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A Foundation for Savantism? Visuo-spatial Synaesthetes Present with Cognitive Benefits

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Abstract

Individuals with ‘time-space’ synaesthesia have conscious awareness of mappings between time and space (e.g., they may see months arranged in an ellipse, or years as columns or spirals). These mappings exist in the 3D space around the body or in a virtual space within the mind’s eye. Our study shows that these extra-ordinary mappings derive from, or give rise to, superior abilities in the two domains linked by this cross-modal phenomenon (i.e., in time, and visualised space). We tested ten time-space synaesthetes with a battery of temporal and visual/spatial tests. Our temporal battery (the *Edinburgh [Public and Autobiographical] Events Battery*) assessed both autobiographical and non-autobiographical memory for events. Our visual/spatial tests assessed the ability to manipulate real or imagined objects in 3D space (the *Three Dimensional Constructional Praxis* test; *Visual Object and Space Perception Battery*, *University of Southern California Mental Rotation Test*) as well as assessing visual memory recall (*Visual Patterns Test*). Synaesthetes’ performance was superior to the control population in every assessment, but was not superior in tasks that do not draw upon abilities related to their mental calendars. Our paper discusses the implications of this temporal-spatial advantage as it relates to normal processing, synaesthetic processing, and to the savant-like condition of *hyperthymestic syndrome* (Parker et al., 2006)

keywords: visuo-spatial forms, hyperthymestic syndrome, savantism, synaesthesia, synesthesia

Synaesthesia is a condition in which perceptual or cognitive activities (e.g., listening to music, reading) trigger exceptional experiences (e.g., of colour, taste). The condition is characterised by the pairing of particular triggering stimuli (or ‘inducers’) with particular resultant experiences (or ‘concurrents’; Grossenbacher, 1997) and inducer-concurrent pairings are known to be remarkably consistent over time. For example, a sound-colour synaesthetes who hears a tone at 2000 Hz and sees a reddish pink photism (Luria, 1968) will always see that same colour triggered by that same sound, and this consistency has been demonstrated across a range of synaesthesias (Dixon et al., 2000; Rich et al., 2005; Simner and Logie, 2008; Simner and Ward, 2006; Simner et al., 2006; Smilek et al., 2002; Ward, and Simner, 2003; Yaro and Ward, 2007). The neurological roots of synaesthesia have been indicated by functional magnetic resonance imaging (fMRI) showing atypical brain activity that mirrors the reports of synaesthetes. For example, those who report colours triggered by letters or words (*grapheme-colour synaesthetes*) show activity in colour selective regions of the visual cortex during language comprehension (Aleman et al., 2001, Hubbard, Arman et al., 2005; Sperling et al., 2006; Nunn et al., 2002). This activity has been traced to increased structural connectivity in the brains of synaesthetes using diffusion tensor imaging (DTI), a technique that tracks the diffusion patterns of water molecules in the human brain in order to indicate the presence of white matter fibre pathways (Rouw and Scholte, 2007).

Variants such as sound-colour synaesthesia show that the condition can give rise to a ‘merging of the senses’ (e.g., audition triggers visual sensations) but synaesthesia is a multi-variant phenomenon, and can also be triggered by non-perceptual activities, such as thinking about word meanings (Simner and Ward, 2006), about personal relationships (Simner et al., 2006; Ward, 2004), or about sequenced units such as letters, numbers or time-units (e.g., days, weeks, years). This study focuses on this latter type, and in particular, on a variant of synaesthesia known as visuo-spatial forms. Visuo-spatial synaesthetes ‘see’ ordered sequences (such as letters, numbers, months etc.) in particular spatial arrays, and in the current study we are interested in those arrays that encode time sequences (minutes, days, months, years). We refer to

these visuo-spatial forms as ‘time-space’ synaesthesia (following Smilek et al., 2007) in order to reflect the nature of the inducer and concurrent. Hence time-space synaesthetes have mental mappings in which time is laid out in set spatial arrangements, and although these arrangements differ from synaesthete to synaesthete, they are highly consistent within each synaesthete over time. In our study we ask whether the exceptional experiences of time-space synaesthetes are accompanied by exceptional abilities in the particular domains that are linked by the synaesthesia (i.e., in temporal and visual/spatial processing). Below we describe time-space associations in more detail, and discuss the relationships of time and space that exist in all people.

TIME IN SPACE

All people have implicit or explicit associations between time and space, and this is seen in conventions shared both within and across cultures (Santiago et al., 2007). In everyday language for example, linguistic expressions systematically relate past events with left or anterior space, and future events to right or front space (e.g., “Back in the 1960’s”; “In the weeks ahead”; Clark, 1973; Lakoff and Johnson, 1980) and this trend can be seen in English, in signed languages (Emmorey, 2001) and cross-linguistically (e.g., see Radden, 2004 for review). Temporal-spatial associations are seen, too, in certain response biases for temporal stimuli. For example, Santiago et al. (2007) found that (Spanish) participants respond faster to words denoting the past (e.g., *ayer* “yesterday”) when they use their left hand over their right, and that the pattern is reversed for future-denoting words (e.g., *mañana* “tomorrow”). In a similar vein, Gevers and colleagues showed faster left-than-right responses for early days of the week (e.g., *Monday*; Gevers et al., 2004) and early months in the year (e.g., *January*; Gevers et al., 2003), and faster right-than-left responses for later days and months (e.g., *Friday, December*; see also Price, 2009, this issue). Such response biases were found in tasks ostensibly unrelated to spatial mapping (e.g., when indicating whether a month falls early or late in the year) and even in tasks unrelated to temporal mapping (e.g., in a grapheme-monitoring task).

This type of spatial mapping for time mirrors the mapping found in all people for number sequences, in a phenomenon known as SNARC (*spatial-numerical association of response*

codes): the SNARC effect is an illustration of faster left-than-right responses to smaller numbers, and the reverse for larger numbers. Again, this response bias arises even in tasks that do not overtly probe spatial properties, such as a number parity task, or where target numbers are judged smaller or larger than a reference number (Dehaene, Bossini, and Giraux, 1993; Dehaene, Dupoux, and Mehler, 1990). This relationship between number representations and spatial encoding has been extensively researched, and has formed the theme of a recent *Cortex* special issue (e.g., see Wood and Fischer, 2008). The SNARC effect appears to be related to linguistic writing conventions, in that left-to-right systems (e.g., English) show left biases for low numbers (Dehaene et al., 1990) while right-to-left writing systems show right biases (e.g., for Iranian; Dehaene et al., 1993). Moreover, this influence of writing convention appears to extend to temporal sequences, too: Tversky et al. (1991) found that American children ordered temporal concepts (breakfast, lunch, dinner) from left to right while Arabic-speaking children ordered them right to left. Together these studies suggest that time and numbers (and other sequences such as the alphabet, Gevers et al., 2003) may be mapped onto an implicit line which runs horizontally in space, and which links left-space to early units in writing systems that unfold from left to right (see Simner, 2009, this issue, for a review of this proposal, and of alternatives). Finally, this association of sequences in horizontal space may be seen as part of a larger sequence-space mapping system, since eye-movement data, for example, shows that larger numbers may map to high space, and smaller numbers map to low space (Schwarz and Keus, 2004; see also Gevers et al., 2006; Ito and Hatta, 2004; Hubbard et al., 2009, this issue).

Visuo-spatial Synaesthesia

Most people have little conscious awareness of their mental mappings between sequences and space. Visuo-spatial synaesthetes are the exception, however, since they are able to consciously report the layout of their spatial forms, which are often convoluted (Sagiv et al., 2006; see also Figures 1-6) and can be highly idiosyncratic. The phenomenon was first noted by Galton (1880) but has received fairly small exposure in the psychology literature since that time (but see Cytowic, 2002; Hubbard, Piazza et al., 2005; Price and Mentzoni, 2008; Sagiv et al., 2006;

Seymour, 1980; Seron et al., 1992; Simner et al., 2006; Smilek et al., 2007). Hence, while research in synaesthesia more generally has enjoyed a renaissance over the past decade (and formed the basis of another *Cortex* special issue; see Ward and Mattingley, 2006) relatively little attention has been given to visuo-spatial variants. Nonetheless, visuo-spatial synaesthesia has been reported for numbers (e.g., Sagiv et al., 2006), letters (e.g., Simner et al., 2006), time units (e.g., Price and Mentzoni, 2008; Smilek et al., 2007), and in extreme cases, for numerous sequenced units, including shoe sizes, height, TV stations and temperatures (Cytowic, 2002; see also Hubbard et al., 2009, this issue). Like non-synaesthetes, visuo-spatial synaesthetes show handedness effects in SNARC-type tasks, but their responses mimic the idiosyncrasies of their visuo-spatial forms. For example, synaesthetes with forms running vertically show SNARC-type effects in the vertical direction, but not the horizontal direction (e.g., Jarick, Dixon, Maxwell, et al., 2009, this issue; Hubbard et al., 2009, this issue). As noted above, the focus of our current study is on those visuo-spatial synaesthetes whose arrays encode time sequences (time-space synaesthetes) and below we present several examples of such arrays, provided by the participants of the current study. These show spatial forms for hours within a day, days within a week, weeks within a month, months within a year, years within a century, and centuries within millennia (Figures 1-6 respectively; see also Simner, 2007, for further description of the visuo-spatial forms of participant IB).

