Musical space synesthesia: Automatic, explicit and conceptual connections between musical stimuli and space

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A B S T R A C T

In musical–space synesthesia, musical pitches are perceived as having a spatially defined array. Previous studies showed that symbolic inducers (e.g., numbers, months) can modulate response according to the inducer's relative position on the synesthetic spatial form. In the current study we tested two musical–space synesthetes and a group of matched controls on three different tasks: musical–space mapping, spatial cue detection and a spatial Stroop-like task. In the free mapping task, both synesthetes exhibited a diagonal organization of musical pitch tones rising from bottom left to the top right. This organization was found to be consistent over time. In the subsequent tasks, synesthetes were asked to ignore an auditory or visually presented musical pitch (irrelevant information) and respond to a visual target (i.e., an asterisk) on the screen (relevant information). Compatibility between musical pitch and the target's spatial location was manipulated to be compatible or incompatible with the synesthetes' spatial representations. In the spatial cue detection task participants had to press the space key immediately upon detecting the target. In the Stroop-like task, they had to reach the target by using a mouse cursor. In both tasks, synesthetes' performance was modulated by the compatibility between irrelevant and relevant spatial information. Specifically, the target's spatial location conflicted with the spatial information triggered by the irrelevant musical stimulus. These results reveal that for musical–space synesthetes, musical information automatically orients attention according to their specific spatial musical-forms. The present study demonstrates the genuineness of musical–space synesthesia by revealing its two hallmarks—automaticity and consistency. In addition, our results challenge previous findings regarding an implicit vertical representation for pitch tones in non-synesthete musicians.

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1. Introduction

Evidence for the relation between music and space has been documented in the literature for a long time. Pratt (1930) suggested that the connection between musical tones and spatial location is inherent in many languages (e.g., people describe notes of higher frequency simply as "high notes" and vice versa). This connection was further elaborated at the phenomenological level by Shepard (1982) who suggested a geometrical organization of the representation of musical pitch

tones in a complex helix. According to this model, the 12 semitones of an octave (i.e., pitch chroma) are represented by a spiral and the octaves (i.e., pitch height) are aligned on a vertical, linear plane. The vertical organization of the pitch height was validated recently, using a pitch discrimination task (Cohen Kadosh, Brodsky, Levin, & Henik, 2008). The authors demonstrated how discrimination of two pitch tones within a distance of one octave is faster compared with two pitch tones within a smaller interval. However, the authors did not address the question regarding the spatial representation of the pitches within the same octave. According to Warren, Uppenkamp, Patterson, and Griffiths (2003), distinct cortical mechanisms are responsible for processing these two processes of pitch representation.

Several works have shown that pitch implicitly affects peoples' spatial judgments and response times. Pratt (1930) showed that upon hearing musical tones of ascending pitch, one perceives movement, and that "higher" pitches are mapped to a higher segment of spatial space (Pratt, 1930; Roffler & Butler, 1968). Recently, Rusconi, Kwan, Giordano, Umiltà, and Butterworth (2006) showed how musical pitch tones are implicitly mapped on both vertical and horizontal meridians for musicians and on a vertical meridian for naïve participants. These implicit spatial representations affected participants' motor performance in comparison tasks. Since 2006, the so-called SMARC (spatial musical association of response code) effect has been replicated (Lidji, Kolinsky, Lochy, & Morais, 2007) and interpreted as a demonstration of an implicit "musical mental line" of pitches in space.
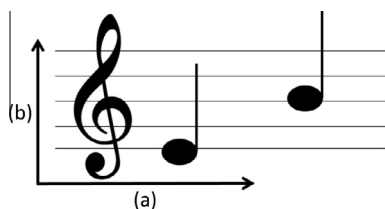
The interaction between space and non-spatial sequences is evident in a unique condition entitled synesthesia. The word synesthesia comes from Latin (*syn* = together, *aesthesia* = sensation) and literally means joined perception. Synesthesia is a fascinating condition in which a sensorial or conceptual stimulation in one modality (referred to as the "inducer") elicits an additional, atypical, experience in a second unstimulated modality (referred to as the "concurrent"). The inducer and concurrent can be of the same modality (e.g., seeing the number 7 induces perception of green) or bimodal (e.g., hearing a trumpet induces perception of yellow). The associations between inducer and concurrent must be automatic and consistent over time in order to meet the basic criteria of synesthesia.

In musical synesthesia, a stimulus from musical origin (e.g., pitch tone, interval or instrumental timbre) elicits an additional non-musical experience (e.g., color, taste or odor). One of the most documented types of musical synesthesia is tone-color synesthesia, also called chromesthesia (Carroll & Greenberg, 1961; Rogers, 1987; Ward, Tsakanikos, & Bray, 2006), or color-hearing (de Thornley, 2006; Peacock, 1985; Marks, 1975) where musical pitches are associated with colors (e.g., *Sol* is red).

In visuo-spatial types of synesthesia, ordinal sequences, such as numerals, graphemes, weekdays, and months, are consciously perceived as having a specific spatial arrangement. Recent studies have shown that symbolic inducers (e.g., numbers, months) can trigger shifts of attention automatically according to the inducer's relative position on the synesthetic spatial form (Diesendruck et al., 2011; Eagleman, 2009; Gertner, Henik, & Cohen Kadosh, 2009; Jarick, Dixon, Maxwell, Nicholls, & Smilek, 2009; Jarick, Dixon, Maxwell, & Smilek, 2008; Jarick, Dixon, Stewart, Maxwell, & Smilek, 2009; Price & Mentzoni, 2008; Sagiv, Simner, Collins, Butterworth, & Ward, 2006).

