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SHORT REPORT

Enhanced mental rotation ability in time-space synesthesia

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Abstract Time-space synesthesia is a variant of sequence–space synesthesia and involves the involuntary association of months of the year with 2D and 3D spatial forms, such as arcs, circles, and ellipses. Previous studies have revealed conflicting results regarding the association between time-space synesthesia and enhanced spatial processing ability. Here, we tested 15 time-space synesthetes, and 15 non-synesthetic controls matched for age, education, and gender on standard tests of mental rotation ability, spatial working memory, and verbal working memory. Synesthetes performed better than controls on our test of mental rotation, but similarly to controls on tests of spatial and verbal working memory. Results support a dissociation between visuo-spatial imagery and spatial working memory capacity, and suggest time-space synesthesia is associated only with enhanced visuo-spatial imagery. These data are consistent with the time-space connectivity thesis that time-space synesthesia results from enhanced connectivity in the parietal lobe between regions supporting the representation of temporal sequences and those underlying visuo-spatial imagery.

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Introduction

Sequence-space synesthesia is a form of synesthesia in which abstract sequences are experienced as spatial forms (Galton 1880; Seron et al. 1992). For example, in time-space synesthesia, sequenced units of time, such as the months of the year and days of the week, are visualized as occupying a spatial path (Smilek et al. 2007). These so-called synesthetic calendars take a variety of forms, ranging from simple lines and circles to elaborate three-dimensional landscapes (Brang et al. 2010). Paralleling other variants of the condition, synesthetic calendars emerge in childhood, are evoked automatically by temporal concepts, and display geometric properties that are remarkably consistent over time (Smilek et al. 2007). Indeed, the spatial calendars of time-space synesthetes may be related to cultural and linguistic practices that utilize spatial schemas for the conceptualization of time (Teuscher et al. 2010, 2008). However, individual synesthetes' spatial forms are highly idiosyncratic, as circular synesthetic calendars almost never mimic the arrangement of a clock face; that is, January is no more likely to occur at the 12 o'clock position than at any other (Eagleman 2009). Further, the months often differ in spatial extent with subjectively important months (e.g., July, August, and December) occupying more space than others (Galton 1880) and the clockwise/counter-clockwise spatial arrangement of these calendars covaries with handedness (Brang et al. 2011).

Synesthesia is generally associated with performance advantages in areas related to the synesthetic experience (e.g., enhanced memory for and discrimination of colors in grapheme-color synesthetes; Banissy et al. 2009; Ramachandran and Hubbard 2001; Rothen et al. 2012). In order to understand the processes involved in the construction of synesthetic calendars, researchers have similarly investigated time-space synesthetes' performance in areas believed related to this experience. Time-space synesthetes show advantages relating to memory for temporal events (viz. important dates; Simner et al. 2009), attentional processes (Smilek et al. 2007; Teuscher et al. 2010), and visuo-spatial processes including enhanced spatial working memory (Simner et al. 2009; Brang et al. 2010) and mental rotation performance (Simner et al. 2009). In line with this evidence, Simner et al. (2009) suggested that time-space synesthesia is associated with enhanced spatial memory and manipulation. However, Rizza and Price (2012) failed to replicate the findings of enhanced mental rotation in a sample of 9 synesthetes, weakening the support for these differences as Simner et al.'s (2009) results were obtained from small groups of participants (4 synesthetes in the working memory task and 5 synesthetes in the mental rotation tasks). Noting findings of enhanced visual imagery in time-space synesthetes (Mann et al. 2009; Price 2009; Rizza and Price 2012), Rizza and Price (2012) suggest that synesthetes' spatial calendars are more likely related to visual imagery than spatial processes per se.