 Insert Figures 1-6 here

Each of our synaesthetes has multiple visuo-spatial forms, which individually or cumulatively occupy a three dimensional (3D) space, either in the peripersonal area outside the body, or in mental space within the mind's eye. Some forms are themselves inherently 3D, as for example, with synaesthete JT's form for the year (see Figure 4). Other forms may occupy two dimensional (2D) planes individually, but these (non-parallel) planes cumulatively make up a 3D

area of synaesthetic experience for each individual. For some synaesthetes, all forms can appear simultaneously (e.g., for synaesthete HB, the form for days can be seen interwoven into the form for months). For others (e.g., synaesthete AC) each form appears as a distinct unit and does not combine. All our participants here report mental arrays for year sequences within centuries (e.g., see Figure 5) and this is particularly important for the current study, since we hypothesise that such forms might endow superior abilities in date/event recall (see below).

Time-space synaesthetes are often surprised to learn that all people do not share their experiences, and first-hand reports suggest that synaesthetes view their forms as integral to their mental competence. Our synaesthete participant SC, for example, reports difficulty understanding how people *without* visuo-spatial forms can perform time management tasks. This suggests that visuo-spatial forms may be actively engaged in daily cognitive functions and raises the possibility that synaesthetes will perform differently to the average person when those functions are assessed. In particular, time-space synaesthetes may show superior levels of performance in temporal and visual/spatial abilities, since these are the facets that are exceptionally experienced within their synaesthesia. Underlying our hypothesis is a recent study by Parker et al. (2006), whose participant AJ demonstrates phenomenal memory for events and dates in time. AJ is able to recall vast quantities of information about events in her own life and about world events, and Parker et al. liken this strong, domain-specific area of knowledge to a savant ability. Key to AJ's superior memory performance is her prodigious relationship with dates, as she explains: "My memory has ruled my life... I'm talking to you and in my head I'm thinking about something that happened to me in December 1982, December 17, 1982 ... It's all about dates... I just know these things about dates..." (Parker et al., 2006, p. 36). Parker et al. termed AJ's experiences as *hyperthymestic syndrome* and demonstrated her extra-ordinary memory with tests of recall for autobiographical and world events. At the same time, Parker et al. mention that AJ has a visual 'mental calendar', and, interestingly, this description is suggestive of a synaesthetic time-space form. As Parker et al. explain:

On four occasions we asked AJ to draw her mental calendars and she drew virtually the same calendars each time... She drew one for years and another for months. Her calendar for years was drawn from left to right and at 1970 changed orientation from top to bottom. She told us her demarcation of years is based on her internal schema that she cannot explain... For months she first drew January in the 11 o'clock position, then counterclockwise filled in the rest of the months. She has no idea why she drew the months this way but insisted again it was how she saw it and always had. (Parker et al., 2006; p. 42)

There are five clues here that AJ's 'mental calendar' is indeed a synaesthetic time-space form of the type examined in this article, and in this special section of *Cortex* more generally. Specifically, AJ's 'mental calendar' is reminiscent of time-space synaesthesia in that time appears in specific mental arrays, which date back as long as she can remember, whose roots are unknown to her, but which are highly consistent over time, and which conform to known shapes common among other time-space synaesthetes. It may be no coincidence then, that her months are represented within a circle or oval, typical of time-space synaesthetes, as has been noted previously ('Ovals of time: time-space associations in synaesthesia'; Smilek et al., 2007).

Parker et al. give a detailed and interesting description of AJ's prodigious abilities in event recall (and also of her obsessive traits, which we will return to in our General Discussion), but placed relatively minor focus on AJ's mental array of time, which they viewed as some type of "mnemonic strategy that may have become automatized with extensive use" (p. 48). Nonetheless, anecdotal reports from visuo-spatial synaesthetes suggest that superior memory for time may be a *general feature* of this type of mental time-space array, suggesting in turn that AJ's abilities are intimately tied to what we now assume is her time-space synaesthesia. For example, our synaesthetes JA and IB spontaneously and independently reported that they have exceptional memories for dates and events. IB reports that his fiancé relies on his memory to recall facts about their life together (e.g., for dates and descriptions of family events and trips), and a similar account is given by Parker et al. (2006), who write that AJ "is the family historian

and her friends turn to her to remember things they did together and when” (pg. 39). JA reported that she has always had an exceptional memory for the dates of songs and films. This memory for events in time again suggests parallels between AJ’s abilities and those of time-space synaesthetes more generally. In order to empirically assess the anecdotal reports from time-space synaesthetes, we presented a group of such participants with recall tests for autobiographical and world events, using dates as cues and responses. Outstanding group-performance compared to controls would suggest that superior skills in temporal encoding/retrieval are a general benefit of time-space synaesthesia, and may lie at the very heart of AJ’s hyperthymestic syndrome.

As well as assessing our participants’ abilities in temporal processing, we also examine whether superior abilities can be seen in a second domain: visuo-spatial processing. Specifically, since time-space synaesthesia links time with the dimension of space, superior performance may be limited to the temporal domain only (as emphasised by Parker et al., 2006), or may also incorporate superiority in visual/spatial processing. When presented with a time period (e.g. a month of the year) time-space synaesthetes report that the associated spatial location is immediately brought to mind (Price and Mentzoni, 2008; Smilek et al., 2007), and that they have a sophisticated ability to mentally manipulate the properties of this spatial representation. Specifically, synaesthetes claim to be able to manipulate the viewing-angle and size of their arrays, by taking multiple perspectives (or sometimes mentally re-orienting the array), or by ‘zooming in’ on certain portions (e.g., see Jarick, Dixon, Stewart et al., 2009, this issue; Eagleman, 2009, this issue). Consequently, time-space synaesthetes would be well-practised in manipulating mental space, and we anticipate that this ability might extend to other cognitive tasks tapping visual/spatial processes. Studies have shown that practice on visual-spatial tasks does indeed result in improved performance, and that this improvement can be generalised to other tasks that require the same visual-spatial aspects (e.g. Wallace and Hofelich, 1992).

There is evidence from the neuroscience literature too, that visuo-spatial synaesthesia may rely on the same areas that are engaged in other tasks of visuo-spatial processing. Taken at face value, the reports of time-space synaesthetes appear to be similar to the image-scanning paradigms used by mental imagery researchers (e.g. Borst and Kosslyn, 2008), and Borst and

Kosslyn have speculated that such scanning is likely to employ areas of the parietal cortex, which are topographically organised (Sereno et al., 2001). Indeed, spatial processes across a range of tasks are generally localised within parietal areas (e.g., mental rotation; Cohen et al., 1996; Harris and Miniussi, 2003). Interestingly, Price and Mentzoni (2008) note that parietal regions are also associated with number-form spatial representations within the non-synaesthete population (see Hubbard et al., 2005 for a review). Moreover, one recent imaging study of visuo-spatial synaesthetes (with number-space arrays) showed activation of posterior parietal regions when synaesthetes were engaged in ordinal sequence processing; Tang et al., 2008). In summary then, time-space synaesthetes might be expected to show superior visuo-spatial processing either as an additional consequence of their synaesthesia (i.e. they are well practiced) or because their conscious awareness of spatial forms is a direct consequence of pre-existing enhanced visuo-spatial abilities. However, an imperative step in this argument is to establish whether synaesthetes do indeed show such an advantage.

Previous studies have shown other areas in which synaesthetes out-perform non-synaesthete control populations (and also areas where they under-perform; see Ward et al., 2009, this issue). Under certain test conditions, for example, grapheme-colour synaesthetes show superior colour memory (Yaro and Ward, 2007) and digit memory (Smilek, Dixon et al., 2002), and ‘tickertape’ synaesthetes (who see visual projections of coloured or achromatic letters when listening to speech) have been shown to have superior abilities in spelling (Linn, Hancock, Simner and Akeroyd, 2008). Here we aim to show similar cognitive benefits for visuo-spatial synaesthetes by demonstrating that the two dimensions that are exceptionally mediated in time-space synaesthesia are each themselves exceptionally functioning in synaesthetes. We presented time-space synaesthetes and matched controls with eight separate tests of visuo-spatial and temporal processing (four within each domain), and our studies reveal benefits for synaesthetes across the board. Importantly, we also demonstrate that our synaesthetes have only average performance in tasks that *do not* draw upon abilities related to their mental calendars. This is necessary to show that our synaesthetes do not have a *general* cognitive superiority, or that they differ from controls simply in their motivation for our tasks.

Tests of Spatial and Temporal Processing

The Psychology literature provides a large number of clinical tests to assess visuo-spatial or temporal functions, but most of this literature is tailored towards identifying cognitive deficits rather than assets. One consequence of this is that published test-scores from normal controls are at high ceiling levels (see Parker et al., 2004 for a similar observation) and for this reason, such tests cannot be used to identify superior performers (because their maximum scores are not significantly higher than the mean for control participants). Given this, a number of the assessments used in the current study have been specially created by us, to allow for the identification of superior behaviour. Other tests have been taken from the literature, but may be used in a way not originally envisaged by the authors of those tests (i.e., by establishing upper cut-offs identifying superior performers, rather than lower cut-offs identifying deficits).

Four of our eight tests assessed synaesthetes on their ability to recall information about the temporal qualities of events (i.e., when events happened in time). These come from an events battery created for this study (*The Edinburgh [Public and Autobiographical] Events Battery*, the *EEB*; Simner and Mayo, in prep) and this assesses knowledge of both world events and autobiographical events. Although tests of autobiographical knowledge do exist in the literature (e.g., The AMI: Kopelman et al., 1990) these suffer from the same limitations as other tests designed to identify deficits, in that normal population scores are close to ceiling. In contrast, the distribution of scores in our *EEB* allows for the identification of both inferior and superior performers. Moreover, this test is web-based, and provides a simple task taking just 25 minutes to administer. In the autobiographical section, participants are shown a series of years selected at specific intervals in their life, and must write as many autobiographical facts from that year as they are able to remember within a fixed period of time, and the dependent measure is the total number of facts recalled. (As in other assessments of autobiographical knowledge, detailed checking of the veracity of reports is not performed, because studies show that people rarely confabulate on such tests; see Kopelman, 1989; Paul et al., 1997; see also General Discussion.) For the non-autobiographical tasks, participants are shown a series of events from recent world

history and culture, and must provide the year in which each event took place. The dependent measures here are an error-metric (i.e., the distance between the event year, and the year given as the participant's response) and also the response reaction time (RT). We hypothesise that synaesthetes will have superior performance in these tasks because their time-space arrays afford them an additional dimension (space) by which to encode or retrieve temporal information.