Recently it has been suggested that musical pitch tones can induce spatial locations much like other ordinal inducers (Linkovski, Akiva-Kabiri, Gertner, & Henik, 2012). In this type of synesthesia, called musical–space synesthesia, auditory pitch tones are visualized in spatially defined arrays. However, unlike the vertical and horizontal representation of musical pitch tones in the general population, our synesthete described a linear diagonal organization of pitch tones, where low pitches were represented on a lower left side of the space and high pitched tones were represented on an upper right position. This unique representation is in line with the modality of writing musical notation. Western musical notes are written from left to right and the frequency of a pitch tone is represented vertically, with higher pitches being written on higher segments of the musical staff. The combination of these two dimensions creates a diagonal pattern (Fig. 1). Recently, it has been suggested that the codification of spatial position of musical notes on a music staff is automatic and irrepressible (Grégoire, Perruchet, & Poulin-Charronnat, 2013).

The current work aims to study musical–space synesthesia in order to address three main goals: first, to verify the authenticity of this type of synesthesia by examining the criteria of automaticity and consistency; second, to reveal the differences in the spatial representation of pitch tones between musical–space synesthetes and non-synesthete matched controls; and third, to improve our understanding of the relationship between musical pitches and space in the general population.

Fig. 1. Separation of two musical dimensions; horizontal dimension (a) represents the left-to-right reading direction (e.g., the left note will be read before the right one). While the vertical dimension (b) represents pitch frequency with higher pitches mapped to higher positions on the musical staff. (e.g., the left note represents lower frequency than the right one).

2. Experiment 1: mapping task

Cytowic (2002) stated that once synesthetic connections are established they remain stable over the years. Thus, the first step to address the issue of authenticity in synesthesia was to test its consistency. This was done by a free mapping task in which the synesthetes were asked to spatially locate specific pitches on a computer display in two different sessions conducted one month apart. We anticipated finding a significant correlation between the spatial locations induced by identical stimuli in the two different sessions. Such a result would reveal that musical–space (M–S) synesthesia is consistent over time.

2.1. Method

2.1.1. Participants

Two synesthetes, SA (25 years old) and AB (23 years old), were right-handed females with 7 years and 12 years of formal musical training, respectively. SA and AB reported visualizing each musical pitch of a given octave in a distinct spatial location. Interestingly, both reported that the pitch tones rose up diagonally from lower left to upper right. Synesthesia was assessed using a short interview. During the interview the synesthetes were asked to draw a sketch that simulated their pitch organization. The synesthetes did not report other types of synesthesia apart from their musical–space synesthesia. In order to assure controls did not meet the criteria for musical–space synesthesia, they were asked if they could "see musical pitches in space". Afterwards, a description of the phenomenon was provided and they were asked again if any of the described features characterized them. Eight control participants were recruited. Controls were matched with the synesthetes for age and musical training. None of the control participants reported any kind of synesthesia.

All participants were also tested for absolute pitch and were found not to possess it (absolute pitch testing was adapted from Zatorre, 2003). Absolute pitch (AP) is the rare ability to identify musical pitches without any reference tone that serves as an external anchor. In the general population, processing music requires relative pitch (RP) ability, that is, the ability to recognize the intervals between two pitches. Hence, when hearing a musical pitch tone without any external reference, participants not endowed with AP are unable to recognize and label it (for a review see Levitin & Rogers, 2005).

Participants signed an informed consent and received a small monetary fee for their participation. The experiment was approved by the local ethics committee.

2.1.2. Apparatus

The experiment was built using E-prime version 1.3 (Psychology Software Tools) and carried out on a Dell computer with an Intel Pentium 4 processor. Stimuli were presented on a 19-inch Dell monitor. Each participant sat approximately 60 cm from the monitor. "Koss" UR-18 earphones were used for auditory presentation of the stimuli. All responses were collected via a Dell mouse.

2.1.3. Procedure

Stimuli consisted of visual musical notes or auditory pitch tones presented in two separate blocks—a visual block and an auditory block, respectively (Fig. 2). Participants were asked to use a mouse to indicate the spatial position (on a computer monitor) induced by the stimulus (for a similar procedure see Hubbard, Ranzini, Piazza, & Dehaene, 2009). Since participants did not possess absolute pitch, at the beginning of the auditory block, a sequence of four orienting chords of the C major scale (C-F-G-C) was played as a reference for recognizing the pitch tones that were to be presented in the subsequent trials. After hearing four chords, in the first trial the lowest note (C4, 261.62 Hz) was played. The second trial featured the highest note (B4, 493.88 Hz). These two trials were not analyzed. All subsequent stimuli were presented randomly. A trial entailed the participant hearing a single musical pitch tone and locating it on a blank screen using the mouse cursor. Each of the 7 pitch tones of the central C major scale (C4, D4, E4, F4, G4, A4, B4; equivalent in hertz to 261.62, 293.67, 329.63, 349.23, 392.00, 440.00, 493.88, respectively) was played 10 times, amounting to a total of 70 experimental trials.

