between synaesthetic spatial representations and the spatial locations of targets is rather artificial and imprecise. Alternatively, and more speculatively, observed effects might not even be based on cueing at all, but rather on perceptual incongruity, which slows *RT* on incongruent trials.

What seems quite clear is that effects differ from conventional exogenous capture by direct cues – the type of cueing which is accepted to most exhibit various hallmarks of automaticity. This challenges any notion that locations in synaesthetic space have a perceptual status similar to stimuli in real external space, which is especially notable given that some sequence-space synaesthetes report their spatial forms are experienced in external space around the body. However the lack of equivalence with real space would parallel arguments that synaesthetic colour experiences of grapheme-colour synaesthetes are not functionally equivalent to experiences of real color (Hupe et al., 2012; Gheri et al., 2008; Mattingley, 2009). Additionally, the available data also fail to demonstrate conclusively that synaesthetic cueing is analogous to the kind of weakly automatic cueing obtained from gaze stimuli. Even if synaesthetic cueing were like gaze cueing, this might only imply that it is automatic in the restricted sense of showing a degree of contextually sensitive involuntariness, rather than in the sense of being a fully reflexive response. Moreover, the cueing could still be explained in terms of overlearned associations rather than special brain mechanisms.

There is one further aspect of these cueing studies that deserves comment. A glance at Table 1 serves to remind us that studies claiming automaticity have so far been based on a very small sample of participants. Given that sequence-space synaesthesia appears to be common, an obvious question is whether these few participants are representative of the phenomenon in general. This is especially the case for a participant like L, who has taken

part in hundreds of cueing trials over 4 published studies, and whose performance in recent studies may therefore reflect the influence of training as much as her initial synaesthetic representations.³

INSERT FOOTNOTE 3 APPROXIMATELY HERE

Smilek et al. (2007), in their seminal cueing study, claimed that spatial forms show one of the “defining characteristics of synaesthesia; namely ... they seem to influence behavior independent of voluntary control” (p. 517). We have argued that this often-repeated claim is premature and that available cueing data are at best ambiguous regarding automaticity. In future studies of cueing with sequence-space synaesthetes we would encourage researchers to (a) eliminate the possibility of endogenous cueing more thoroughly by including CTOAs of *100msecs* or less, and by masking targets to control the time window during which target processing can be influenced; (b) include neutral cues to establish the relative contributions of facilitatory and inhibitory cueing; (c) test larger samples of naïve participants who may be more representative of sequence-space synaesthetes in general; and (d) examine whether cueing effects arise from the detailed reported layout of the spatial forms rather than very general left-right or up-down associations.

6. Do spatial incongruity effects and distance effects support the automaticity of spatial forms?

6.1 Magnitude comparison of two simultaneous numerals can be slower when they are displayed in a spatial layout that is incongruent with a spatial form

A third paradigm, that has been used behaviourally to validate number forms, involves presenting two numerals on screen simultaneously and asking participants to indicate which has the larger magnitude. Responses are made by pressing one of two keys that are arranged in spatial congruence with the two numerals. A few studies have shown that *RT* on this type of magnitude comparison can be slower if the relative spatial

layout of the two numerals is incongruent with their relative layout in the number form of a sequence-space synaesthete. This was first demonstrated by Piazza et al. (2006) in a single case study, by Sagiv et al. (2006) in a study of 5 participants with number forms, all of whom showed a congruency effect (mean 28 *msecs*), and by Tang et al. (2008) who found a congruency effect over 10 participants (mean 15 *msecs*). More recently Hubbard et al. (2009) reported a similar trend in their single case study of DG, although this did not reach significance, and Gertner et al. (2009) reported that two out of their three participants with number forms showed the effect.

While again demonstrating that some peoples' default spatial associations for numbers are explicit, unusually strong and sometimes atypical in layout, this basic spatial incongruency effect is itself neutral with respect to whether number forms are mediated by 'low-level' reflexive spatial associations or by 'higher-level' mental set. However the effect has been taken by some (e.g., Piazza et al., 2006) as highly suggestive that the forms are *involuntarily* triggered, at least in the context of the numerical comparison task. In this respect the effect could be seen as convergent with some interpretations of the spatial cueing literature discussed above – namely that number forms at least qualify for the automaticity criterion of involuntariness. Even this conclusion might be premature since the incongruency effect is not immune to the general criticism that synaesthetes may sometimes try to elicit the behavioural patterns they perceive are expected of them (Gheri et al., 2008), or might deliberately evoke the synaesthetic mental representations that then generate these patterns.

6.2 Using distance effects in magnitude comparison to argue that number forms are involuntary and inflexible

In an attempt to address the automaticity issue more directly, one of the above-mentioned studies of incongruity effects also examined numerical distance effects shown during magnitude comparison of numeral pairs (Gertner et al., 2009). The distance effect (Moyer and Landauer, 1967) is the relative speeding of magnitude comparison that occurs as the numerical distance between the two numerals increases. Routinely observed

in normal participants, it is often taken to reflect the existence of spatially extended mental number lines.

To measure distance effects, Gertner et al. (2009) manipulated across trials whether presented numeral pairs were 1, 2 or 5 numerals apart. To measure spatial incongruity effects, the numerals were displayed horizontally or (in separate blocks) vertically about fixation, with the location of the smallest numeral varying across trials between left/right or bottom/top. This yielded four different spatial layouts for the smaller versus larger numeral. For each of the 3 participants with a number form, only one of these layouts was spatially congruent with early segments of their number form (numbers 1-9) from which the test stimuli were drawn. Gertner et al. then found that each number form participant only showed a significant distance effect (i.e., faster *RT* for larger numerical distance) in this spatially congruent condition, suggesting that it was only in the congruent condition that a spatial layout was adopted. By contrast, control participants showed significant distance effects at a group level for *all* spatial layouts. Gertner et al. interpreted this as indicating that non-synaesthetes can flexibly re-orient their mental number line according to task demands, but that people with number forms have an involuntary and inflexible predisposition to represent numbers in a particular spatial layout.

6.3 Some problems in using distance effects as evidence for the automaticity of number forms

The interpretation of these distance effects by Gertner et al. (2009) is laudably circumspect, avoiding blanket claims of automaticity. Instead they make more specific claims about certain components of automaticity – namely *involuntariness* and *inflexibility*. Yet even here, as with the basic incongruency effect, we recommend caution.