A key difference between models of time-space synesthesia thus concerns whether the condition is associated with enhanced visual imagery (Rizza and Price 2012), or a more general enhancement of spatial processing (Price 2009). Here, we examine importance of spatial processes in time-space synesthesia using a slightly larger sample of synesthetes ($n = 15$) than that in prior studies, as well as a group of neurotypical controls carefully matched for age, gender, and education. To this end, we compared the performance of these two groups on the *spatial span task*, a test of spatial working memory capacity developed by (Shah and Miyake 1996). In contrast to many clinical instruments assessing visuo-spatial ability, the spatial span task was designed for the normal population and specifically targets spatial as distinct from visual processing ability (Shah and Miyake 1996). If time-space synesthesia is associated with enhanced spatial memory, we should expect to observe greater spatial span scores among time-space synesthetes than neurotypical controls.

In addition to spatial span, we also report participants' performance on a mental rotation task that was embedded in the larger spatial span task (see "Methods" section for details). Mental rotation performance does not figure into the calculation of spatial span and is not typically reported by investigators who use this instrument. Its inclusion here was intended to replicate prior research that showed enhanced performance by time-space synesthetes on mental rotation tasks (Simner et al. 2009). Moreover, it is thought to provide an index of spatial visualization processes that are partially distinct from those in spatial working memory (Huyn and Luck 2007; Wolbers et al. 2006). If time-space synesthesia is associated with increased spatial visualization processes, we should expect to observe greater accuracy rates on the mental rotation task among synesthetes than controls.

Finally, to help detect the presence of motivational differences between groups, we assessed participants' verbal working memory using a version of the sentence span task designed by Daneman and Carpenter (1980). This instrument has been normed extensively on the same population as the spatial span, and scores on the two span tasks are typically uncorrelated (Shah and Miyake 1996). We predicted no group differences on the sentence span task.

Methods

Data were collected from 15 time-space synesthetes, and 15 non-synesthetic controls recruited from the undergraduate population at the University of California, San Diego. All participants had normal or corrected-to-normal vision, and none had any history of psychiatric or neurological disorders. Synesthetes included 12 females and 3 males (mean age 21.5 years, $SD = 1.5$, 14 right-handed), and controls likewise included 12 females and 3 males (mean age 21.5 years, $SD = 2.0$, 15 right-handed).[1] One synesthete was a non-native English speaker and so was excluded from the verbal working memory test. Synesthetes reported either 2D ($n = 8$) or 3D ($n = 7$) circular calendars. Synesthesia was confirmed by means of a detailed interview regarding aspects of the subject's synesthetic calendar and consistency testing over time either for the visual (as described in Brang et al. 2010) or descriptive depiction of synesthetic calendars (minimum of three weeks between test and retest; mean 45.6 days). Consistency testing for the descriptive depiction of synesthetic calendars was consistent with the methods in Brang et al. (2011): subjects were asked to provide detailed responses to ten questions probing elements of their calendars including its shape, size, location/orientation relative to the body and/or head. All participants gave signed informed consent prior to the experiment and participated either for cash or in fulfillment of a course requirement.

[1] Twenty-two control subjects initially participated in these tasks, but seven were removed in order to match control and synesthetic groups according to gender; control subjects included in this final number were selected chronologically based on participation date. The exclusion of these subjects had no impact on the pattern of significant and non-significant differences between the groups.

The spatial span task was taken from Shah and Miyake (1996). On each trial, participants were presented with a series of two to five sequentially presented letters (e.g., F, J), oriented either normally or mirror-reversed. Each letter appeared at one of seven randomly chosen rotations, varying in 45° increments from 45 to 315 degrees. After the appearance of each letter, participants indicated via button press whether it was mirror-reversed or normal. At the conclusion of each set of letters, participants indicated the orientation of each letter in the set via a series of temporally ordered mouse clicks. Testing began at level 2 (i.e., presentation of 2-letter sequences), included five sets in each level, and progressed sequentially to level 5, resulting in 70 mental rotation trials and 20 spatial working memory trials. Mental rotation ability was defined as overall accuracy on the judgment of whether each letter was normal or mirror-reversed. Subjects' mean accuracy was compared across the groups using two-sample *t* tests. Follow-up ANOVAs to further explore accuracy differences were conducted post hoc. Greenhouse–Geisser corrections were used where appropriate, but we report the original degrees of freedom for clarity.