The visual block procedure differed in stimuli presentation and lacked the opening chords since visual musical stimuli encompass all the information needed for their identification. Each trial began with a presentation of a visual musical note (e.g., Fig. 2). The participant was required to position the mouse cursor at the induced spatial location of the note. All analyzed notes were presented randomly, each one 10 times, amounting a total of 70 visual trials.

Block order was counter-balanced both within and between participants. Location was measured by collecting two spatial dimensions (X and Y coordinates) in every trial. All participants completed both blocks in two separate sessions approximately one month apart.

Fig. 2. Example of a visual musical note presented in the visual block. Reprinted from Linkovski et al. (2012). Copyright 2012 by Springer. Reprinted with permission.

2.2. Results

X and Y coordinates of spatial locations were averaged separately for each participant and every pitch tone/musical notation in a given session, resulting in 4 averages—two modalities in two sessions. All averages were transformed into vectors (X and Y coordinates of a spatial position were squared, summed and then a square root was taken). A Pearson correlation coefficient was calculated on vector sizes between sessions for each modality separately. For the synesthetes, all correlations were significant in both modalities. AB had an adjusted R^2 of .98 for musical notes ($p < .001$) and .99 for pitch tones ($p < .001$). SA had adjusted R^2 values of .97 ($p < .001$) and .99 ($p < .001$) for musical notes and for pitch tones, respectively. Fig. 3 illustrates the averaged spatial alignments of each synesthete in the visual and auditory mapping.

In order to assess average correlations for control participants and in order to evaluate consistency differences between the groups, a Fisher transformation was applied to all Pearson correlations. We then averaged the Fisher values for control participants for every modality and inversed the averages back to two Pearson correlations. The average correlation of control participants was .98 for visual notations and .92 for auditory tones.
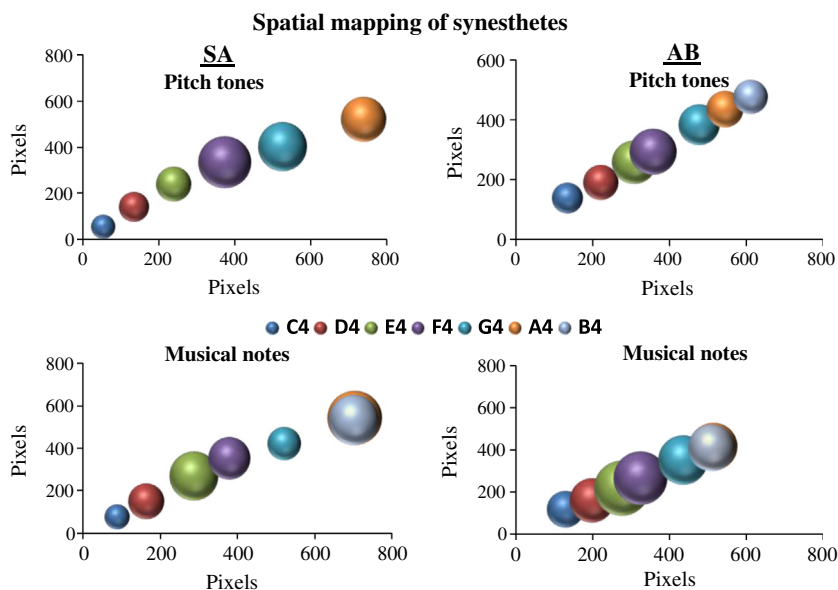
Two independent t-tests were used to contrast synesthetes and controls in the auditory and visual modalities. Results of the auditory task yielded a significant difference between the groups $t(8) = 2.57$, $p = .05$. Moreover, the consistency of both synesthetes was higher than every single control. In the visual task, consistency did not differ between the groups, $t(8) = .57$, *ns*. This null effect seemed to be caused by relatively higher correlations of the control group in this task.

2.3. Discussion

The current experiment assessed consistency of associations between musical stimuli and spatial representation in synesthetes and in control participants in a free mapping task. The significant correlations over time of AB and SA support the participants' subjective reports about the consistency of their spatial concurrent. This is sufficient to say that AB and SA meet the consistency criterion of synesthesia.

The relatively high correlations of the control group suggest that all musicians possess some degree of consistency in their spatial representation of musical stimuli. Associations between pitch tones and space are inherent to music and have been well established in the literature (Lidji et al., 2007; Marks, 1975; Rusconi et al., 2006). The fact these representations have some temporal consistency is intriguing and should be replicated by using larger samples of musicians as well as non-musicians.

The lack of difference in results between groups in the visual task may have resulted from a ceiling effect, or perhaps some strategy that participants adopted. All participants were non-absolute-pitch possessors; hence, they were unable to recognize tones without an external reference. In the visual task, the identity of the musical notes was given by the musical notation (i.e., Fig. 2), whereas, in the auditory task, participants were required to use their relative pitch ability in order to identify the tone. This process is less automatic compared with reading note names, and requires greater attentional resources in order to be carried out (see also Akiva-Kabiri & Henik, 2012). Therefore it is not surprising that correlations were higher in the visual task. However, we assume that sessions separated by longer durations of time (e.g., a year) may prove synesthetes to be more consistent.