First, regarding the difference between number form and control participants, it should be noted that the synaesthetes in the study of Gertner et al. (2009, Fig.2) showed numerical trends for distance effects even in some of their spatially incongruent conditions (although these trends did not reach significance, no formal comparison was presented of their magnitude in relation to the size of distance effects in congruent

conditions). If these trends were mediated by participants' ability to adopt spatial orientations that occur in other parts of their number forms, as was speculated by the authors, this seems to counter the claim of involuntariness and inflexibility. Additionally, the significant distance effects obtained in each spatial condition for the combined group of 20 control participants could mask individual differences. If some of these control participants failed to show significant distance effects in some conditions, as is likely, this would further compromise the difference between synaesthetes and controls.

Second, the central finding that control participants were able to flexibly adopt different spatial representations according to the layout of stimulus displays suggests the possibility that synaesthetes could have intentionally chosen *not to adopt* different spatial representations. In other words, the apparent inflexibility of participants with number forms could have been a strategy induced by experimenter demand, again reflecting the concerns of Gheri et al. (2008). The fact that the quantitatively largest distance effect shown by any of the number form participants (Gertner et al., 2009, Fig 2C) was comparable in size to the distance effects shown by non-synaesthetes is consistent with the suggestion that the number lines of synaesthetes and controls were similarly mediated by voluntary control.

Third, even if we rule out confounds due to experimenter demand, the proposed inflexibility of spatial forms has to be moderated by evidence that, in other contexts, sequence-space synaesthetes are rather good at adopting different spatial representations of sequence members. For example, Brang et al. (2010) showed that people with spatial forms for calendar months are better than controls at memorizing novel spatial arrangements of months, indicating unusually good rather than unusually poor flexibility of spatial representation.

A last problem with using distance effects as a measure of representational flexibility is that some studies of the effect have concluded that it is a general reflection of processes involved in magnitude comparisons, rather than of spatial representations (e.g., Cohen-Kadosh et al., 2008; Piazza et al., 2006). This includes the finding by Piazza et al. (2006) that distance effects observed in their single case number-form synaesthete were related to numerical distance rather than to geometrical distance in the number form. The idea that distance effects do not primarily reflect spatial representations is also supported by

the indifference of Gertner et al.'s (2009) control participants to spatial layout, given that nonsynaesthetes often appear to have a default spatial association for numbers (e.g., left to right or bottom to top) when tested in paradigms involving SNARC effects and spatial cueing. But why then would number form synaesthetes only show numerical distance effects when displays are oriented congruently with their number forms? One possibility is that when displays are incongruent for the synaesthete, the limiting factor on *RT* is the general slowing due to incongruency, leaving no influence of numerical distance. Consistent with this suggestion, the synaesthete in the Gertner et al. study who showed the largest *RT* cost of incongruency was also the one with the least indication of any distance effects in incongruent conditions.

6.4 Summary

During magnitude comparison of two simultaneously presented numerals, two aspects of the performance of number-form synaesthetes have been used to support the specific claim that the forms are involuntary and inflexible. First, the synaesthetes show slower responses when displays are spatially incongruent with the layout of their number form. Second, the synaesthetes only show distance effects when displays are spatially congruent with their form. However the data also seem compatible with the possibility that differences between synaesthetes and controls are mediated by demand characteristics, and they conflict with evidence from other paradigms that demonstrate a degree of flexible voluntary control over spatial representation of sequences for which one has a spatial form. With regard to distance effects, potential overlap between the performance of controls and sequence-space synaesthetes does not yet seem to have been tested rigorously enough, and it is possible that distance effects per se are not a reliable measure of spatial representations (Cohen-Kadosh et al., 2008; Piazza et al., 2006).

7. General discussion

7.1 Sequence-space synaesthesia may not be so automatic after all, and any automaticity needs to be more precisely characterized.

The idea that synaesthesia is expressed automatically has been a dominant theme in past research on synaesthesia. A second theme, which draws partly on this proposed automaticity for support, has been that synaesthesia is mediated by qualitatively abnormal brain structures or processes. These proposed properties of synaesthesia have together helped to characterize it as a distinct condition that is worthy of scientific investigation and separable from normal cognition. Sequence-space synaesthesia is no exception. The automaticity of people's vivid spatial forms for sequences such as calendar units and numbers has been used as an important justification for including these experiences as a variety of synaesthesia, and has encouraged suggestions that special mechanisms are involved. However we have argued above that the 3 major experimental paradigms used to demonstrate the automaticity of sequence-space synaesthesia have not yet established this automaticity convincingly, despite claims to the contrary. These paradigms reflect different behavioural effects of the spatial congruency between spatial forms, presented stimuli and overt responses – namely SNARC-like effects, spatial cueing, and perceptual incongruity effects. Our specific concerns with existing data from each of these paradigms are already summarized above in Sections 4.5, 5.7, and 6.4 respectively, and will not be repeated here.

We do not claim to have ruled out the possibility that sequence-space synaesthesia may turn out to exhibit some of the characteristics that are regarded as typical properties of automaticity. Rather, our main point is that existing data are either ambiguous or in some respects even favour interpretations in terms of learning or controlled strategies. Our analysis of sequence-space synaesthesia therefore mirrors previous challenges to the automaticity of grapheme-colour synaesthesia (Gheri et al., 2008; Mattingley, 2009; Treisman, 2005). Recent data on a type of visuospatial synaesthesia in which sounds induce experiences of coloured geometrical objects in specific spatial locations, and whose concurrents therefore have interesting similarities to sequence-space synaesthesia, also show directly that the influence of synaesthetic concurrents on performance is modulated by attention (Chiou et al., in press).

Whether rejecting or accepting the automaticity of sequence-space synaesthesia, it is important to specify exactly what one means by automaticity. Much of the literature to

date on sequence-space synaesthesia has treated automaticity as a unitary construct but, as stressed by Treisman (2005) in her analysis of grapheme-colour synaesthesia, there are several dissociable criteria by which a process can be said to demonstrate automatic properties. Thus we suggest it is important to evaluate sequence-space synaesthesia in relation to each of these criteria before embarking on debates as to whether the phenomenon qualifies for the blanket term of ‘automatic’. Additionally, we have argued in our discussion of spatial cueing data (e.g., sections 5.2, and 5.7) that automaticity *per se* needs to be disentangled from related issues such as the perceptual status of synaesthetic sensations and the need for special explanatory mechanisms. In these respects, we suggest the following conclusions can be drawn from our analysis of sequence-space synaesthesia.