Comparison of response times between the groups was additionally compared with a two-sample *t* test in order to rule out the possibility that any observed effects were due to a speed-accuracy trade-off. Response time measures on spatial visualization tasks are typically not analyzed as past research suggests performance does not improve with greater time on task (Lohmann 1986). Consequently, accuracy rate on mental rotation trials was the primary dependent variable of interest.

Visuo-spatial working memory span was defined as the highest level for which all of the spatial orientations were recalled in the correct sequence in at least three of the five sets. An additional half-point was added to the span score for identifying the placement of two of the five sets above the participant's base score. Performance on the visuo-spatial working memory task was compared across the groups using two-sample *t* tests.

The verbal working memory task was taken from Daneman and Carpenter (1980). Participants heard sets of 2–5 unrelated sentences. At the conclusion of each set, they were instructed to write down the last word in each of the sentences. The number of sentences in each set increased sequentially from two to five, with three sets at each level. Participants' verbal working memory span was the highest level for which all sentence-final words were accurately remembered in at least two of the three sets. An additional half-point was added for accurate performance in one of the three sets above the participant's base score. Performance on verbal working memory task was compared across the groups using two-sample *t* tests.

Results

Results from the three tasks are displayed in Table 1. On the test of mental rotation ability, synesthetes were significantly more accurate (mean = 90.7 %, SD = 7.6 %) than non-synesthetes (mean = 78.1 %, SD = 18.3 %), $t(28) = 2.45$, $p < .05$. Groups did not reliably differ in mean response time on the mental rotation task (synesthetes: mean = 2797 ms, SD = 964; controls: mean 3451 ms, S.D. = 1775), $t(28) = 1.25$, $p = .22$, arguing against the possibility that the group difference in accuracy is attributable to a speed-accuracy trade-off.

In order to examine any possible interactions between the groups, we conducted a three-way repeated measures ANOVA comparing group (synesthetes, controls) x stimulus (letters F, J, L, P, R) x orientation (45°, 90°, 135°, 180°, 225°, 270°, 315°) accuracy data. While we observed significant main effects of group [$F(1, 28) = 6.03$, $p < .05$], stimulus [$F(4, 112) = 4.41$, $p < .05$], and orientation [$F(6, 168) = 9.65$, $p < .001$], no interaction was observed for stimulus × orientation [$F(24, 672) = 0.84$, $p = .60$], group × stimulus [$F(4, 112) = 0.28$, $p = .81$], group × orientation [$F(6, 168) = 1.04$, $p = .38$], or group × stimulus × orientation [$F(24, 672) = 1.06$, $p = .39$].

Post hoc comparisons were conducted on the main effects of stimulus and orientation to examine which particular stimuli are driving these main effects. Results from these analyses are displayed in Fig. 1 and are consistent with past research demonstrating decreased accuracy with angles approaching 180°, and differences between stimulus letters based on mirror symmetry of letter features.

Given prior evidence on differences in medial versus lateral rotations (Ionta et al. 2013), we additionally conducted a two-way repeated measure ANOVA examining factors of group (synesthetes, controls) × rotation (clockwise rotations: 225°, 270°, 315° and counter-clockwise rotations: 45°, 90°, 135°) accuracy data. Results revealed a significant main effect of group [$F(1, 28) = 6.50$, $p < .05$], but neither a main effect of rotation [$F(1, 28) = 0.35$, $p = .56$], nor an interaction of group × rotation [$F(1, 28) = 1.56$, $p = .22$].

In contrast to the test of mental rotation ability, synesthetes and controls failed to differ on either test of working memory. Specifically, synesthetes' mean spatial working memory span of 2.13 (SD = 1.06) did not reliability differ from that of controls' (mean = 2.07, S.D. = 1.12), $t(28) = 0.17$, $p = .87$. Similarly, synesthetes' mean verbal working memory span of 3.18 (SD = 0.99) did not reliably differ from that of controls' verbal working memory score of 3.47 (SD = 0.97), $t(27) = 0.79$, $p = .44$.