The final four tests assess visual memory and spatial awareness, and these four have been used extensively in previous studies. All our synaesthete participants have multiple visuo-spatial forms which (independently or together) occupy a 3D area, and so we tested their ability to manipulate objects in 3D space (*Three Dimensional Constructional Praxis test*; Benton and Fogel, 1962), their ability to mentally project shapes into 3D space (*Visual Object and Space Perception Battery*, Warrington and James, 1991), and their ability to mentally rotate drawings of 3D objects (*University of Southern California Mental Rotation Test*, Cherry et al., 2007). In addition, because our synaesthetes apparently have the ability to recall complex visual patterns (i.e., their time-space arrays) with great consistency over time, we tested their visual memory recall (*Visual Patterns Test, VPT*, Della Sala et al., 1997). The VPT is considered a relatively 'pure' test of visual memory, in comparison to other visual recall tasks which have additionally required the recall of sequencing information (e.g., the Corsi Blocks Test). [For clarity, we point out that synaesthetes' spatial forms are "consistent" in as much as their own internal co-ordinates stay the same, even though the spatial relationship between the array and the synaesthete may alter depending on shifts in perspective or orientation; for further discussion see Eagleman, 2009, this issue; and Jarick, Dixon, Stewart et al., 2009, this issue.]

EXPERIMENTAL INVESTIGATIONS

Case Descriptions

We recruited a population of 10 visuo-spatial synaesthetes, from which we drew participant groups for each of our eight tasks. (In all cases, every synaesthete available at the time of each test was recruited.) Participants came primarily from the Sussex-Edinburgh Database of Synaesthete Participants, who have been recruited over the past decade via our

research group websites (www.syn.psy.ed.ac.uk; www.syn.sussex.ac.uk). A small number of participants were also recruited from the University of Edinburgh community. Our 10 participants have a mean age of 35:9 years, and their cases are summarised in Table 1. All participants report experiencing spatial representations for three or more of the following six time units: days (e.g., minutes within the day), weeks (i.e., days within the week), months (i.e., days or weeks within a month), years (i.e., months within the year), centuries (i.e., years with the century), and a millennia (i.e., centuries within the millennium). All participants experienced a form for years within a century, which was the necessary requirement for recruitment in our study.

All synaesthete participants claim to have experienced their sensations for as long as they remember and most were surprised to learn that others do not share their experiences. A subset of our participants also report synaesthetic colour sensations (e.g., from letters, music, days) and those that are triggered by time units are shown in Table 1. One participant, PS, also reports synaesthetic concurrents of taste (triggered by faces and words), and JC and AC also have concurrents of personality (e.g., triggered by sequences; i.e., *ordinal linguistic personification* synaesthesia; Simner and Holenstein, 2007). Synaesthete participants were asked to draw each of their forms twice, separated by at least 3 months. As in other studies of visuo-spatial synaesthesia (e.g., Sagiv et al., 2006) our synaesthetes were highly consistent over time, and such consistency has been taken a hallmark of genuineness (e.g., Sagiv et al., 2006; Rich et al., 2005; Baron-Cohen et al., 1987).

Experiment 1

In this study we tested whether individuals with time-space synaesthesia show superior abilities in their knowledge about the temporal placement of events. Participants took four tests of temporal awareness, using the EEB (the Edinburgh [Public and Autobiographical] Events Battery), designed specifically for this study.

Method

Participants

We tested six synaesthetes (IB, JA, AC, JT, SC and JC) and two controls per synaesthete (12 controls in total; two male). Each synaesthete was matched to his/her controls on age, sex, nationality (all participants were British), and educational background (see below). The mean age was 36.3 years (SD 5.0) for synaesthetes and 32.5 years (SD 5.4) for controls. Our synaesthete sample comprised four participants with postgraduate education, and two with high school education.

Materials

The *Edinburgh (Public and Autobiographical) Events Battery* contains four sub-tests, falling within two broad categories: three sub-tests for Public Events (i.e., world politics and popular culture) and one sub-test for Autobiographical Events. These are described below.

Public Events. This assessed memory for the dates of (i) international world events, and (ii) cultural events. The materials for the former comprised 60 international news events (e.g., death of Pope John Paul II) which took place between 1950 and 2008 inclusive, with 10 events per decade (1950's, 1960's etc.). The Cultural Events section comprised one test for films, and one test for popular music. For films, materials comprised the names of 30 titles that have each won the Oscar for Best Picture, between 1950 and 2008 (e.g., *The Godfather*), with five films selected from each decade. For popular music, the test presented the names of songs and their singers (e.g., *Hello, Goodbye*; The Beatles) that have all been UK Number 1 Singles on Christmas day, between 1950-2008 inclusive (again, five per decade).

Autobiographical Events. The materials comprised nine different years within the lifetime of each participant, for which that participant would be required to provide as many facts as possible about his/her life during each year. The nine years were automatically and individually selected for each participant, and these years were as follows: when the participant was aged 5, when the participant was at their current age minus three years, and at seven equi-spaced intervals in between. This proportional selection of years allows us to probe regular intervals

within the life of each participant, while at the same time avoiding unfair biases towards any particular age group. (For example, if we had specified *fixed* years of, say, ages 19 and 21, we might expect 22 year old participants to perform better than those who are middle aged.) Our lower limit (age 5 years) was chosen to represent an age when participants might have their own first-person knowledge of events, and our upper limit (current age minus 3 years) was selected to require some amount of past reflection (rather than relating to events that are ongoing).

Procedure

The *Edinburgh Public and Autobiographical Events Battery* has an internet interface which runs via WebExp2, a Java toolbox for web-based psychological experiments (Keller et al., 2009). Participants log on and provide ethical consent and demographic details (e.g., age, sex, nationality, educational background), after reading opening instructions. These instructions explain the general aim of our test (to assess knowledge of public and autobiographical events) and these instructions emphasise the importance of not using external reference sources (books, websites). Participants then move through each test in order (International Events, Cultural/film Events, Cultural/music Events, Autobiographical Events) with instructions specific to each test shown at their start.

For Public Events (news, film, music) participants are told to write the exact year between 1950-2008 inclusive in which each event took place (i.e., the year of the news event; the year the film won best Oscar; or the year the song became UK Christmas Number 1). Participants were told to write a date for every event as quickly as possible, and to guess if they did not know the answer. They had a maximum of 10 seconds per item, and were prompted to respond (with an on-screen prompt: 'Quickly!') after 6 seconds. This 10 second time-limit was chosen during our development stage in order to effectively prevent participants from using external reference sources (books, websites). At the end of each section, participants were shown all correct responses, without an indication of their score.

For Autobiographical Events, participants were told they would see nine different years within their life-time (e.g., 1986, 1994) and that they must list as many facts as possible about

their life during each year (i.e., what they were doing, who they were seeing etc.). They were told to include any fact at all so long as it related to something that was personally experienced by them, and a number of examples were provided. Instructions stressed the importance of providing true information only. Participants were given 1 minute per year, and space was provided for up to 30 facts for each year. The entire experiment lasted 25 minutes, taking 15 minutes for Public Events (7 minutes for World Events, 3.5 minutes each for Film and Music), and 10 minutes for Autobiographical Events.

Results

Public Events

For each of three tests (news, film, music) our dependent measures were for accuracy and reaction time. There were 76 missing data-points, where participants failed to provide a response within the time allocated, and this constituted 0.4% of responses overall (and were approximately equally distributed between our two participant groups). Additionally, a technical fault lost RT data for participant (JC) in one condition (international news), and this missing data point was replaced by the mean of the remaining items per cell.

Accuracy was calculated as an ‘error-distance’, this being the absolute distance in years between the correct response and the response given by the synaesthete (e.g., a response of 2001 for the 2005 death of Pope John Paul would give an error-distance of 4 years) and lower error-distances represent superior performance. We removed 86 outliers (0.5% of responses overall), which fell outside 3 standard deviations from the mean of each participant’s error-distance per test. Given this, Figure 7 shows the mean error-distance for synaesthetes and controls in each test. Synaesthetes had lower error-distances (i.e. were more accurate) in world events, in film and in music -- and this was confirmed in a mixed design ANOVA crossing group (synaesthetes, controls) and test (news, film, music). There was a main effect of group ($F(1,16)=11.0, p<.01$) and no interaction ($F(2,32)<1$), showing that synaesthetes outperformed controls across all tests. There was also a main effect of test itself ($F(2,32)=6.7, p<.01$), since all participants found cultural/music events (mean error-distance= 4.8, SD .4) easier than both political world events

(mean error-distance= 7.6, SD .9; $t(17)=3.4$, $p<.01$) and cultural/film events (mean error-distance= 7.4, SD .8; $t(17)=3.5$, $p<.01$), using Bonferonni-corrected paired sample t-tests. Participants were equally accurate for world events and films ($t(17)<1$).