First, there is no strong evidence so far, for example from spatial cueing studies, that spatial forms are equivalent to perceptual signals in their effects on behaviour and attention. This again mirrors arguments that the subjective colours of grapheme-colour synaesthetes arise at a ‘cognitive’ rather than ‘perceptual level’ (Gheri et al., 2008; Hupe et al., 2012; Mattingley, 2009; Nijboer et al., 2011; van Leeuwen et al., 2010; Ward et al., 2010).

Second, of the various properties associated with automatic processes, the only ones for which there is even provisional support so far are the related properties of involuntariness and inflexibility. Even for this limited sense of automaticity, however, caution is needed since current data also seem compatible with controlled processes mediated by demand characteristics. Furthermore, any extent to which the spatial relations expressed in a spatial form are involuntary and inflexible for an individual synaesthete may be contextually relative. This is suggested by demonstrations that the synaesthetes can sometimes represent sequences in novel spatial layouts more successfully than controls (Brang et al., 2010). The extent to which spatial forms are involuntarily activated is also qualified by a recent report which studied the hand reaching movements of a month-space synaesthete in a 3D virtual reality environment; Diesendruc et al. (2010) found that synaesthete SM was able to touch the locations of her months in peripersonal space with high consistency when cued with a visually presented month name but, if she was told to ignore the month names, they had no influence on

reaching movements to other targets in peripersonal space. On other criteria of automaticity the data are so far silent. For example we do not yet know whether spatial forms are (a) activated very rapidly; (b) whether they can be induced non-consciously (e.g., by subliminally masked stimuli); (c) whether sequence-space synaesthesia and its behavioural correlates are attenuated by the influence of secondary tasks, or (d) whether targets in cued locations of spatial forms show pop-out in the sense of having shallower than usual visual search slopes with increases in distractor set size. In sum, the ‘automaticity’ of sequence-space synaesthesia may be at best limited to a weak manifestation of just one out of the many typical hallmarks of automaticity. A related caution against characterizing sequence-space synaesthesia as automatic in an oversimplistic manner comes from Sagiv et al. (2007) who suggest we should distinguish between (a) automaticity in relation to initial activation of spatial forms, and (b) the mental inspection or navigation of spatial forms which some people report to be effortful.

Third, if sequence-space synaesthesia is not strongly automatic, the need for special explanatory mechanisms is removed. This is also the case if a weak degree of automaticity could in principle be derived via standard top-down processes such as those of visuospatial imagery. For example, the fact that activation of spatial forms sometimes appears obligatory might merely indicate overlearned representations which originally derive from standard top-down, controlled strategies and which are activated when they are contextually relevant (for another example of the distinction between obligatory and strongly automatic processes see Loomis et al., 2007). Sequence-space synaesthesia need not be more special than the many other aspects of human experience and performance that are influenced by automatic processes derived from learning. This is resonant with a more recent emerging theme within synaesthesia research – namely with calls to explore the continuity rather than the discontinuity between normal and synaesthetic mental processes and to avoid postulating unnecessary special mechanisms for synaesthesia (Brang et al., 2011; Chiou et al., in press; Cohen Kadosh et al., 2007; Ward et al., 2006, 2007). It is also resonant with recent arguments that challenge the traditional concept of an innate mental number line in non-synaesthetes, and instead suggest that spatial coding of number is culturally mediated via top-down, higher order cognitive mechanisms (Nunez, 2011).

Of the 3 paradigms we have reviewed, spatial cueing tasks probably hold the most promise for future attempts to test automaticity because so much is already known from normal participants about the contributions of automatic versus controlled processes to performance in these tasks. We have already given some specific recommendations for how cueing studies with sequence-space synaesthetes could be procedurally improved (Section 5.7). However we would also suggest generally that researchers should be more proactive in seeking counterfactual evidence for automaticity, whatever paradigm is being employed. For example, future studies should manipulate task demands to encourage naïve synaesthete participants to deliberately withhold the influence of their synaesthetic associations. It should also be tested whether control participants are able to use controlled strategies to emulate the performance of synaesthetes, as has already been observed for SNARC-like effects (Price, 2009).

Although automaticity has been taken as one of the gold standards for synaesthesia, challenges to the automaticity of sequence-space synaesthesia need not in themselves be taken to question their status as a variety of synaesthesia. This is an evolving definitional issue, over which we are currently agnostic, and which involves both the desired scope of the term *synaesthesia* and the extent to which the automaticity of other varieties of synaesthesia is confirmed or refuted. In this respect it should be noted that the same challenge has been directed at grapheme-colour synaesthesia (which continues to be referred to as a classic variety of synaesthesia), both at the behavioural level (Mattingley, 2009; Treisman, 2005) and at the experiential level. Cytowic and Eagleman (2009) state quite clearly in their recent overview of synaesthesia that grapheme-colour synaesthetes experience their colours when they *attend* to letters, and that letters are not strongly coloured all the time.

This raises the question of why synaesthetes who experience spatial forms or coloured graphemes often say these experiences are triggered involuntarily whenever the inducer is internally activated or externally perceived (e.g., a sequence-space synaesthete might report that she cannot think about January, or hear the word “January”, without having the concurrent spatial experience). Two explanations suggest themselves. The first, which is merely a manifestation of Minsky’s (1986) ‘immanence illusion’⁴, is that the very act of answering whether one’s synaesthetic experience is present has already

engaged attention on that dimension of our experience. In other words, if perceptual or conceptual synaesthetic inducers are present and we look for our synaesthetic experience, it always appears to be there. The second explanation, which acknowledges the importance of individual differences between synaesthetes (Hubbard et al., 2005a; Ward et al., 2007)), is that automaticity may be one of various dimensions on which the experience of spatial forms varies continuously (Price, 2009a), even if it is not a defining characteristic of sequence-space synaesthesia. In this respect it should be noted that some people who experience detailed visuospatial images for common sequences such as the calendar months explicitly report that these images *are* under their voluntary control (personal observation), a fact that is not commonly acknowledged in the published literature on spatial forms. This would suggest the possibility, for example, that spatial cueing effects for spatial forms might be more automatically mediated for some synaesthete participants, whereas endogenous cueing might best explain performance in other synaesthete participants, particularly in those who show very long *RTs* and exceptionally large cueing effects.