Fig. 3. Spatial mapping of seven musical pitch notes completed by synesthetes SA and AB. Y and X axes represent actual coordinates in pixels. Bubble radius was determined by averaging standard deviation of the X and Y coordinates for each note. Spatial mapping of synesthete AB reprinted from Linkovski et al. (2012). Copyright 2012 by Springer. Reprinted with permission.

3. Experiment 2

As previously mentioned, automaticity is another crucial characteristic of synesthesia (Cytowic, 2002; Hochel & Milan, 2008; Ward & Mattingley, 2006). When adopting this principal to M–S synesthesia, in order to find out whether musical pitch tones constitute valid inducers, we aimed at illustrating that musical pitches automatically induce attentional shifting to the concurrent position of the pitch tones in external space. The current experiment was designed in order to address this matter by using a spatial cueing task adopted from Fischer, Castel, Dodd, and Pratt (2003). We tested a diagonal array based on our synesthetes' reports that were corroborated in Experiment 1. In addition, we used a vertical control task, based on previous findings of an implicit vertical representation of musical pitch tones in the general population (e.g., Lidji et al., 2007; Rusconi et al., 2006).

3.1. Method

3.1.1. Participants

The same two synesthetes participated in Experiment 2. Twelve control participants who did not participate in Experiment 1 were recruited. Control participants were matched for age and musical training. One failed to complete the tasks and was excluded from the analysis. The recruitment procedure was identical to that of Experiment 1. None of the control participants reported any kind of synesthesia and were found not to possess absolute pitch ability (absolute pitch testing was adapted from Zatorre, 2003).

3.1.2. Stimuli

The auditory stimuli were composed of 2 synthesized low-pitched tones (C4 and D4) and 2 high-pitched tones (A4 and B4) that were taken from the same middle octave in order to eliminate a possible confound of different pitch heights.
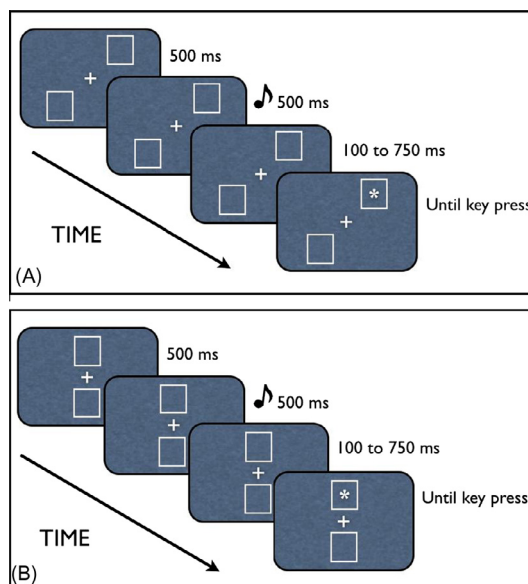
The visual stimuli were presented on a black screen and consisted of a white fixation cross located at the center of the screen and two white boxes located on the perimeter at opposite sides of each other. The experiment was composed of two tasks: a diagonal task and a vertical task. In the diagonal task, the boxes were positioned diagonally, in the top right and bottom left corner of the screen, approximately 10 cm apart. In the vertical task, the boxes were positioned vertically above and below the fixation cross. The detection target was composed of a white asterisk that appeared in one of the two boxes in 2/3 of the trials.

3.1.3. Apparatus

The apparatus was identical to what was used in Experiment 1.
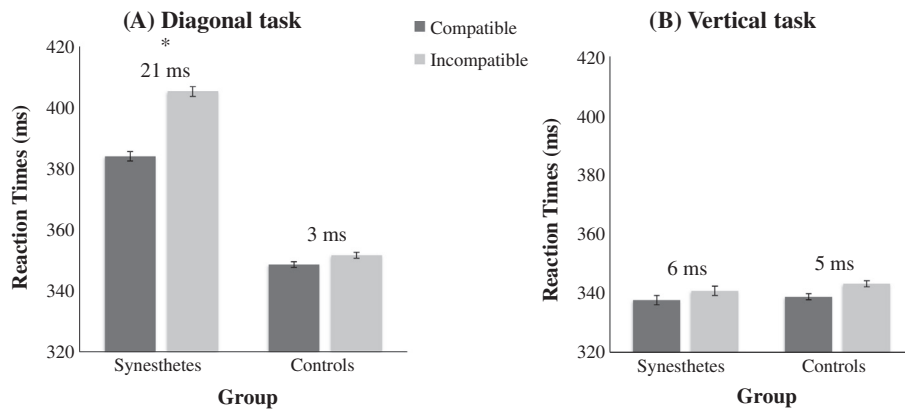
3.1.4. Procedure

Participants were asked to ignore the auditory pitch tone (cue) and respond as fast as possible to the appearance of an asterisk (target) by pressing the spacebar (Fig. 4). Participants were asked not to respond in trials where no target appeared.

Fig. 4. Time course of a typical trial in the diagonal task (A) and in the vertical task (B).

Fig. 5. (A) Mean reaction times for synesthetes and controls in the diagonal task. (B) Mean RTs for synesthetes and controls in the vertical task. RTs are presented as a function of group and validity. Bars represent standard errors. *Indicates a significant difference, $p < .01$.

Table 1
Results of synesthetes and control participants for the various conditions in experiment 2.