Table 1 Individual subject performance for synesthetes and control subjects for each of the three tasks

																Mean
Controls																
Mental rotation accuracy (%)	90.0	98.6	71.4	95.7	50.0	88.6	87.1	82.9	94.3	97.1	88.6	52.9	52.9	70.0	51.4	78.1
Spatial working memory span	2.0	4.0	1.0	1.0	1.0	1.0	2.5	3.0	2.0	3.0	4.0	1.0	1.5	1.0	3.0	2.07
Verbal working memory span	2.5	2.5	2.5	2.5	2.5	3.0	3.0	3.5	3.5	3.5	3.5	4.5	5.0	5.0	5.0	3.47
Synesthetes																
Mental rotation accuracy (%)	95.7	85.7	95.7	97.1	95.7	98.6	85.7	78.6	97.1	95.7	77.1	95.7	84.3	95.7	81.4	90.7
Spatial working memory span	1.0	1.0	1.5	2.0	3.0	4.5	3.0	1.0	3.0	3.0	3.0	1.0	1.5	1.5	2.0	2.13
Verbal working memory span	1.0	1.5	2.5	3.0	3.0	3.0	3.0	3.5	3.5	4.0	4.0	4.0	4.0	4.5		3.18

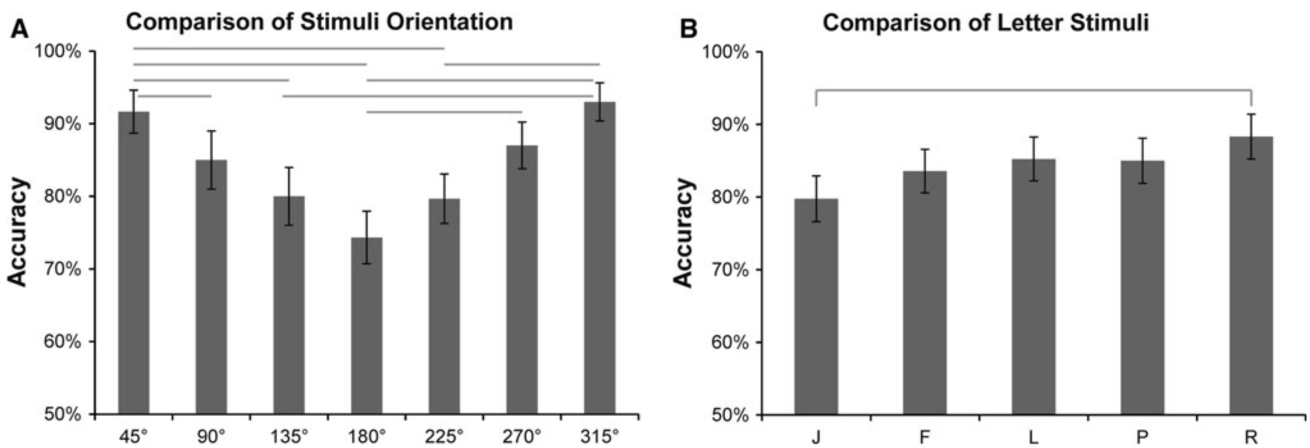

Fig. 1 Average subject accuracy in mental rotation task based on stimulus orientation (**a**) or letter (**b**). *Error bars* reflect standard error of the mean. Raised *horizontal gray lines* denote post hoc comparisons significant at $p < .05$, Bonferroni corrected

Discussion

These outcomes indicate that time-space synesthesia is associated with a greater-than-normal ability for the spatial imagery translation processes in mental rotation, but argue against an association between time-space synesthesia and enhanced spatial short-term working memory. The absence of group differences in either working memory test highlights the specificity of the mental rotation result and argues against the possibility that this finding is an artifact of group differences in motivation. Results of the present study thus speak to the issue of whether time-space synesthesia is associated with performance advantages in areas related to the synesthetic experience. Whereas time-space synesthetes do show enhanced memory for temporal events (Simner et al. 2009), the present results suggest these benefits do not extend to spatial memory.