INSERT FOOTNOTE 4 APPROXIMATELY HERE

7.2 Many observed characteristics of spatial forms suggest continuity with controlled visuospatial imagery

If sequence-space synaesthesia were strongly automatic, we might expect spatial forms to be characterised by stable, inflexible, unelaborated, one-to-one correspondences between synaesthetic inducers and concurrents. However, spatial forms often show characteristics that are much more reminiscent of the dynamic, contextually sensitive, and creatively elaborate processes of controlled visuospatial imagery. We would argue that this is convergent with our challenge to the automaticity of sequence-space synaesthesia, and suggests an area of normal cognition where continuity with synaesthetic spatial forms can be fruitfully explored.

This continuity was commented on long ago in the survey studies of Phillips (1897), has been argued more recently by Price (2009; in press) (see also Brang et al., 2010; 2011), and is supported by several observations:

(a) As with normal mental imagery, synaesthetes often report being able to zoom into their spatial forms. When attention is directed to a particular member of a sequence, some synaesthetes also report that their mental image of the form rotates in relation to their viewpoint, or that they feel they move within their form (e.g., Diesendruc et al., 2010). Thus spatial forms can be highly dynamic.

(b) Spatial forms are often more elaborated than a simple spatial trajectory of sequence members. For example, the layout of the sequence members may be experienced as a ribbon or tube. Moreover, the form may include a background, or complex visual imagery of scenes (Cytowic and Eagleman, 2009; Price, in press), and the experience of sequence members such as months may include visualized ‘labels’ of their written names whose inclusion is even sometimes reported to be under voluntary control (personal observation).

(c) The complexity of spatial forms often increases from childhood into adulthood (Phillips, 1897), and completely new forms may emerge in adulthood (Cytowic and Eagleman, 2009). By contrast, but also arguing against strongly automatic associations, spatial forms have been reported to sometimes fade from childhood to adulthood (Phillips, 1897).

(d) Although the existence of sequence-space synaesthetes with a great many different spatial forms, such as participant DF reported by Hubbard et al. (2009) or participant CS described by Cytowic et al. (2002), could be taken to reflect strong involuntary predispositions to create spatial forms, it could alternatively suggest a continuum between spatial forms and intentional visuospatial encoding strategies. In our view, this is especially likely given that the tendency may extend to complex verbal ‘sequences’ such as the Lord’s Prayer (Phillips, 1897).

(e) As discussed by Price (in press), the layout of spatial forms often creatively expresses the significance of a sequence member in terms of its spatial extension (e.g., holiday months taking up more space than other months; see also Diesendruc et al., 2010), or in terms of bends or protuberances in the trajectory of a form. For example,

calendar forms may bend or distort at personally significant dates, number lines often bend at decade breaks (Makioka, 2009; Sagiv et al., 2006), the number 12 tends to be emphasised in older samples of British number lines, reflecting the use of the duodecimal system (Galton, 1880a; Phillips, 1897), and bends and breaks in alphabet forms tend to reflect the verbal parsing of the Alphabet Song that is often used to teach the alphabet sequence in English speaking countries (Jonas et al., 2011). This symbolic use of imagery may overlie more innate tendencies to arrange spatial forms in particular ways, as illustrated by the recent finding that the clockwise versus anticlockwise direction of circular forms for the calendar months is correlated with synaesthetes' handedness (Brang et al., 2011).

In summary, there are several respects in which spatial forms express properties of mental models that are adaptive and fluid, albeit highly overlearned. These indications of a continuity between spatial forms and controlled visuospatial imagery are obviously consistent with data showing that sequence-space synaesthetes perform unusually well on visuospatial tests (Simner et al., 2009), that they report more visual imagery in everyday life (Price, 2009), and that intentional imagery can simulate some known behavioural correlates of sequence-space synaesthesia (Price, 2009).⁵

INSERT FOOTNOTE 5 APPROXIMATELY HERE

7.3 Conclusion

Our hope is that this critical discussion of some central experimental paradigms used to study sequence-space synaesthesia will help to guide future research on this fascinating phenomenon. Any arguments that synaesthetic spatial forms are strongly automatic should be based on more incontestable empirical evidence than presently exists, and should acknowledge fractionation of the concept of automaticity. We think it is important to challenge evidence for the automaticity of sequence-space synaesthesia because the automaticity assumption tempts researchers to seek explanations of the phenomenon in terms of special mechanisms such as abnormal brain connectivity, which often lack parsimony. This in turn tends to legitimize the phenomenon in a manner that de-

emphasizes potential continuity with normal cognition. We suggest that research in this area should place more emphasis on evaluating the extent to which learning processes are involved in establishing people's 'synaesthetic' spatial associations with sequences, on the extent to which normal processes of visuospatial imagery are involved in mediating these associations, and on the extent to which controlled strategies play a role in mediating behavioural differences between synaesthetes and control participants. In as far as normal mental processes are involved, this common yet poorly understood phenomenon becomes increasingly informative for the wider research community, providing a useful platform to study the interface between mental imagery, learning and individual differences in encoding strategies.

Footnotes.

1. “Note that in cultures with other reading directions, these spatial associations may be altered – e.g., run right to left in native Arabic speakers (e.g., see Shaki, Fischer and Petrusic, 2009).”
2. “The magnitude of SNARC effect can be formalized as the steepness of the regression slope (independent of +/- value) that is obtained when plotting the difference between left-hand and right-hand RTs against the sequence position of the target stimulus (e.g., numerals from 1-9 or months from 1-12).”
3. “One indication that practice may have started to modify her cueing performance is that in one recent study (Jarick et al., 2011a) she differed from controls by showing a significant (and very large) cueing effect from predictive numeral cues during a horizontally aligned target detection task, even at a CTOA of 150 *msecs*. Crucially, the cueing numerals were taken from a vertical portion of her number line so it had been predicted that she would show no cueing effect, as was indeed found in an earlier study (Jarick et al., 2009a), albeit with non-predictive cues and longer CTOAs. Jarick et al. (2011a) offered the post hoc speculation that L had spontaneously adopted a new egocentric vantage point on her number line, placing it in alignment with the horizontal layout of targets and response keys in a manner that then generated an automatic cueing effect. However in our opinion the short CTOA of 150 *msecs* was insufficient to rule out the more parsimonious suggestion that, unlike control participants, L was motivated and practiced enough to engage in strategic cueing that was unrelated to her number line but related to the cue-target contingency. As a side note, if L did adopt a new context-driven vantage point on her number line, this would itself admit an influence of controlled strategies on her synaesthetic associations and would counter the claim for strong automaticity.”
4. ““Whenever you can answer a question without a noticeable delay, it seems as though the answer were already active in your mind.” (Minsky, 1986, section 15.5)”