SOA	Conditions							
	Invalid				Valid			
	100	250	500	750	100	250	500	750
Diagonal task								
Synesthetes								
RT	430	407	388	396	394	398	369	375
SD	(78)	(86)	(86)	(91)	(98)	(106)	(77)	(72)
Controls								
RT	369	348	356	364	366	351	348	365
SD	(39)	(34)	(36)	(40)	(38)	(36)	(37)	(40)
Vertical task								
Synesthetes								
RT	360	334	324	325	361	330	310	320
SD	(58)	(62)	(64)	(56)	(65)	(53)	(56)	(60)
Controls								
RT	350	334	335	357	350	335	329	344
SD	(42)	(46)	(46)	(48)	(46)	(42)	(44)	(49)

Note. Reaction time (RT), standard deviation (SD) and stimulus onset asynchrony (SOA) are in milliseconds.

The target appeared after one of four variable delays (100 ms, 250 ms, 500 ms, and 750 ms). Half of the trials were valid and half were invalid with respect to cue-target validity. There were two different tasks: a diagonal (Fig. 4A) and a vertical (Fig. 4B) task. Cue-target validity was determined according to the synesthete's spatial pitch-form in the diagonal task and according to previous findings (see Rusconi et al., 2006) in the vertical task. The two tasks were conducted in separate sessions approximately a week apart.

Within each task, each musical pitch appeared 4 times in the compatible location and 4 times in the incompatible locations for each of the four SOAs, resulting in 128 trials for each task (4 notes X 4 repetitions X 2 compatibility X 4 SOAs). In addition, for each pitch, 8 catch trials were presented without any following visual target (resulting in 32 catch trials for each task). Both tasks began with 20 training trials. Thus, the entire experiment had 360 trials (i.e., 2 tasks X 160 experimental trials + 40 training trials). Participants were asked to ignore the auditory cue and respond to the visual target as fast as possible and refrain from responding when a visual target did not follow the auditory cue.

3.2. Results

Reaction time (RT) was defined as the time recorded from the onset of the target asterisk until the participant pressed the space bar. Mean RTs were calculated for each participant in every condition. In order to remove possible outliers, for each participant, RTs that were above or below 3 standard deviations from participant's mean were removed from analysis. In total, RTs of 73 trials were removed from analysis (less than 2% of the total valid trials). In order to compare two synesthetes to twelve control participants, the two synesthetes completed two sessions of the task a month apart with every session entered into the analysis separately (for a similar logic of analysis see Cohen Kadosh & Henik, 2006). For each task

(diagonal and vertical), a three-way analysis of variance (ANOVA) (2 X 2 X 4) was performed with validity (valid vs. invalid) and SOA (100 ms, 250 ms, 500 ms and 750 ms) as within subjects factors and group (synesthetes and controls) as a between subjects factor. RTs as a function of group and validity are presented for each task in Fig. 5 (see also Table 1).

The diagonal task yielded a significant main effect for validity, $F(1,13) = 8.59$, $MSE = 364$, $p < .05$, with slower RTs for invalid trials compared with valid trials, and a significant main effect for SOA, $F(3,39) = 5.6$, $MSE = 434$, $p < .01$, with slower RTs for faster SOAs. In contrast, the main effect for group was insignificant, $F(1,13) = 2.1$, $MSE = 14,255$, $p = .16$, ns.

Furthermore, a significant interaction between group and validity was found, $F(1,13) = 6.07$, $MSE = 364$, $p < .05$ (Fig. 5). Planned comparisons showed a significant validity effect of 21 ms for the synesthetes, $F(1,13) = 9.92$, $MSE = 364$, $p < .01$, but not for controls, $F < 1$, ns. For the synesthetes, shorter RTs were observed for valid (e.g., low pitch followed by a lower-left asterisk and high pitch followed by an upper-right asterisk) than for invalid (e.g., low pitch followed by an upper-right asterisk) trials.

In the vertical task, a main effect of validity was observed, $F(1,13) = 5.08$, $MSE = 125$, $p < .05$, with slower RTs for invalid compared with valid trails. Separate analyses for each group did not show a statistically significant effect for synesthetes, $F(1,13) = 2.08$, $MSE = 125$, $p = .17$, ns, or for controls, $F(1,13) = 3.9$, $MSE = 125$, $p = .07$ ns. These simple validity effects were not statistically significant, although for controls the validity effect approached significance. In addition, the interaction between validity and group was insignificant, $F < 1$, ns (Fig. 5). A significant main effect was observed for SOA, $F(3,39) = 10.85$, $MSE = 357$, $p < .001$, with slower RTs for faster SOAs. No other interaction with compatibility was significant.

3.3. Discussion

In Experiment 2 we aimed to reveal the automaticity of attention shifting in synesthetes and controls by using an auditory cue detection task. Results yielded a significant validity effect in the diagonal task (i.e., the task that corresponded to the synesthetes' pitch representation) for synesthetes but not for controls. This finding corroborates our hypothesis that synesthetes are unable to suppress spatial shifts of attention in response to auditory cues, in spite of explicit instructions to ignore these cues. These results suggest that in musical–space synesthesia, a pitch tone automatically orients attention to the spatial position associated with that pitch. The present study extends previous findings (Jarick et al., 2009) suggesting that the shift of attention in response to a synesthetic inducer is automatic and impossible to suppress. Hence, pitch tones are another type of inducer that triggers shifts of attention involuntarily according to the rigid spatial pitch representation of the synesthete.