 Insert Figure 7 here

The superior performance of synaesthetes came with no extra time cost. We analysed RT data after removing 89 outliers (constituting 0.5% of the data) which fell more than 3 standard deviations from the mean per participant per test. There was no main effect of group in RT data ($F(1,16)<1$), and in fact, there was a suggestion that synaesthetes were slightly *faster*, in one test at least. A group x test interaction ($F(2,32)=5.1$ $p<.02$) arose because there was a slight trend for synaesthetes to be faster than controls in world events (4692ms [SD 1045] vs. 5483 [SD 832] respectively; $t(16)=-1.7$, $p=.099$). All other reaction time differences were non-significant (all t s <1 for synaesthetes vs. controls: 4610ms [SD 1175] vs. 4449ms [SD 1057] in film; 4698ms [SD 1369] vs. 4666ms [SD 1066] in music). Finally, as with accuracy, there was a main effect of test in RT data ($F(2,32)=6.4$, $p<.01$), and paired sample Bonferonni corrected t-tests show that world events were responded to more slowly (5219ms, SD 957) than both films (4502ms, SD 1065) and music (4676ms, SD 1154), while the latter two were equivalent ($t(17)=3.6$, $p<.01$; $t(17)=3.2$, $p<.01$; $t(17)=-1.3$, $p>.05$). To summarise, then, synaesthetes were significantly more accurate than controls in all three tests of world events, with approximately equivalent reaction times.

Autobiographical Events

Next we analysed data from the Autobiographical Events section, and the dependent measure was the mean number of autobiographical events recalled across nine years for each group of participants. The mean for synaesthetes was 73.7 facts (SD 26.4) compared to just 38.9 facts (SD 11.6) for controls, and this difference was confirmed by an independent samples t-test with equal

variance assumed ($t(16)=3.9$, $p<.01$). Hence synaesthetes recalled almost twice as many autobiographical memories as their controls, within the same test period. Particularly impressive in this domain was participant IB: while five out of six synaesthetes (AC, SC, JC, IB, JA) had Z-scores that were significantly higher than the mean of controls, IB was superior to an extraordinary degree, generating 123 facts for his nine years, and this score was 7.2 standard deviations higher than the mean of controls. Given the extremeness of IB's responses, we independently verified the genuineness of his reports in interviews with three other family members (his sister, his aunt and his fiancée). All IB's reports were verified as accurate. Although this corroboration does not enable us to unequivocally conclude that all of the generated memories of the other synaesthetes and controls were veridical, IB's performance does suggest that our technique can provide a window onto individual differences in the ability to recall autobiographical information, and how time-space synaesthesia can influence this ability.

Discussion

Our data show that synaesthetes have superior abilities in recalling temporal information, compared to matched controls. They were more accurate in recalling the dates of world political events, and two types of cultural event (film and music). They were also able to recall significantly more autobiographical information than controls within a matched time interval, and we return to both these findings in the General Discussion. We point out that although our synaesthete participants were clearly superior to the control population, they were still, on average, 4.5 years away from the true date that each event took place (in our Public Events Battery). Hence visuo-spatial forms appear to provide an accuracy that is not absolute, but which endows significant advantages, nonetheless.

This study has shown that synaesthetes demonstrate superior abilities in the domain that represents their inducer (i.e., representations of time). The following study assesses whether they also show superior abilities in the domain of their concurrent (i.e., spatial processing). In addition, Experiment 2 will also test our participants in a task that *does not* draw upon abilities related to their mental calendars. Showing that synaesthetes have no more than average

performance in tasks relating to cognitive abilities that do not involve space and time will allow us to rule out other potential explanations for our findings: namely that our time-space synaesthetes might have a some *general* superior ability (rather than in time/space specifically), or that they might simply be more motivated to perform well (see Gheri et al., 2008 for a discussion on motivational factors in synaesthesia research).

Experiment 2

In this study we tested whether synaesthetes show superior abilities in visual and/or spatial processing, compared to non-synaesthetes. Participants were tested in four tasks of visual memory and spatial functioning, and all tests come from previous literature. Three tests (Benton and Fogel, 1962; Warrington and James, 1991; Della Sala et al., 1997) compare performance to clinical norms established from large populations (n=100, 86, 345 respectively) and one test (Cherry et al., 2007) allows the performance of our synaesthetes to be compared to a set of controls run in our own lab. The methods for each test are described below.

In addition, we also assessed our participants in a task that does not draw on abilities related to their mental calendars (the National Adult Reading Test - NART, Nelson, 1982). If visuo-spatial benefits (and event-memory advantages; see Experiment 1) are associated specifically with our synaesthetes' visuo-spatial forms (rather than some other general cognitive ability or motivational difference) then their performance in other cognitive domains should be no different from that of non-synaesthetic controls.

Method: Participants and Design

Benton's test of 3D Praxis (Photographic Stimuli; Form B; Benton and Fogel, 1962)

Eight synaesthetes (JT, IB, JA, HB, PS, AC, FW, RD) took part in this test, which assesses the ability to manipulate objects in 3D space, with reference to a target image. Participants were given 29 wooden blocks of different sizes and were required to replicate in turn three different block models, presented as photographs¹. The three models increase in complexity and required

6, 8, and 15 blocks for their construction, respectively. The experimenter instructed participants to use one hand only to construct the models, and returned to blocks to their starting positions in between trials. Accuracy was emphasised over speed, and a maximum of 5 minutes was allowed for each trial. The test is scored according to the number of blocks that are correctly placed (to a maximum of 29).

VOSP Progressive Silhouettes (Warrington and James, 1991)

Six synaesthetes took part in this test (JT, IB, JA, HB, PS, AC), which assesses the ability to recognise a 3D object from a 2D representation presented in silhouette and initially from an unusual angle. Participants must mentally project the shape into three-dimensional space in order to recognise it. The test comprises two pictured items (a gun, a trumpet) each with 10 trials. Each trial shows the object in silhouette, from one of 10 different angles, moving through 90°. The first trial corresponds to the most difficult to identify (e.g., viewing a gun through the grip) while the last trial represents the most easy to identify (e.g., viewing the gun sideways on). Participant view each silhouette in turn, and are required to identify the object as soon as they can. Incorrect responses result in a move to the next trial, and the test stops when the items has been correctly recognised. The test is scored according to the number of trials required before correct identification takes place for both objects (to a maximum of 20), where lower scores indicate better performance.

Visual Patterns Test (Della Sala et al., 1997)

Four synaesthetes took part in this test (JT, IB, JA, AC) which assesses non-verbal visual short term memory. Participants were presented with matrix ‘checkerboard’ patterns of black and white squares in grids of varying sizes (2x2 to 5x6), with the number of blacked-out squares increasing from 2 to 15 through the course of the test. Each pattern is shown for 3 seconds, and participants are then required to replicate the pattern in a blank grid. Participants have three attempts at each level (i.e., for 2-15 blacked-out squares) to correctly replicate the pattern, and

the test stops if all three attempts fail. The test is scored according to the maximum grid that was correctly achieved (to a maximum of 15).

California Mental Rotation Test (Cherry et al., 2007) and the NART (Nelson, 1982)

Five synaesthetes (JT, IB, JA, AC, HB; one male) were matched to ten controls (two controls per synaesthetes) on sex, handedness, age, and number of years of formal education. Synaesthetes had a mean of 17.2 years education (SD=4.5) and non-synaesthetes had 17.4 years (SD=3.4). Their respective ages were 36.6 (SD=4.4) and 36.2 years (SD=9.2) respectively. The California Mental Rotation Test assessed their ability to mentally manipulate 2D drawings of 3D objects, and is a simplified version of a test developed by Vandenberg and Kuse (1978; and modified by Rizzo et al., unpublished; reported in Cherry et al., 2007). The test contains 20 targets, and each target depicts a shape formed by six conjoined blocks with two right-angle turns at varying locations in the shape. Each target is presented along with two test images, one of which is a rotated version of the target. Participants were instructed to identify which image was the rotated version, and to be as fast and accurate as possible. The test was scored according to the number of correct responses (to a maximum of 20), and was timed to also provide RT data. The same set of participants were also tested on their performance in the NART test (Nelson, 1982). This is a task of reading ability used as an assessment of general cognitive ability, and contains 50 single written words of graded difficulty (from *chord* to *campanile*) to be read aloud by the participant. The test is scored by the number of errors in pronunciation out of 50, where low scores indicate superior performance.

Results

Benton's test of 3D Praxis

Normative published control data comes from n=100 participants (non-neurologic hospital patients; Benton, 1976). All eight of our synaesthetes achieved the maximum score of 29. The difference between 29 and the norming population mean 27.3 (Benton, 1976) with standard

deviations of 0 and 2.3 respectively was significant in an independent samples t-test ($t(106) = -2.08$; $p < .05$).

VOSP Progressive Silhouettes

The mean score for our six synaesthetes was 4.3 (SD = 0.5) out of 20. This was significantly lower (where low scores indicate better performance) than the mean from the $n=86$ norming population (mean 9.8, SD = 2.4; Warrington and James, 1991) in an independent samples t-test ($t(90) = 5.58$, $p < .05$).

Visual Patterns Test

The mean score for our four synaesthetes was 12.0 (SD = 1.6) out of 15. This was significantly higher than the mean (adjusted for age and education) from 345 individuals in the norming population (mean 8.95, SD = 1.87; Della Sala et al., 1997) in an independent samples t-test ($t(347) = 3.25$, $p < .05$).

California Mental Rotation Test, and the NART

The mean score for our five synaesthetes was 19.4 (SD = 0.9) out of 20. This was significantly higher than the mean of our 10 controls (mean 14.9, SD = 4.5) in an independent samples t-test ($t(13) = 2.17$, $p < .05$). Synaesthetes were also numerically faster, with a mean RT of 147.8 sec (SD=46.9) compared to 179.9 sec (SD=97.3) for controls, but this difference was non-significant ($t(13) = -.689$, $p > .05$). The equivalence in RTs rules out the possibility that the synaesthetes' greater accuracy was the result of speed-accuracy trade-off. Finally, despite our synaesthetes' superior scores in mental rotation, there was no difference across groups in NART performance. Mean error scores (out of 50, where low scores = better performance) were 7.6 for synaesthetes and 9.2 for controls, and this was non-significant ($t(13) = .73$, $p > .05$).