5. “It should be noted that this continuity may not be unique to sequence-space synaesthesia. For example, as pointed out by one of our reviewers, synaesthetically experienced grapheme colours may be elaborated to include texture or patterns, may show dynamic properties, and are on average not random but show tendencies to represent semantic or phonological associations (e.g., Simner, 2005). Interestingly there are also claims that grapheme-colour synaesthesia, like sequence-space synaesthesia, is associated with above-average imagery experience (Barnett and Newell, 2008) and imagery skill (Spiller and Jansari, 2008). The extent to which different synaesthetic varieties show similar or different degrees of continuity between conventional and synaesthetic imagery remains, however, almost unexplored (see Price, in press).”

Author Note

MCP was supported by grant 101936 from the University of Bergen and the Norwegian Research Council (NFR). JBM was supported by an Australian Research Council (ARC) Australian Laureate Fellowship (FL110100103).

References

- Bachot J, Gevers W, Fias W, and Roeyers H. Number sense in children with visuospatial disabilities: Orientation of the mental number line. *Psychology Science*, 47 (1):172-183, 2005.
- Brang D, Teuscher U, Miller LE, Ramachandran VS, and Coulson S. Handedness and calendar orientations in time-space synaesthesia. *Journal of Neuropsychology*, 5 (2):323-332, 2011.
- Brang D, Teuscher U, Ramachandran VS, and Coulson S. Temporal sequences, synesthetic mappings, and cultural biases: The geography of time. *Consciousness and Cognition*, 19:11-320, 2010.
- Bächtold D, Baumüller M, and Brugger P. Stimulus response compatibility in representational space. *Neuropsychologia*, 36:731-735, 1998.
- Caessens B, Notebaert W, Burle B, and Soetens E. Voluntary and involuntary control over automatic processing in spatial congruency tasks. *European Journal of Cognitive Psychology*, 17:577-589, 2005.
- Cheal M-L, and Lyon DR. Central and peripheral precuing of forced-choice discrimination. *Quarterly Journal of Experimental Psychology*, 43A (4):859-880, 1991.
- Chiou R, Stelter M, and Rich AN. Beyond colour perception: Auditory-visual synaesthesia induces experiences of geometric objects in specific locations. *Cortex*, in press.

- Cohen Kadosh R, Henik A, Catena A, Walsh V, and Fuentes LJ. Induced cross-modal synaesthetic experience without abnormal neuronal connections. *Psychological Science*, 20 (2):258-265, 2009.
- Cohen Kadosh R, Henik A, and Walsh V. Small is bright and big is dark in synaesthesia. *Current Biology*, 17 (19): R834-835, 2007.
- Cohen Kadosh R, Levin M, Brodsky W, and Henik A. Mental representation: Domain specific or task specific? *Cortex*, 44:470-477, 2008.
- Cytowic RE. *Synaesthesia: A Union of the Senses*. Cambridge, MA: MIT Press, 2002.
- Cytowic E and Eagleman DM . Number hangs above me to the left. In E Cytowic, and DM Eagleman (Eds), *Wednesday is indigo blue. Discovering the brain of synaesthesia*. Cambridge MA: MIT Press, 2009: 109-125.
- Day S. Some demographic and socio-cultural aspects of synaesthesia. In Robertson LC, and Sagiv N (Eds), *Synaesthesia: Perspectives from Cognitive Neuroscience*. New York: Oxford University Press, 2005: 11-33.
- Dehaene S, Bossini S, and Giraux P. The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, 122: 371-396, 1993.
- Dehaene S, Dupoux E, and Mehler J. Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance*, 16: 626-641, 1990.
- Diesendruc L, Gertner L, Botzer L, Goldfarb L, Karniel A, and Henik A. Months in space: Synaesthesia modulates attention and action. *Cognitive Neuropsychology*, 27 (8):665-679, 2010.

Duffy PL. *Blue cats and chartreuse kittens. How synaesthetes colour their worlds*. New York: Holt, 2001.

Eagleman DM. The objectification of overlearned sequences: A new view of spatial sequence synaesthesia. *Cortex*, 45 (10): 1266-1267, 2009.

Fischer MH. The future for SNARC could be stark. *Cortex*, 42: 1061-1142, 2006.

Fischer MH, Castel AD, Dodd MD, and Pratt J. Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience*, 6 (6):555-556, 2003.

Fischer MH, Mills RA, and Shaki S. How to cook a SNARC: Number placement in text rapidly changes spatial-numerical associations. *Brain and Cognition*, 72 (3):333-336, 2010.

Fischer MH, Shaki S, and Cruise A. It takes only one word to quash the SNARC. *Experimental Psychology*, 56 (5):361-366, 2009.

Friesen CK, and Kingstone A. The eyes have it! Reflexive orienting is triggered by nonpredictive gaze. *Psychonomic Bulletin and Review*, 5:490-495, 1998.

Frischen A, Bayliss AP, and Tipper SP. Gaze cueing of attention: Visual attention, social cognition, and individual differences. *Psychological Bulletin*, 133:694-724, 2007.

Galfano G, Rusconi E, and Umiltà C. Number magnitude orients attention, but not against one's will. *Psychonomic Bulletin and Review*, 13:869-874, 2006.

Galton F. Statistics on mental imagery. *Mind*, 5: 301-318, 1880a.

Galton F. Visualised numerals. *Nature*, 21: 494-495, 1880b.

Galton F. Visualised numerals. *The Journal of the Anthropological Institute of Great Britain and Ireland*, 10:85-102, 1881.