Unlike synesthetes, controls did not show any significant cueing effect in either the diagonal or vertical task, although the validity effect in the vertical task approached significance. These finding are surprising since it has been demonstrated that pitch tones are implicitly represented vertically in the general population (Lidji et al., 2007; Nishimura & Yokosawa, 2009; Rusconi et al., 2006). Yet, a deeper examination of the literature revealed that the cueing effect has not always been replicated (Galfano, Rusconi, & Umiltà, 2006; Jarick et al., 2009; Ristic, Wright, & Kingstone, 2006). In addition, non-synesthetes infer these spatial representations of musical stimuli only implicitly. It is possible that the cue detection task is not sensitive enough to reveal the implicit spatial–musical associations in non-synesthetes.

When or at what processing level are the associations between musical pitch tones and space created? Specifically, these associations could be induced by a primary auditory property of the pitch tones (i.e., the frequency of the pitches), which would suggest that the cross-modal interaction occurs at an early stage of perception and is mediated by the primary auditory cortex. Alternatively, it might be that such associations are created at a conceptual level. The latter suggests that the cross-modal interaction involves multimodal associative brain areas. Experiment 3 was designed to answer this question.

4. Experiment 3

Experiment 3 had two goals: first, to strengthen our previous findings regarding automaticity of musical–space synesthesia by using a different task—a spatial Stroop-like task; and second, to explore the origin of the compatibility effect in synesthetes. In particular, we aimed to test whether the synesthetic association originates at an auditory perceptual level or at a semantic conceptual level. In the latter case, such an association is mediated by the identity of the pitch. The present experiment included two different tasks. The first task was auditory, and the second task was visual, with musical pitches presented visually as notes on a musical staff.

Unlike in Experiment 2 where only the extreme musical pitches (i.e., highest and lowest auditory pitches) of the diatonic scale were used, the present experiment employed pitch tones from the entire musical scale. This was done in order to demonstrate the exact correspondence of each one of the pitches to a certain position in space and not only a rough distribution of high and low pitch tones. Participants were presented with four musical pitches that either preceded or appeared simultaneously with an asterisk (i.e., target). The asterisk could appear either at a location that corresponded to the note position on the synesthetic pitch-form (i.e., a compatible condition) or at a conflicting location (i.e., an incompatible location).

We postulated that synesthetes would demonstrate a significant compatibility effect in the auditory and visual tasks (i.e., slower RTs in incompatible trials than in compatible ones). In addition, we aimed at exploring whether the diagonal mental representation of the musical pitches is unique to synesthetes or whether it is inherent also in non-synesthete controls.

4.1. Method

4.1.1. Participants

Two synesthetes who took part in the previous experiments and a new control group of 8 undergraduate students from Ben-Gurion University of the Negev participated in the current experiment. Control participants matched the synesthetes in age, musical training and handedness. All participants were tested for absolute pitch and were found not to possess it (absolute pitch testing was adapted from Zatorre, 2003). All participants signed an informed consent and received either a small monetary fee or course credits.

4.1.2. Apparatus

The same apparatus that used in Experiments 1 and 2 was used in Experiment 3.

4.1.3. Procedure

The experiment consisted of two tasks, each composed of a different class of inducers: auditory and visual. The auditory task utilized four pitch tones of the C major scale (C4, E4, G4, B4) as inducers. They were chosen because most of them are equally spaced across the scale. The stimuli of the visual task were musical notations of the same pitches (Fig. 1).

As in Experiment 1, tasks began with 4 orienting chords of the C major scale (C-F-G-C), in order to permit the participants to recognize the subsequently presented pitch tones. A trial began with a fixation circle appearing in the lower right segment of the screen, indicating the initial point from which the participants should start their response. Once a participant moved the mouse cursor to the fixation circle, a musical stimulus was presented for 150 ms. For the auditory task, an auditory pitch tone was presented and for the visual task, a musical staff with one of the possible 4 notes (Fig. 2) was presented in the lower right segment of the screen. Presentation of the musical stimulus was accompanied with four empty squares (see Fig. 6). The squares' locations represented the different synesthetic spatial positions of the four pitch tones of C4, E4, G4, and B4 (in Hz: 329.63, 261.62, 392.00 and 493.88, respectively) and were adjusted to each synesthete according to her mapping in Experiment 1. Control participants were randomly assigned to a synesthete's spatial mapping (four controls to each synesthete). After a varied SOA (0 ms, 250 ms, 500 ms, 750 ms) a target asterisk emerged inside one of the squares.

The asterisk could appear in a compatible location (e.g., lower-left-hand square for C4) or an incompatible location (e.g., upper-right-hand square for C4). In the auditory task, participants were instructed to ignore the musical pitch tone and reach for the asterisk using the mouse cursor. In the visual task, participants were asked to ignore the written musical note and reach the target using the mouse cursor.

Each note appeared three times in the compatible location and one time in each incompatible location for each of the four SOAs, resulting in 96 trials for each task (4 notes X 3 repetitions X 2 compatibility X 4 SOAs). Both tasks began with 12 training trials. Thus, the entire experiment had 216 trials (192 experiential + 24 training).

Reaction time was defined as the time recorded from the onset of the target asterisk until the participant clicked one of the mouse buttons. A response was considered accurate only if the participant hit the target asterisk.