Discussion

Our data provide evidence that time-space synaesthetes demonstrate superior performance in visual/spatial tasks. Synaesthetes outperformed controls in tests of 3D spatial mapping (*Benton's test of 3D Praxis*), in inferring 3D shapes from 2D images (*VOSP Progressive Silhouettes*), in mentally manipulating 2D images of 3D objects (*California Mental Rotation Test*), and in visual short-term memory (*Visual Patterns Test*). Together this suggests that the exceptional mappings of time and space possessed by time-space synaesthetes exists along-side exceptional abilities in visual and spatial processing, and we return to this in the General Discussion. Finally, our NART assessment showed that synaesthetes are no different from non-synaesthetes in a task that is unrelated to time/space processing. This argues against a motivational explanation of our key findings, or one that entails a general cognitive advantage for synaesthetes, rather than the specific time-space advantage we argue for here.

GENERAL DISCUSSION

Our ten time-space synaesthetes outperformed controls in eight separate temporal and visual-spatial processing tasks (but not in a task that is unrelated to time/space processing). In our Discussion we examine each task-category in turn, and assess what superior scores might tell us about the cognitive characteristics of visuo-spatial synaesthetes.

Superior Time/Event Processing

Our study is the first to examine the consequence of visuo-spatial representations for dates/years, and we show that our synaesthetes convincingly dominated over non-synaesthetes in tests that assessed their recall of dates/events in time. Synaesthetes out-performed controls in their ability to name the dates of public events, of both political and cultural significance (world events, film and music). Moreover, their ability was not limited to simple date recall, because they also out-performed controls in recalling the content of events in their own life. The question of *how* this superior memory arises from synaesthetic visuo-spatial forms is one that has not been assessed empirically in our study, but we have interviewed a subset of our participants about the

phenomenology of their experiences in our tasks. Overall, our participants report that target events were retrieved from their spatial locations within the visuo-spatial form(s). Participant IB for example, describes his search process as taking one of two paths; events of high familiarity are marked *directly on his form for centuries*: World War II, for example, is seen as a dark bar in the middle of his form for the 20th Century. Other less familiar events (e.g., Chernobyl disaster) are found by inspecting *his forms for individual years* within an estimated target radius (e.g., within the 1980s). For example, each year within the 1980s is individually inspected until the Chernobyl disaster is found (or until a ‘best guess’ is generated with reference to events that were occurring at a similar time; e.g., “Chernobyl happened at the same time as event X, which is spatially located in 1986”). In this way, events in time appear to be slotted into the time-lines, and are retrieved via a process that has at least some features in common with visuo-spatial search. Nonetheless, other, non-spatial, mechanisms appear to also be implicated, such as the mechanism by which IB knows to limit his search space to any particular decade.

Our results may shed light on the case of AJ, whose exceptional recall of public and private events was described by Parker et al. (2006) as a case of hyperthymestic syndrome. AJ, too, had a mental mapping of time in space, and our study suggests that this mental calendar was perhaps the key to her exceptional abilities. When our group of individuals with time-space forms were tested on similar dimensions, they too show superior abilities in those same domains. This finding raises the immediate question of whether *all* time-space synaesthetes necessarily have hyperthymestic syndrome. The answer is no, because Parker et al. identify *two* traits that are necessary for this condition: not only a prodigious ability with dates in time (which in the case of AJ appears to be even yet superior to that of our synaesthetes here), but also a compulsion to spend an abnormally large amount of time thinking about the past. Regarding AJ, for example, Parker et al. write “She is dominated by her constant, uncontrollable remembering, finds her remembering both soothing and burdensome, thinks about the past “all the time” (p.

46)”. This type of compulsion is not the case for our participants here, and nor has it been reported for visuo-spatial synaesthetes more generally. In other words, while our current research shows that visuo-spatial synaesthesia is associated with superior past recollection, it does not imply that visuo-spatial forms necessarily involve the imprisonment of someone by those past memories, as is found in cases of hyperthymestic syndrome.

What, then, might we say about the relationship between time-space synaesthesia and hyperthymestic syndrome? We suggest that time-space forms may be a necessary but not sufficient component of hyperthymestic syndrome, and that this latter may arise from the unification of two independent features that have co-incidentally co-occurred in case AJ. Specifically, while Parker et al. indicate that AJ has a mental calendar, they also report she has obsessive tendencies associated with a neurodevelopmental frontostriatal disorder (unlike the participants in the present study, who showed no indication of any obsessive traits). We suggest then that AJ’s obsessive tendencies may give a fixation on the particular system of her time-space synaesthesia, and that this in turn accounts for all features of her hyperthymestic syndrome (i.e., an obsession with dates and their prodigious recall). In other words, her obsessive tendencies give her not only an obsession with the past (the first trait of hyperthymestic syndrome), but have also allowed the superior recall normally associated with time-space synaesthesia to become heightened and refined over time, into a savant-like ability (the second trait of hyperthymestic syndrome). A related, but more conservative proposal might simply be that synaesthetic mental calendars *increase the likelihood* of hyperthymestic syndrome.

Our hypotheses are based on previous accounts explicitly linking prodigious recall abilities with synaesthesia (e.g., Yaro and Ward, 2007) and obsessive behaviours (Baron-Cohen et al., 2007). Baron-Cohen et al. (2007) for example, suggest that a case of savantism in a man with prodigious recall of digits may result from the combination of his Autism Spectrum Condition and his digit-colour synaesthesia. Indeed, Baron-Cohen et al. have proposed that

whenever autism and synaesthesia co-occur, the likelihood of savantism is increased. Like DT and other savants, AJ is described as having prodigious domain-specific knowledge, as well as repetitive and obsessive tendencies (Heavey et al., 1999) and a neuropsychological profile that involves areas of both superiority and deficit (Winner, 2000). Given this, AJ appears to possess all the necessary components of a savant's profile (i.e., prodigious abilities combined with deficits, indications of synaesthesia, and obsessive tendencies). Indeed, even retrospective medical analyses of famous historical savants, such as the musical savantism assumed in Wolfgang Mozart (Simkin, 1999) show a similar pattern: Mozart, for example, displayed periods of obsessive compulsive behaviour, as well as a suggestion of traits now assumed to be associated with music-colour synaesthesia (e.g., migraine headaches; perfect pitch; Cytowic, 1993; Jawer, 2006; but see Rich et al., 2005). Clearly, such historical cases can only be interpreted speculatively, but they raise intriguing support for the proposal that savantism may be derive from the coincidental co-occurrence of obsessive tendencies and synaesthesia.

We have shown that visuo-spatial synaesthetes have superior abilities in the recall of dates and time, but are no different from non-synaesthetes in a task unrelated to their mental calendars (i.e., the NART; Nelson, 1982). This argues against a motivational explanation for our findings (i.e., that synaesthetes might simply have been trying harder; see Gheri et al., 2008) and also argues against some type of *general* cognitive advantage for synaesthetes. One other possibility however, is that synaesthetes performed well in date/event recall because they have some type of *general memory* superiority (i.e., superior memory for *any* stimuli). Such an ability might not have been tapped by our NART test because this assesses verbal abilities, not recall. So to assess this memory hypothesis empirically, we tested the general memory abilities of our most outstanding synaesthete performer, using the digit-span subtest of the WAIS-III (Wechsler Adult Intelligence Scale; Wechsler, 1997). Participant IB recalled an astonishing 123 autobiographical facts in the Edinburgh Events Battery, placing him 7.2 standard deviations

above the mean for controls. However, despite this extra-ordinary recall of autobiographical information (and a similar achievement in all our other tests of time and space, in which he was either the highest, or second-highest performer) IB had only average performance in the NART, and also, importantly, only an average performance in the digit span test. His age-adjusted digit-span score (= 13) was not significantly different from the standardised population mean (= 10; SD = 3; $Z= 1.0$ $p= .3$). In other words, IB performs within the average range in general cognitive and memory tasks that do not relate to his mental calendar (NART; digit span) but shows exceptional abilities in skills that concern time and space.

Superior Visual Memory and Spatial Processing

Our synaesthetes showed superior performance in four tasks tapping visual memory/imagery and/or spatial abilities. Benton's 3D Block Construction task (Benton, 1976) was originally designed to illustrate deficits in visuo-constructional ability. However, clinical studies suggest that performance is not based on primary motor function, but is sensitive to visuo-perceptive abilities in right frontal and parietal regions (see Spreen and Strauss, 1998, for discussion). Hence the superior performance by our synaesthetes in this task may indicate superior skills in the ability to mentally assess or recall visual structures in space, and we assume that this is precisely the type of activity involved in the mental generation of synaesthetic visuo-spatial forms. Synaesthetes also out-performed clinical control norms in the Progressive Silhouettes tasks (Warrington and James, 1991). This task was originally designed to assess object memory independently of any spatial component, although it has an inherent spatial requirement in that participants must mentally project a 2D image into 3D space. This component may be especially relevant for our synaesthetes, given that their spatial forms, too, are projected into a 3D domain. Alternatively, since the task also requires generating a mental image (of an object recalled from visual memory; e.g., a gun), it may be the imagery component that triggers our synaesthetes' superior performance. Indeed, a more pure task of visual recall/imagery also gave our synaesthetes a superior profile (Visual Patterns Test; Della Sala et al., 1997). Moreover, this

finding is supported by data from Price (2009, this issue) who shows that synaesthetes score significantly higher than the average person in self-rated tests of visual imagery. This is certainly compatible with our findings in the Visual Patterns Tests, and may also be at the root of our synaesthetes' superiority in both the Benton task and the Progressive Silhouettes task.