- Gertner L, Henik A and Cohen Kadosh R. When 9 is not on the right: Implications from number-form synaesthesia. *Consciousness and Cognition*, 18:366-374, 2009.
- Gevers W, Reynvoet B, and Fias W. The mental representation of ordinal sequences is spatially organized. *Cognition*, 87: B87-B95, 2003.
- Gevers W, Reynvoet B, and Fias W. The mental representation of ordinal sequences is spatially organised: Evidence from days of the week. *Cortex*, 40:171-172, 2004.
- Gevers W, Verguts T, Reynvoet B, Caessens B, and Fias W. Numbers and space: A computational model of the SNARC effect. *Journal of Experimental Psychology: Human Perception and Performance*, 32:32-44, 2006.
- Gheri C, Chopping S, and Morgan MJ. Synaesthetic colours do not camouflage form in visual search. *Proceedings of the Royal Society B*, 275:841-846, 2008.
- Grossenbacher PG and Lovelace CT. Mechanisms of synaesthesia: Cognitive and physiological constraints. *Trends in Cognitive Sciences*, 5:36-41, 2001.
- Herrera A, Macizo P, and Semenza C. The role of working memory in the association between number magnitude and space. *Acta Psychologica*, 128 (2):225-237, 2008.
- Hubbard EM, Arman AC, Ramachandran VS, and Boynton GM. Individual differences among grapheme-color synesthetes: Brain-behavior correlations. *Neuron*, 45:975-985, 2005a.
- Hubbard EM, Brang D, and Ramachandran VS. The cross-activation theory at 10. *Journal of Neuropsychology*, 5:152-177, 2011.
- Hubbard EM, Piazza M, Pinel P, and Dehaene S. Interactions between numbers and space in parietal cortex. *Nature Reviews Neuroscience*, 6:435-448, 2005b.

- Hubbard EM and Ramachandran VS. Neurocognitive mechanisms of synesthesia. *Neuron*, 48 (3):509-520, 2005.
- Hubbard EM, Ranzini M, Piazza M, and Dehaene S. What information is critical to elicit interference in number-form synesthesia? *Cortex*, 45:1200-1216, 2009.
- Hubbard EM and Simner J. *Oxford handbook of synaesthesia*. Oxford: Oxford University Press, in press.
- Hupe JM, Bordier C, and Dojat M. The neural bases of grapheme-color synesthesia are not localized in real color-sensitive areas. *Cerebral Cortex*, 22:1622-1633, 2012.
- James W. *The Principles of Psychology, Vol. 1*. New York: Dover, 1890/1950.
- Jarick M, Dixon MJ, Maxwell EC, Nicolls MER, and Smilek D. The ups and downs (and lefts and rights) of synaesthetic number forms: Validation from spatial cueing and SNARC-type tasks. *Cortex*, 45:1190-1199, 2009a.
- Jarick M, Dixon, MJ, and Smilek D. 9 is always on top: Assessing the automaticity of synaesthetic number-forms. *Brain and Cognition*, 77 (1): 96-105, 2011.
- Jarick M, Dixon MJ, Stewart MT, Maxwell EC, and Smilek D. A different outlook on time: Visual and auditory month names elicit different mental vantage points for a time-space synaesthete. *Cortex*, 45:1217-1228, 2009b.
- Jarick M, Jensen C, Dixon MJ, and Smilek D. The automaticity of vantage point shifts within a synaesthetes' spatial calendar. *Journal of Neuropsychology*, 5:333-352, 2011b.
- Jonas C and Jarick M. Synaesthesia, sequences, and space. In E Hubbard and J Simner (Eds), *Oxford handbook of synaesthesia*. Oxford: Oxford University Press, in press.

- Jonas CN, Taylor AJG, Hutton S, Weiss PH, and Ward J. Visuospatial representations of the alphabet in synaesthetes and non-synaesthetes. *Journal of Neuropsychology*, 5:302-322, 2011.
- Klein, R. Inhibition of return. *Trends in Cognitive Sciences*, 4:138-147, 2000.
- Kuhn G and Kingstone A. Look away! Eyes and arrows engage oculomotor responses automatically. *Attention, Perception, and Psychophysics*, 71:314-327, 2009.
- Lau H and Passingham RE. Unconscious activation of the cognitive control system in the human prefrontal cortex. *Journal of Neuroscience*, 27:5805-5811, 2007.
- Loomis JM, Klatzky RL, Avraamides M, Lippa Y, and Golledge RG. Functional equivalence of spatial images produced by perception and spatial language. In F Mast and L Jäncke (Eds), *Spatial processing in navigation, imagery and perception*. NY: Springer, 2007: 29-48.
- MacLeod CM and Dunbar K. Training and Stroop-like interference: Evidence for a continuum of automaticity. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 14:126-135, 1988.
- Makioka S. A self-organizing learning account of number-form synaesthesia. *Cognition*, 112:397-414, 2009.
- Mann H, Korzenko J, Carriere JS, Dixon MJ. Time-space synaesthesia - A cognitive advantage? *Consciousness and Cognition*, 18:619-627, 2009.
- Mattingley JB. Attention, automaticity, and awareness in synaesthesia. *The Year in Cognitive Neuroscience 2009: Annals of the New York Academy of Sciences*. NY: Academy of Sciences, 1156:141-167, 2009.
- Minsky M. *The society of mind*. NY: Simon and Schuster, 1986.

- Moyer RS and Landauer TK. Time required for judgments of numerical inequality. *Nature*, 215:519-1520, 1967.
- Nijboer TC, Satris G, and Stigchel SV. The influence of synesthesia on eye movements: No synesthetic pop-out in an oculomotor target selection task. *Consciousness and Cognition*, 20 (4):1193-1200, 2011.
- Notebaert W, Gevers W, Verguts T, and Fias W. Shared spatial representations for numbers and space: The reversal of the SNARC and the Simon effects. *Journal of Experimental Psychology. Human Perception and Performance*, 32:1197-1207, 2006.
- Nunez RE. No innate number line in the human brain. *Journal of Cross-Cultural Psychology*, 42 (4):651-668, 2011.
- Nunn JA, Gregory LJ, Brammer M, Williams SC, Parslow DM, Morgan MJ, Morris RG, Bullmore ET, Baron-Cohen S, and Gray JA. Functional magnetic resonance imaging of synesthesia: Activation of V4/V8 by spoken words. *Nature Neuroscience*, 5 (4):371-375, 2002.
- Pashler HE. *The Psychology of Attention*. Cambridge, MA: MIT Press, 1998.
- Phillips DE. Genesis of number-forms. *American Journal of Psychology*, 8:506-527, 1897.
- Piazza A, Pinel P, and Dehaene S. Objective correlates of an unusual subjective experience: A single-case study of number-form synaesthesia. *Cognitive Neuropsychology*, 23 (8):1162-1173, 2006.
- Posner MI and Cohen YA. Components of visual orienting. In H Bouma and DG Bouwhuis (Eds), *Control of language processes: Attention and Performance X*. Hillsdale, NJ: Erlbaum, 531-556:1984.