4.2. Results

The average error rates of the synesthetes were .07 (AB) and .21 (SA), and the average of the control group was .06 (see Table 2). Analysis of RTs was conducted as follows: a separate mixed three-way ANOVA (2 X 2 X 4 experimental design) was applied to each of the tasks (auditory, visual) with group (synesthetes, non-synesthetes) as a between subjects variable and compatibility (compatible, incompatible) and SOA (0 ms, 250 ms, 500 ms, 750 ms) as within subject variables. Removal of possible outliers was conducted as follows: for each participant, RTs that were above or below 3 standard deviations from participant's average RT were removed from analysis. In total, RTs of 20 trials were removed from analysis (less than 1% of the total valid trials). In order to compare two synesthetes to eight control participants, the two synesthetes completed two
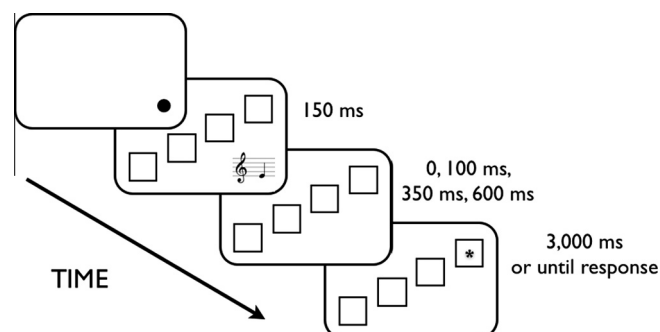

Fig. 6. Illustration of a visual trial.

Table 2
Results of synesthetes and control participants for the various conditions in experiment 3.

SOA	Conditions							
	Incompatible				Compatible			
	0	250	500	750	0	250	500	750
Auditory task								
Synesthetes								
RT	789	705	669	661	766	665	569	581
SD	(138)	(121)	(157)	(132)	(150)	(130)	(168)	(140)
Errors	2%	25%	21%	15%	17%	8%	6%	17%
Controls								
RT	837	818	804	794	849	795	730	715
SD	(193)	(221)	(209)	(234)	(202)	(204)	(184)	(216)
Errors	3%	6%	9%	12%	8%	6%	6%	9%
Visual task								
Synesthetes								
RT	900	799	718	692	856	757	612	537
SD	(136)	(139)	(164)	(179)	(132)	(140)	(138)	(177)
Errors	12%	15%	19%	19%	12%	15%	15%	12%
Controls								
RT	861	797	786	753	858	793	731	747
SD	(120)	(123)	(166)	(130)	(119)	(137)	(144)	(165)
Errors	7%	5%	3%	5%	3%	5%	5%	6%

Note. Reaction time (RT), standard deviation (SD) and stimulus onset asynchrony (SOA) are in milliseconds.

sessions of the tasks a month apart with every session entered into the analysis separately (for similar logic see Cohen-Kadosh & Henik, 2006).

In the auditory task, a significant compatibility effect of 51 ms was found, $F(1, 10) = 9.71$, $MSE = 5,699$, $p = .01$, with compatible trials faster than incompatible trials for both synesthetes and controls. Separate planned comparisons of the compatibility effect in each of the groups yielded similar significant effects: synesthetes exhibited a compatibility effect of 61 ms, $F(1, 10) = 5.19$, $MSE = 5,699$, $p < .05$, while a smaller effect of 44 ms was evident for control participants, $F(1, 10) = 4.74$, $MSE = 5699$, $p = .05$ (Fig. 7). A two-way interaction between compatibility and SOA was significant, $F(3, 30) = 3.25$, $MSE = 2464$, $p < .05$. The compatibility effect was evident only in long SOAs (e.g., 500 ms, and 750 ms). Planned comparisons of the compatibility effect for the different SOAs revealed that a compatibility effect was present in long SOAs, in both groups, $F(1, 10) = 6.8$, $MSE = 6865$, $p < .05$ and $F(1, 10) = 4.7$, $MSE = 6865$, $p = .055$, for control participants and synesthetes, respectively.