Our synaesthetes also out-performed matched controls on the University of Southern California Mental Rotation Test (Cherry et al., 2007). As mentioned above, visuo-spatial synaesthetes can mentally manipulate the orientation and size of their arrays, and can take multiple perspectives (e.g., Jarick, Dixon, Stewart et al., 2009, this issue). Given this, it might be no surprise to find that the type of cognitive skills required for the mental rotation test should be exceptionally active. Nonetheless, one study in this special section gives pause for thought: Price (2009, this issue) found superior scores in self-report for visual imagery (noted above), but found no superiority in scores for self-rated *spatial* abilities. This is especially surprising given that scores in self-rated spatial abilities might be expected to correlate with performance on mental rotation of the type used here. It is possible that our synaesthetes' extremely high visual imagery (e.g., Price, 2009, this issue) affords them some alternative mechanisms by which to perform mental rotation tasks, and we speculate that Price's spatial assessment might show particularly high scores on rotation-related questions (even if other questions show average scores). As such, the issue of spatial abilities in synaesthetes who project sequences into space is an area that appears to require further research.

Implications of these Data

In summary, our study has shown that synaesthetes with extra-ordinary mappings of time and space also have superior performance when those domains are assessed independently in behavioural tasks. But what can we conclude from this finding? One important conclusion has been to relate our synaesthetes' temporal superiority to the savant-like condition of hyperthymestic syndrome, as we have discussed above. A second conclusion is that the exceptional experiences of synaesthetes are not limited to the synaesthetic sensation in and of itself: in other words, synaesthetes are exceptional not only because they see time in space, but

because they have other unusual abilities associated to that experience. What we *cannot* tell from this study, however, given the tasks presented here, is the direction of causality. In other words, do exceptional temporal and/or spatial abilities *cause* visuo-spatial forms, or are they the result of such forms? It is also possible that the experiences may exist symbiotically, in that superior visual or spatial ability gives rise to time-space forms, which in turn re-enforce the temporal and visual/spatial skills that originally spawned them. It is an important duty of scientific studies to recognise their limitations, and one limitation of the current study is an inability to answer this question. What we *may* do, however, is present our study as an addition to the growing body of literature suggesting that synaesthetes have superior abilities in cognitive domains associated with their synaesthetic experiences, and we discuss this further below.

Our study has shown cognitive advantages for time-space synaesthetes, and other studies have found superior visual recall/imagery both in other visuo-spatial populations (Price, 2009, this issue) and in other forms of synaesthesia more generally. Barnett and Newell (2008) found that that self-rated imagery experiences (using the Vividness of Visual Imagery Questionnaire; Marks, 1973) were higher in a group of grapheme-colour synaesthetes compared to controls, and this finding has been mirrored in behavioural studies by Weiss et al. (2005) and by Spiller and Jansari (2008). Weiss et al. found that grapheme-colour synaesthetes were superior performers in several tests of visuo-spatial processing (Hooper Visual Organization Test, Fragmented Pictures Test, Visual Object and Space Perception test battery, Benton Line Orientation Test; Lezak, 1995), while Spiller and Jansari found their grapheme-colour synaesthetes performed better than matched controls on a visual imagery task which involved generating and inspecting images of graphemes. Hence both self-report and behavioural tasks have suggested that other forms of synaesthesia, too (e.g., grapheme-colour synaesthesia) may go hand-in-hand with enhanced visual/spatial and imagery abilities. Nonetheless, care should be taken on this point, and for two reasons. First, Sagiv et al. (2006) have shown that visuo-spatial forms are highly common among grapheme-colour synaesthetes. This means that the superior performance previously attributed to grapheme-colour synaesthetes by Barnett and Newell (2008), Spiller and Jansari (2008), and by Weiss et al. (2005) may instead have derived from their participants' co-occurring visuo-spatial

forms. By the same token, we too are obliged to show that our own findings, which we have attributed to visuo-spatial forms, have not instead arisen from co-occurring grapheme-colour synaesthesia. We are confident that this is not the case: although four of our participants do indeed have grapheme-colour synaesthesia, the remaining six do not, and post-hoc examination shows that the test score of these two groups do not differ (all $t_s < 1$). Indeed, those time-space synaesthetes with concurrent grapheme-colour synaesthesia were numerically *out-performed* by the remaining time-space synaesthetes in three out of our four tasks. For this reason, we are able to conclude that the visuo-spatial superiority found in our tasks is likely not attributable to grapheme-colour synaesthesia, but rather, is a function of mental calendars themselves.

In reporting possible limitations of our study, we must also identify a potential draw-back in comparing our synaesthetes to control norms provided by large samples (as we have done in the 3D Praxis test, and in the VOSP test) rather than by matched control populations. First, the norming population for the 3D Praxis task were non-neurological hospital patients, which may have provided a baseline not representative of the general population. More importantly, however, weak but significant associations have been reported between education and IQ on the one hand, and performance in the VOSP silhouettes task on the other (Bird et al., 2004; Bonello et al., 1997; Herrera-Guzman et al., 2004). Since five of our eight participants in the praxis task, and four out of six participants in the VOSP task had post-graduate education (either complete or in progress), this raises the possibility that participants may have performed at a superior level in visual/spatial tests not because they were synaesthetes, but only because they have high levels of education. There are two arguments that speak against this. First, there is no indication that our superior scores in 3D praxis and VOSP arise from education, since synaesthetes with lower levels of education scored the same, or even higher, than synaesthetes with postgraduate education. In 3D praxis, all synaesthetes achieved the maximum score regardless of education, and in VOSP, the high school synaesthetes even marginally *out-performed* postgraduate synaesthetes (mean Z-scores for high school vs. postgraduate synaesthetes were 2.32 vs. 2.12 respectively). Second, in mental rotation and the Visual Patterns test, synaesthetes continued to out-perform controls, even when these latter had been carefully matched on education (for

Mental Rotation) or when control norms had been corrected for the effects of education (for Visual Patterns). For both these reasons, we are confident that our study has indeed illustrated superior visuo-spatial abilities that are properly associated with visuo-spatial forms, rather than other demographic qualities. In other words, despite drawbacks on any one particular test, the overall pattern of our results tells a coherent story of superior visuo-spatial performance by synaesthetes with visuo-spatial forms.

Finally, we point out that our study of time-space arrays may be considered an important addition to the synaesthesia literature on visuo-spatial forms, since this body of work has tended to focus on number-space arrays (or ‘number forms’; i.e., spatial representations of numerical sequences), and theoretical neural models of visuo-spatial forms have reflected this (see Hubbard, Piazza et al., 2005 for review). In contrast, our study, and others emerging (e.g., Price and Mentzoni, 2008; Sagiv et al., 2006; Smilek et al., 2007; Eagleman, 2009, this issue; Hubbard et al., 2009, this issue) emphasise the role of sequences, rather than other numeric qualities. This switch of emphasis has been supported by a recent imaging study mapping the neural roots of number form visuo-spatial synaesthetes (Tang et al., 2008). Tang and colleagues found that differences emerge between synaesthetes and controls when tasks require ordinal, rather than cardinal processing, suggesting in turn that sequencing may lie at the heart of this variant of synaesthesia. Our own work here contributes to this debate by showing behavioural evidence of sequence-triggered arrays, from time-space synaesthetes. Finally, we point out that a parallel debate has arisen, too, in the non-synaesthetic literature centring around the SNARC effect. Here too, researchers have questioned the extent to which spatial co-ordinates are assigned to numbers, magnitude, or to sequence representations in general (Walsh; 2003; Wood and Fischer, 2008). In the same way that sequences may be key to visuo-spatial representations in non-synaesthetes, studies such as our own on time-space synaesthesia lead to parallel conclusions for visuo-spatial synaesthetes.

In conclusion, the mappings between time and space consciously experienced by visuo-spatial synaesthetes appear to co-occur with superior abilities in each of the two domains that are exceptionally linked in this condition. Synaesthetes have superior scores in tasks that assess

visual memory recall and spatial processing, and also in tasks that assess their memory for events in time. In the latter case, we have hypothesised that such arrays may be a key component of hyperthymestic syndrome (Parker et al., 2006), and hence that that visuo-spatial forms may provide the foundation upon which repetitive or obsessive tendencies operate to create savant-like ability for dates and events in time.

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Figure Captions

Figure 1. Spatial form depicting the day, reproduced from drawings made by participant SC.

Figure 2. Spatial form depicting the week, reproduced from drawings made by participant ST.

Figure 3. Spatial form depicting the month, reproduced from drawings made by participant JC.

Figure 4. Spatial form depicting the year, reproduced from drawings made by participant JT.

Figure 5. Spatial form depicting a century, reproduced from drawings made by participant FW.

Figure 6. Spatial form depicting millennia, reproduced from drawings made by participant JS.

Figure 7. Mean error-distance (in years) for synaesthetes and controls in three tests of date recall (for international events, cultural events: music, cultural events: film), with standard error bars.

‘Error-distance’ is the absolute distance in years between the year of the event, and the year given by participants (where low error-distances represent superior performance).

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Table 1: A summary of our n=10 visuo-spatial synaesthete population. Columns 1-2 show identification (ID) initials, sex (in subscript) and age at time of testing. Columns 3-8 show time units mapped to spatial arrays for each synaesthete, and Column 8 shows other sequences reported to trigger spatial forms (S. = seconds; M. = minutes; N = numerals, L = letters; T = temperature; A = ages; H = heights; Sl = salaries; MN. = musical notation). Column 9 shows time units also triggering synaesthetic colour.