- Posner MI and Snyder CRR. Facilitation and inhibition in the processing of signals. In PMA Rabbitt and S Dornic (Eds), *Attention and Performance V*. New York: Academic Press, 669-682:1975.
- Posner MI, Snyder CRR, and Davidson BJ. Attention and the detection of signals. *Journal of Experimental Psychology: General*, 109 (2):160-174, 1980.
- Price MC. Spatial forms and mental imagery. *Cortex*, 45 (10):1229-1245, 2009a.
- Price MC. What kind of mental images are spatial forms? *Cognitive Processing*, 10 (Suppl 2):276-278, 2009b.
- Price MC. Synaesthesia, imagery and performance. In E Hubbard and J Simner (Eds), *Oxford handbook of synaesthesia*. Oxford: Oxford University Press, in press.
- Price MC and Mentzoni RA. Where is January? The month-SNARC effect in sequence-form synaesthetes. *Cortex*, 44 (7):890-907, 2008.
- Proctor RW and Cho YS. Polarity correspondence: A general principle for performance of speeded binary classification tasks. *Psychological Bulletin*, 132:416-442, 2006.
- Proctor RW and Vu K-PL. Eliminating, magnifying, and reversing spatial compatibility effects with mixed location-relevant and irrelevant trials. In Prinz W and Hommel B (Eds), *Common Mechanisms in Perception and Action: Attention and Performance XIX*. Oxford: Oxford University Press, 2002: 443-473.
- Ramachandran VS and Hubbard EM. Synaesthesia - A window into perception, thought and language. *Journal of Consciousness Studies*, 8:3-34, 2001.
- Reuss H, Kiesel A, Kunde W, and Hommel B. Unconscious activation of task sets. *Consciousness and Cognition*, 20:556-567, 2011.

- Rich AN, Bradshaw JL, and Mattingley JB. A systematic, large-scale study of synaesthesia: Implications for the role of early experience in lexical-colour associations. *Cognition*, 98 (1):53-84, 2005.
- Rich AN and Mattingley JB. Anomalous perception in synaesthesia: A cognitive neuroscience perspective. *Nature Reviews Neuroscience*, 3 (1):43-52, 2002.
- Ristic J, Wright A, and Kingstone A. The number line effect reflects top-down control. *Psychonomic Bulletin and Review*, 13 (5):862-868, 2006.
- Rizza A and Price MC. Do sequence-space synaesthetes have better spatial imagery skills? Maybe not. *Cognitive Processing* 13 (1):299-303. 2012.
- Robertson LC and Sagiv N. *Synesthesia. Perspectives from cognitive Neuroscience*. New York: Oxford University Press, 2005.
- Rouw R and Scholte HS. Increased structural connectivity in grapheme-color synesthesia. *Nature Neuroscience*, 10 (6):792-797, 2007.
- Rouw R, Scholte HS, and Colizoli O. Brain areas involved in synaesthesia: A review. *Journal of Neuropsychology*, 5:214-242, 2011.
- Sagiv N, Simner J, Collins J, Butterworth B, and Ward J. What is the relationship between synaesthesia and visuospatial number forms? *Cognition*, 101:114-128, 2006.
- Santens S and Gevers W. The SNARC effect does not imply a mental number line. *Cognition*, 108:263-270, 2008.
- Shaki S and Fischer MH. Reading space into numbers - A cross-linguistic comparison of the SNARC effect. *Cognition*, 108 (2):590-599, 2008.

- Shaki S, Fischer MH and Petrusic WM. Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin and Review*, 16:328–331, 2009.
- Simner, J. (2007). Beyond perception: Synaesthesia as a psycholinguistic phenomenon. *Trends in Cognitive Sciences*, 11(1), 23-29.
- Simner J. Synaesthetic visuo-spatial forms: Viewing sequences in space. *Cortex*, 45 (10):1138-1147, 2009.
- Simner J. Defining synaesthesia. *British Journal of Psychology*, 103:1–15, 2012.
- Smilek D, Callejas A, Dixon MJ, and Merikle PM. Ovals of time: Time-space associations in synaesthesia. *Consciousness and Cognition*, 16:507-519, 2007.
- Tang J, Ward J, and Butterworth B. Number forms in the brain. *Journal of Cognitive Neuroscience*, 20:1547-1556, 2008.
- Teuscher U, Brang D, Ramachandran VS, and Coulson S. Spatial cueing in time-space synesthetes: An event-related brain potential study. *Brain and Cognition*, 74:35-46, 2010.
- Treisman A. Synesthesia: Implications for attention, binding and consciousness - A commentary. In L Robertson and N Sagiv (Eds), *Synesthesia: Perspectives from Cognitive Neuroscience*. Oxford: Oxford University Press, 239-254:2005.
- van Dijck JP, Gevers W, Fias W. Numbers are associated with different types of spatial information depending on the task. *Cognition*, 113(2): 248-253, 2009.
- van Leeuwen TM, Petersson KM, Hagoort P. Synaesthetic colour in the brain: Beyond colour areas. A functional magnetic resonance imaging study of synesthetes and matched controls. *PLoS One* 5 (8): e12074, 2010.

Vecera SP and Rizzo M. What are you looking at? Impaired “social attention” following frontal-lobe damage. *Neuropsychologia*, 42:1657-1665, 2004.

Ward J. *The frog who croaked blue : Synesthesia and the mixing of the senses*. London: Routledge, 2008.

Ward J. Synesthesia. *Annual Review of Psychology*, in press.

Ward J, Huckstep B, and Tsakanikos E. Sound-colour synaesthesia: To what extent does it use cross-modal mechanisms common to us all? *Cortex* 42 (2):264-280, 2006.

Ward J, Jonas C, Dienes Z, and Seth A. Grapheme-colour synaesthesia improves detection of embedded shapes, but without pre-attentive 'pop-out' of synaesthetic colour. *Proceedings of the Royal Society of London - Series B: Biological Sciences*. 277 (1684):1021-1026, 2010.