The demonstration here of synesthetes' superior performance on mental rotation is consistent with results reported by Simner et al. (2009), but not with the null effect reported by Rizza and Price (2012). Given the dissociability of 2D and 3D spatial processes (Harris et al. 2000; Cohen et al. 1996), these differences might also reflect the use of a 2D mental rotation task here versus the 3D rotation tasks used in both prior studies. Estimates from our own lab suggest that approximately half of time-space calendars are 2D (unpublished observation taken from 120 synesthetes in our database), raising the possibility that the performance gains of these synesthetes would be limited to 2D mental rotation tasks like the one employed here. Future research should compare the performance of synesthetes who experience 2D versus 3D calendars on rotation tasks involving both two- and three-dimensional objects.

Results of the present study also contrast with previous reports of superior spatial working memory in time-space synesthesia (Brang et al. 2010; Simner et al. 2009). These prior reports might have been artifacts of motivational differences between the groups, or other confounds, such as their gender makeup. We find it more likely, however, that performance differences on the spatial recall task used by (Brang et al. 2010) and the visual patterns test used by (Simner et al. 2009) are attributable to synesthetes' superior spatial visualization rather than spatial memory per se. Indeed, our use of the spatial span task was motivated by the fact that it specifically targets spatial as distinct from visual processing ability (Shah and Miyake 1996).

Further, the dissociation observed here between synesthetes' performance on mental rotation and spatial span tasks is in keeping with the report that, in neurotypical adults, the neural substrate of spatial imagery and spatial working memory are somewhat different (e.g., Huyn and Luck 2007), with mental rotation tasks activating parietal areas, especially the intra-parietal sulcus, and spatial working memory relying on coordinated activations in frontal and parietal regions (Zimmer 2008). In fact, the importance of frontally mediated executive processes in spatial working memory argues against its relevance for the connectivity theory, that is, that time-space synesthesia arises due to an over-abundance of connections between parietal lobe structures important for the representation of time sequences and those utilized in the representation of space (Hubbard et al. 2005). Greater parietal connectivity in time-space synesthetes would not necessarily predict superior spatial working memory, but rather spatial processes with a more exclusive parietal lobe substrate.

Time-space synesthetes' superior mental rotation ability is consistent both with the connectivity theory of time-space synesthesia and with investigations of the normal population demonstrating a strong positive correlation between mental rotation ability and parietal connectivity (Wolbers et al. 2006). Given that increased neural connectivity has been documented for a number of forms of synesthesia (e.g., Rouw and Scholte 2007), increased parietal connectivity may provide a critical link to understanding the spatial calendars experienced by time-space synesthetes and the neural substrate of visuo-spatial imagery in the general population. Of course, this leaves open the issue of whether increased parietal connectivity is the primary cause of time-space synesthesia. Indeed, it remains possible that some unmeasured factor mediates the development of synesthesia, increased parietal connectivity, and the enhanced spatial visualization skills reported here.

Lastly, the present study is one of a handful to demonstrate superior performance among synesthetes without the explicit evocation of synesthesia (c.f. Banissy et al. 2009; Brang et al. 2012) suggesting the potentially beneficial nature of this condition. Time-space synesthesia has similarly been tied to enhanced attentional processes (Smilek et al. 2007; Teuscher et al. 2010), enhanced memory (Parker et al. 2006), and increased control of visual imagery (Price 2009; Rizza and Price 2012). These results provide further support for the association of synesthesia with superior perceptual (Banissy et al. 2009; Ramachandran and Hubbard 2001) and cognitive (Brang and Ramachandran 2010; Rothen et al. 2012) processes, arguably motivating the survival of these traits through evolution (Brang and Ramachandran 2011).