ID	age	day	week	month	year	century	millennium	Other	coloured time
JT _f	32.6	x	x	x	x	x	x	S., M.	days, months
SC _f	32.3	x			x	x	x	N., A	
IB _m	32.9		x		x	x	x		days
JA _f	42.1		x		x	x	x	N.	days, months
HB _f	39.8	x	x	x	x	x	x	L., N., T.	
PS _m	42.3		x	x	x	x		S., A	
AC _f	38.7	x	x	x	x	x	x	L., N., MN.	days, months
FW _f	28.3		x		x	x		L., N., A	days
RD _f	27.0		x	x	x	x	x	L., N.	
JC _f	42.4	x	x	x	x	x	x	L., N., H	days, months

Figure 1

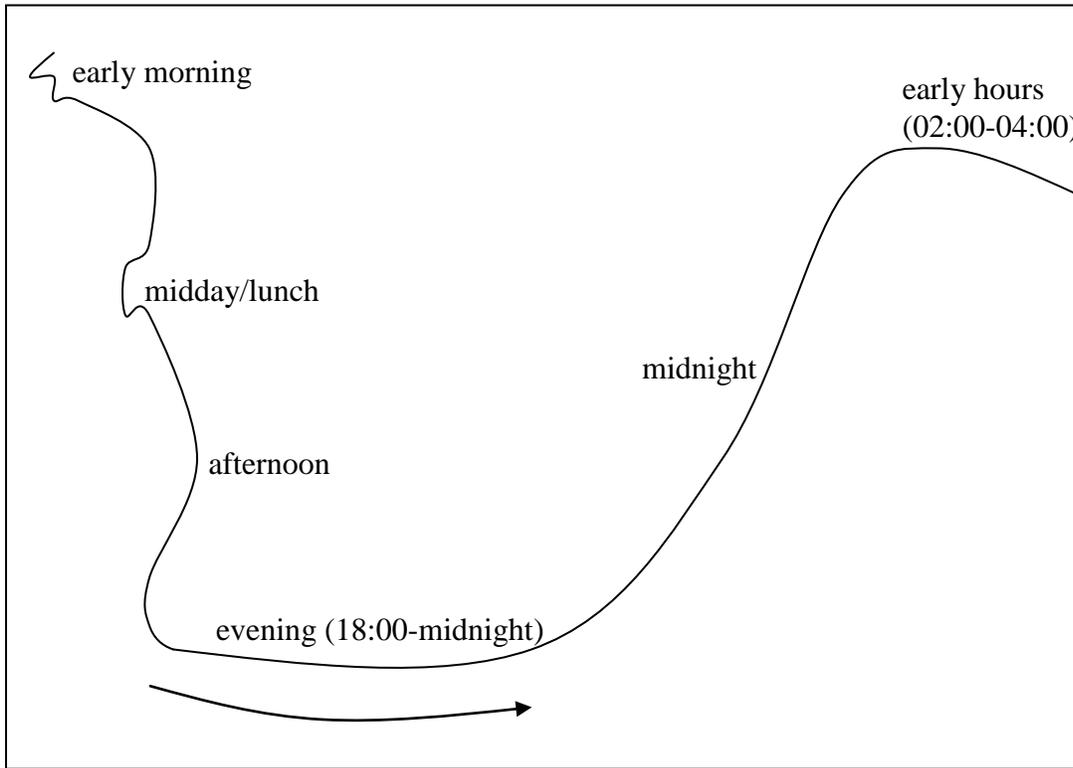


Figure 2