Ward J and Mattingely JB. Synaesthesia: An overview of contemporary findings and controversies. *Cortex*, 42:129-136, 2006.

Ward J, Li R, Salih S, and Sagiv N. Varieties of grapheme-colour synaesthesia: A new theory of phenomenological and behavioural differences. *Consciousness and Cognition*, 16:913-931, 2007.

Ward J, Sagiv N, and Butterworth B. The impact of visuo-spatial number forms on simple arithmetic. *Cortex*, 45 (10):1261-1265, 2009.

Wood G, Nuerk H-C, and Willmes K. Variability of the SNARC effect: Systematic interindividual differences or just random error? *Cortex*, 42:1119-1123, 2006.

Wright RD and Ward LN. *Orienting of Attention*. Oxford: Oxford University Press, 2008.

Yaro C and Ward J. Searching for Shereshevskii: What is superior about the memory of synaesthetes? *Quarterly Journal of Experimental Psychology*, 60 (5):681-695, 2007.

Table 1: Summary of cueing results in sequence-space synaesthetes from published studies that have claimed automatic effects. Each row presents data from 1 participant in 1 experimental condition. Only data for visual cues (e.g., month names, numerals) and from conditions or participants yielding significant cueing effects are presented. Individual participants are identified by the letters in column 2. (¹Approximate data estimated from graphs; ²Specific instruction was given to use the counter-predictive cues; ³Visual cues were randomly intermixed with auditory cues within trial blocks).

Study	Ss	Type of spatial form tested	CTOA range (msecs)	Cue-target contingency	Target & response key alignment	Mean cueing effect over all CTOAs (msecs)	Incongruent RT at shortest CTOA (msecs)	Congruent RT at shortest CTOA (msecs)	Cueing effect at shortest CTOA (msecs)
Smilek et al., 2007	PD	month	150-600	non-predictive	horizontal	368	1070	705	365
Smilek et al., 2007	CS	month	150-600	non-predictive	horizontal	130	589	464	125
Smilek et al., 2007	JK	month	150-600	non-predictive	horizontal	17	320	309	11
Hubbard et al., 2009	DG	number	400-900	non-predictive	vertical	31	304	273	31
Jarick et al., 2009a ¹	L	number	350-800	non-predictive	vertical	70	350	280	70
Jarick et al., 2009a ¹	B	number	350-800	non-predictive	vertical	40	350	310	40
Jarick et al., 2009a ¹	L	number	350-800	non-predictive	horizontal	115	365	250	115
Jarick et al., 2009a ¹	B	number	350-800	non-predictive	horizontal	20	330	305	25
Jarick et al., 2009b	L	month	600	non-predictive	horizontal	34	343	309	34
Jarick et al., 2009b	L	clock time	600	non-predictive	horizontal	180	417	237	180
Jarick et al., 2011a	L	number	150-500	counter-predictive	vertical	79	510	428	82
Jarick et al., 2011a ²	L	number	150	counter-predictive	vertical	23	425	402	23
Jarick et al., 2011b ³	L	month	600	non-predictive	horizontal	138	486	348	138
Jarick et al., 2011b	L	month	150-800	counter-predictive	horizontal	53	456	386	70

Figure captions

Fig. 1: Examples of spatial forms for the months of the year, as depicted by 4 Norwegian synaesthetes' pencil sketches. The forms depicted range from 2D ovals to a 3D ribbon and torus.

Fig. 2: Scatterplots of the magnitude of spatial cueing effects (incongruent – congruent *RT*) as a function of (a) *RT* on congruent trials and (b) *RT* on incongruent trials. Each point represents 1 participant, and indicates data at the shortest CTOA used for the participant in one of the previously published studies listed in Table 1 (but excluding participant PD).

Fig. 1

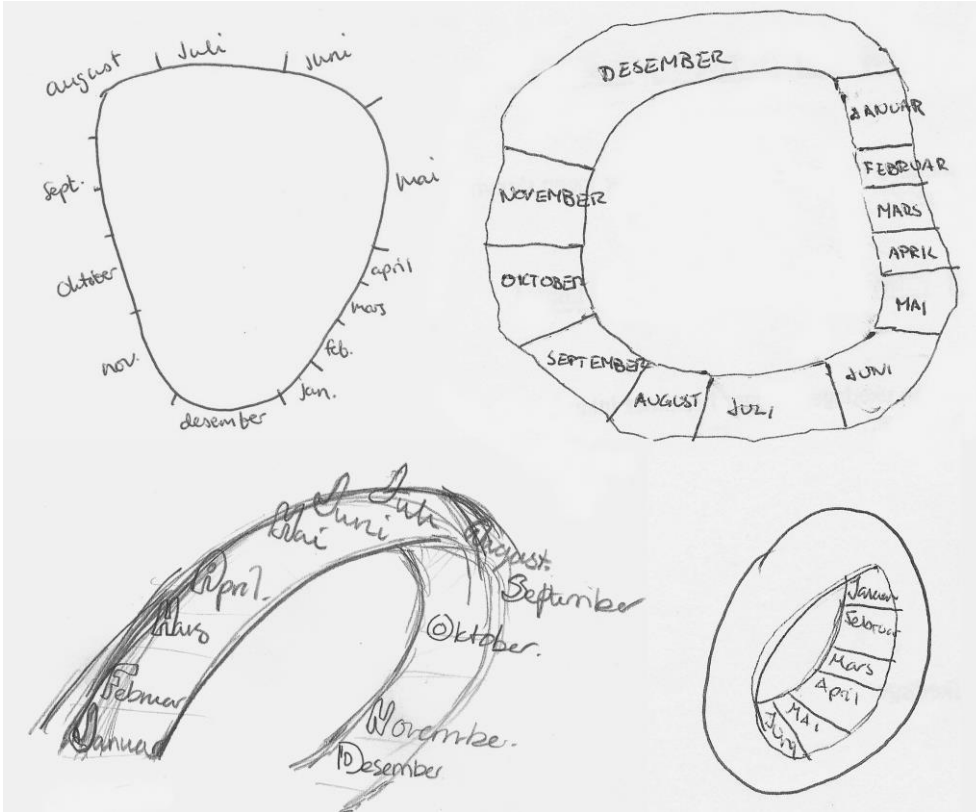


Fig. 2