References

Banissy MJ, Walsh V, Ward J (2009) Enhanced sensory perception in synaesthesia. Exp Brain Res 196:565–571

Brang D, Ramachandran VS (2010) Visual field heterogeneity, laterality, and eidetic imagery in synesthesia. Neurocase 16:169–174

Brang D, Ramachandran VS (2011) Survival of the synesthesia gene: why do people hear colors and taste words? PLoS Biol 9:e1001205

Brang D, Teuscher U, Ramachandran VS, Coulson S (2010) Temporal sequences, synesthetic mappings, and cultural biases: the geography of time. Conscious Cogn 19:311–320

Brang D, Teuscher U, Miller L, Ramachandran V, Coulson S (2011) Handedness and calendar orientations in time-space synaesthesia. J neuropsychol 5:323–332

Brang D, Williams LE, Ramachandran VS (2012) Grapheme-color synesthetes show enhanced crossmodal processing between auditory and visual modalities. Cortex 48:630–637

Cohen MS, Kosslyn SM, Breiter HC, DiGirolamo GJ, Thompson WL, Anderson AK et al (1996) Changes in cortical activity during mental rotation a mapping study using functional MRI. Brain 119:89–100

Daneman M, Carpenter PA (1980) Individual differences in working memory and reading. J verbal learning verbal behav 19:450–466

Eagleman DM (2009) The objectification of overlearned sequences: a new view of spatial sequence synesthesia. Cortex 45:1266–1277

Galton F (1880) Visualised numerals. Nature 21:252–256

Harris IM, Egan GF, Sonkkila C, Tochon-Danguy HJ, Paxinos G, Watson JD (2000) Selective right parietal lobe activation during mental rotation. Brain 123:65–73

Hubbard EM, Piazza M, Pinel P, Dehaene S (2005) Interactions between number and space in parietal cortex. Nat Rev Neurosci 6:435–448

Huyn JS, Luck SJ (2007) Visual working memory as the substrate for mental rotation. Psychon Bull Rev 14(1):154–158

Ionta S, Sforza A, Funato M, Blanke O (2013) Anatomically plausible illusory posture affects mental rotation of body parts. Cogn Affect Behav Neurosci 13(1):197–209

Lohmann DF (1986) The effect of speed-accuracy tradeoff on sex differences in mental rotation. Percept Psychophys 39:427–436

Mann H, Korzenko J, Carriere JSA, Dixon MJ (2009) Time–space synaesthesia—a cognitive advantage? Conscious Cogn 18:619–627

Parker ES, Cahill L, McGaugh JL (2006) A case of unusual autobiographical remembering. Neurocase 12:35–49

Price MC (2009) Spatial forms and mental imagery. Cortex 45:1229–1245

Ramachandran VS, Hubbard EM (2001) Psychophysical investigations into the neural basis of synaesthesia. Proc Biol Sci 268:979–983

Rizza A, Price MC (2012) Do sequence-space synaesthetes have better spatial imagery skills? Maybe not. Cogn Process 13:299–303

Rothen N, Meier B, Ward J (2012) Enhanced memory ability: insights from synaesthesia. Neurosci Biobehav Rev 36:1952–1963

Rouw R, Scholte SH (2007) Increased structural connectivity in grapheme-color synesthesia. Nat Neurosci 10:792–797

Seron X, Pesenti M, Noël MP, Deloche G, Cornet JA (1992) Images of numbers, or "when 98 is upper left and 6 sky blue". Cognition 44:159–196

Shah P, Miyake A (1996) The separability of working memory resources for spatial thinking and language processing: an individual differences approach. J Exp Psychol Gen 125:4–27

Simner J, Mayo N, Spiller MJ (2009) A foundation for savantism? visuo-spatial synaesthetes present with cognitive benefits. Cortex 45:1246–1260

Smilek D, Carriere JS, Dixon MJ, Merikle PM (2007) Grapheme frequency and color luminance in grapheme-color synaesthesia. Psychol Sci 18:793–795

Teuscher U, McQuire M, Collins J, Coulson S (2008) Congruity effects in time and space: behavioral and ERP measures. Cogn sci 32:563–578

Teuscher U, Brang D, Ramachandran VS, Coulson S (2010) Spatial cueing in time-space synesthetes: an event-related brain potential study. Brain Cogn 74:35–46

Wolbers T, Schoell ED, Buchel C (2006) The predictive value of white matter organization in posterior parietal cortex for spatial visualization ability. Neuroimage 32:1450–1455

Zimmer HD (2008) Visual and spatial working memory: from boxes to networks. Neurosci Biobehav Rev 32:1373–1395