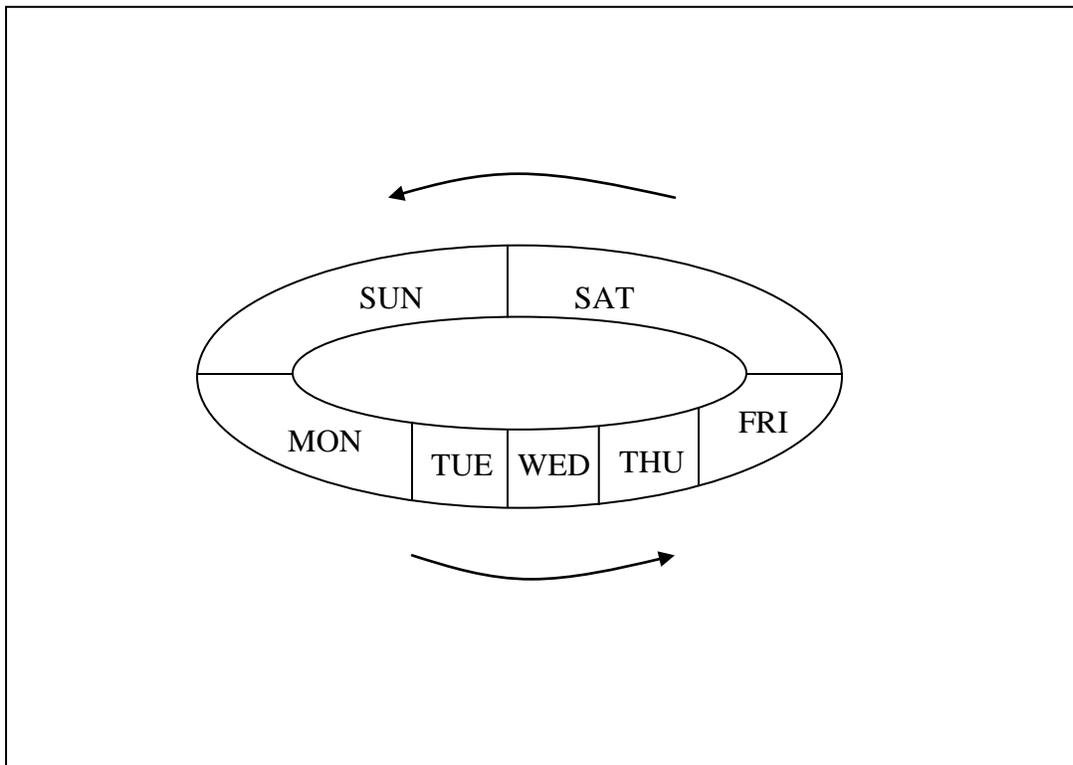


Figure 3

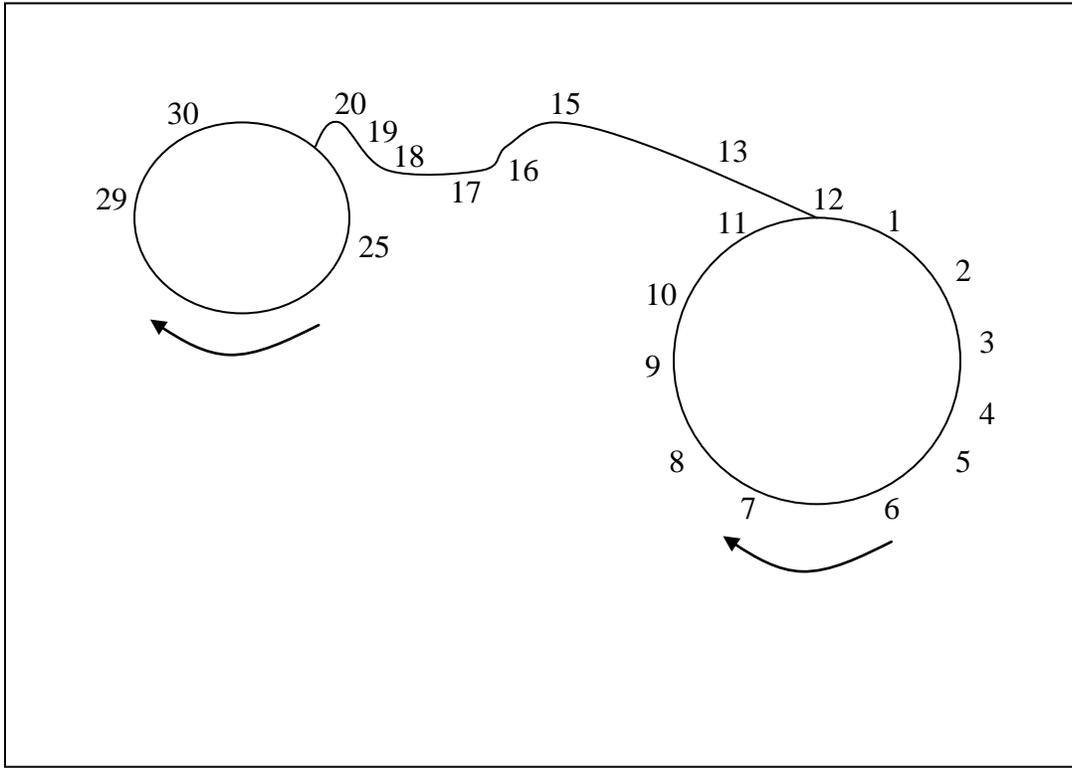


Figure 4

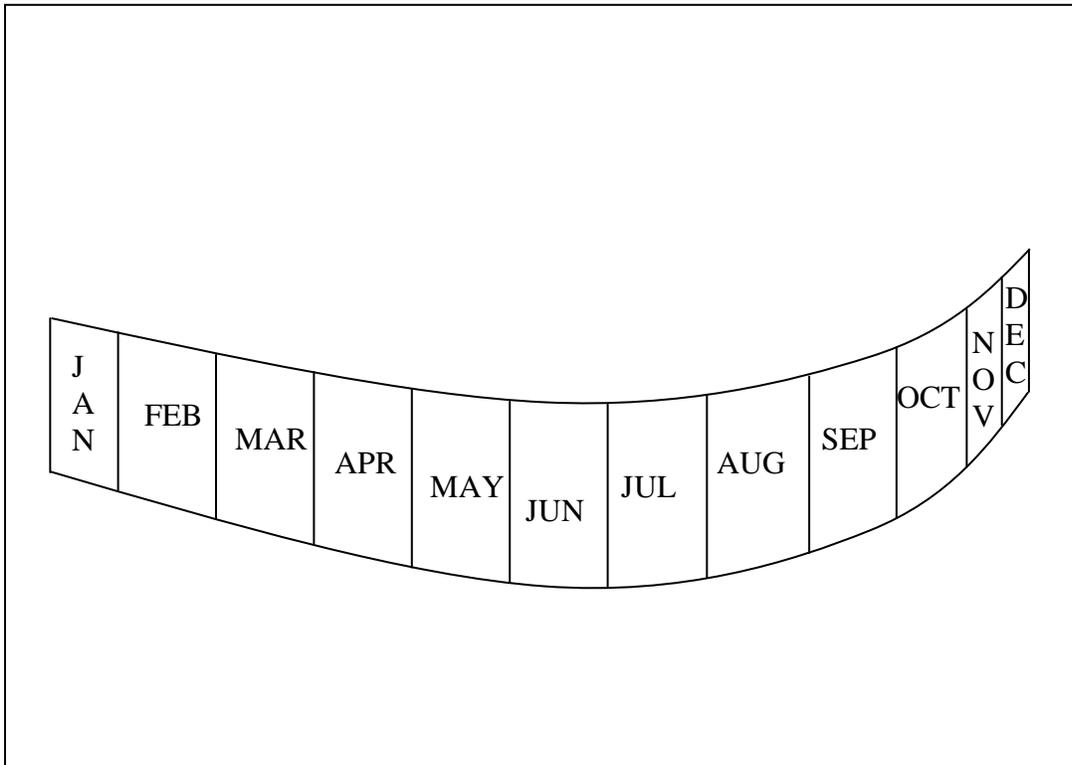


Figure 5

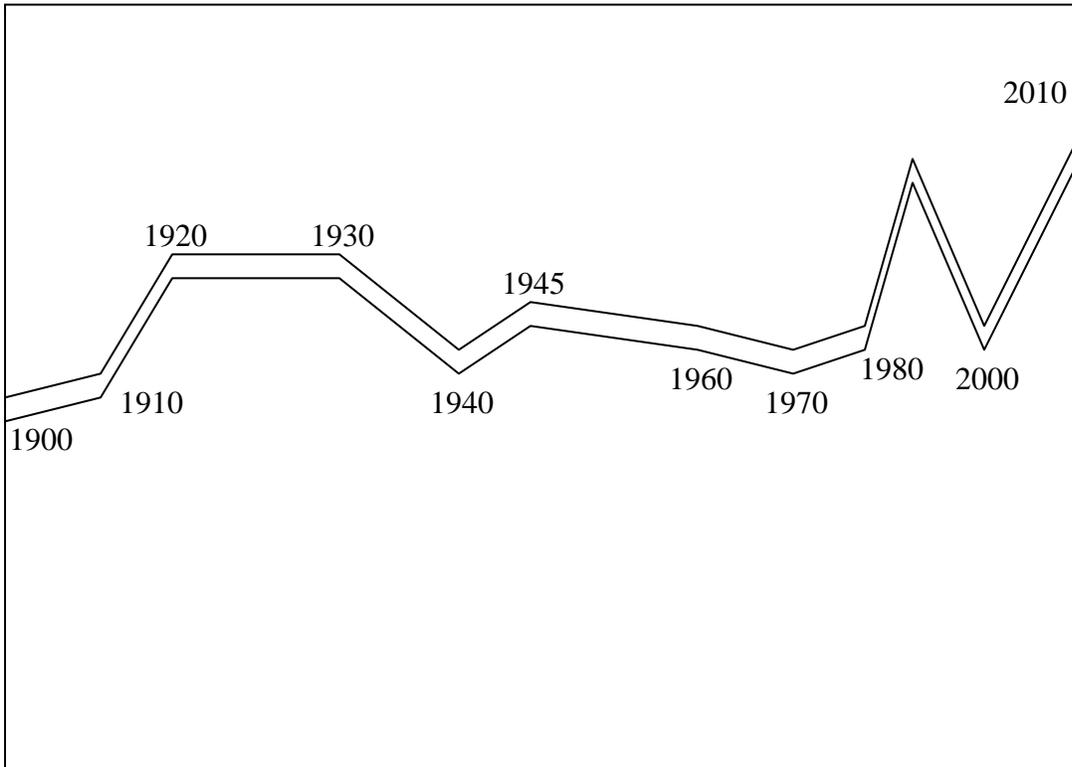


Figure 6

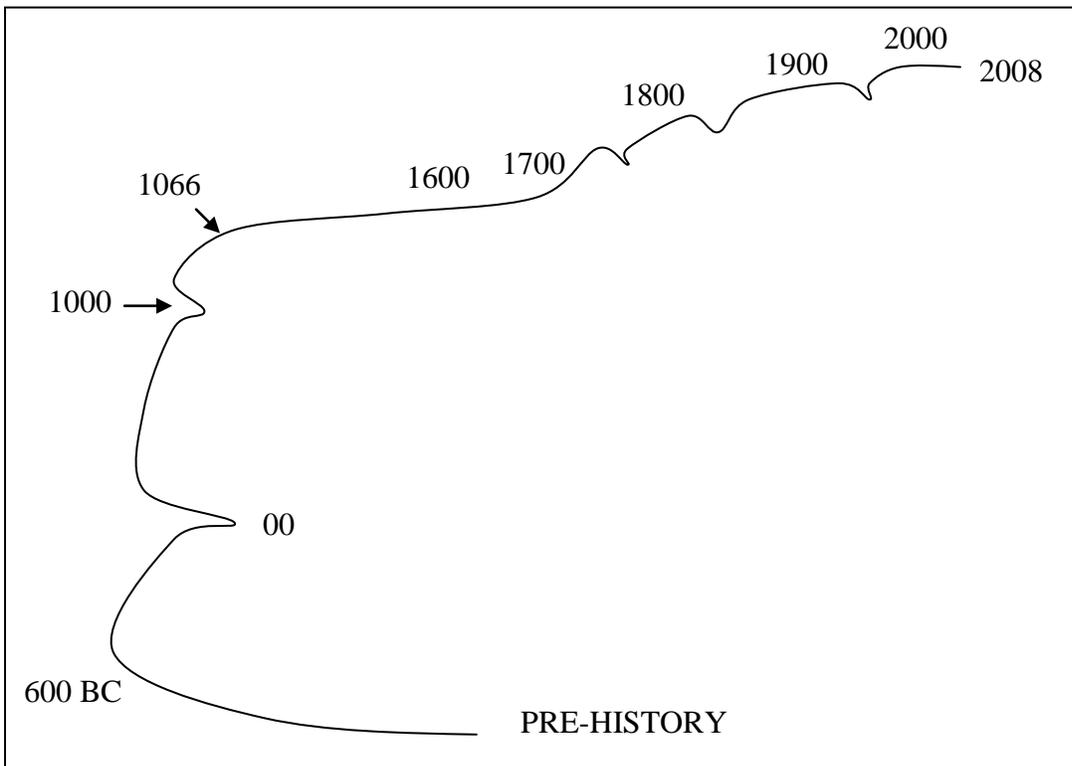
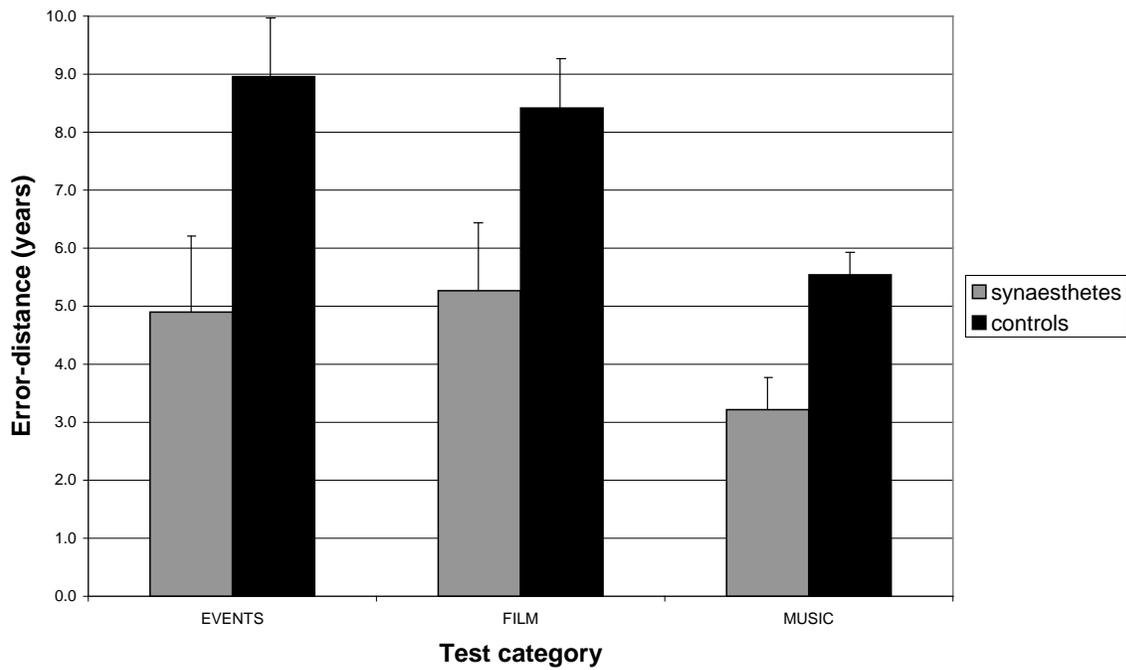


Figure 7



¹ In an alternative version of Benton's test, constructions are copied from sample models, but the photographic version was selected here because its normal population scores are further from ceiling.