Results of the visual task were quite different. A significant two-way interaction between group and compatibility was found, $F(1, 10) = 15.7$, $MSE = 1673$, $p < .01$. Further analysis of this interaction revealed a significant compatibility effect of 87 ms for synesthetes, $F(1, 10) = 35.9$, $MSE = 1673$, $p < .001$, but not for controls, $F(1, 10) = 2.55$, ns (Fig. 7). The synesthetes' compatibility effect was evident at short SOAs (i.e., 0 ms, 250 ms; $F(1, 10) = 12$, $MSE = 608$, $p < .01$) and at long SOAs (i.e., 500 ms, 750 ms; $F(1, 10) = 18.33$, $MSE = 3715$, $p < .01$) (Fig. 8).
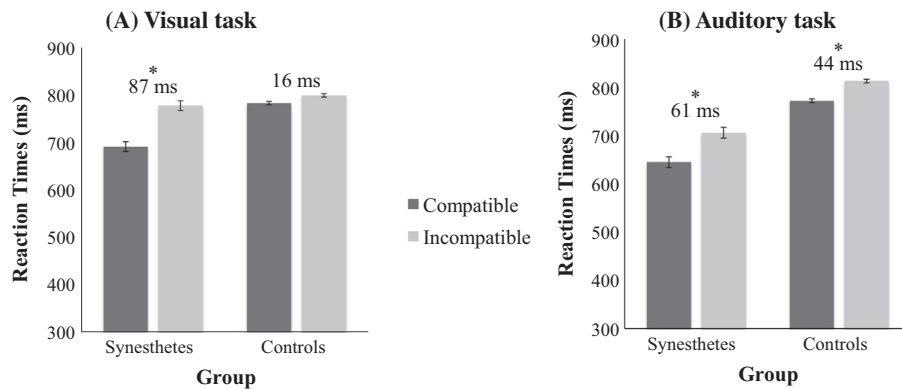
Error rates were subjected to the same three-way ANOVA with group as a between subject variable and SOA and compatibility as within subject variables for each task separately. No significant differences were found in the visual task and in the auditory task. These results indicate that differences in RT could not be accounted for by differences in error rates.
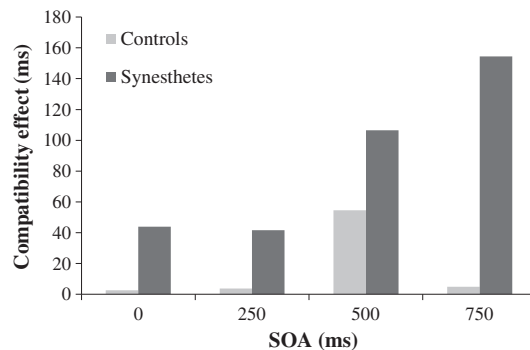
4.3. Discussion

In Experiment 3 we used two versions of a Stroop-like task in order to study musical–space synesthesia. The results converged and extended our findings from the two previous experiments, showing a compatibility effect for synesthetes in both auditory and visual tasks. However, in the auditory task, controls also exhibited a similar compatibility effect whereas in the visual task only synesthetes were affected by the compatibility. The compatibility effect was generally greater at long SOAs.

The existence of the compatibility effect in the auditory task suggests that irrelevant auditory pitch tones orient attention to the relative position of the pitch on a virtual diagonal plane. Both synesthetes and controls were faster to move the mouse cursor to the target when the auditory pitch tone was compatible with the relative position of the pitch tone on the diagonal array compared with the incompatible condition. The present results suggest that diagonal representation of auditory pitch tones is common in the general population and is not exclusive to synesthetes. This is surprising because previous research suggested that pitch representation in the general population was vertical or horizontal but not diagonal (Lidji et al., 2007; Nishimura & Yokosawa, 2009; Rusconi et al., 2006).

In addition, the present results suggest that auditory pitch tones are automatically associated with a diagonal spatial array not only for synesthetes but for controls as well. However, there are also some important differences between these groups. Synesthetes report their associations explicitly whereas non-synesthetes are unaware of these representations, which are evident only under certain experimental conditions. In fact, in the present work, non-synesthetes showed a compatibility effect only in the Stroop-like task and not in the cue detection task that was proven to be less sensitive and

Fig. 7. (A) Mean reaction times for synesthetes and controls in the visual task. (B) Mean RTs for synesthetes and controls in the auditory task. RTs are presented as a function of group and compatibility. Bars represent standard errors. *Indicates a significant difference, $p < .05$. Bars represent standard errors.

Fig. 8. Size of compatibility effects of different SOA's in the visual task for synesthetes and control participants.

whose results were more difficult to replicate (Galfano et al., 2006; Jarick et al., 2009; Ristic et al., 2006). Furthermore, for synesthetes spatial representation of the musical tones was elicited also in the visual task, where musical tones were presented visually in the absence of a direct auditory stimulation.

The different patterns of compatibility effects could shed some light on the origin of the associations between music and space. It is possible to suggest that for non-synesthetes, spatial representation of pitch is related to the perceptual auditory dimension of the pitch, whereas for synesthetes, the mental representation of pitches is elicited both by the perceptual auditory dimension but is also elicited in the absence of any auditory stimulation. Hence, the spatial association could also be related to a more conceptual level of the musical tone identity or its position on the musical staff. This idea is also supported by our findings from both Stroop-like tasks, which showed a larger compatibility effect for longer SOAs and will be further elaborated on in the general discussion.

5. General discussion

The current work set out to deepen our understanding of this phenomenon. In order to do so, two M–S synesthetes preformed: (a) a spatial mapping task of their musical pitch tones in order to verify consistency, (b) a cue detection task in order to test automaticity, and (c) a Stroop-like task in order to test the origin of musical–space synesthesia. The synesthetes' results were compared to those of matched controls. This discussion will address the three main research questions: (a) Does M–S synesthesia meet the criteria of consistency and automaticity (as is the case with other types of synesthesia)? (b) What are the differences between spatial–musical associations of M–S synesthetes and of non-synesthete musicians? (c) What aspect of the inducer—perceptual or conceptual—triggers the spatial concurrent?

In Experiment 1, synesthetes' spatial concurrents were found to be consistent over time. Experiment 2 revealed an auditory validity effect only for synesthetes in the diagonal task but not for control participants. Experiment 3 demonstrated an auditory compatibility effect for all participants, while for musical written notes, a compatibility effect was evident only for the synesthetes. The results of our three experiments show converging evidence for the authenticity of music–space synesthesia. The present study suggests that a diagonal representation of the auditory musical scale is common both for synesthetes and matched controls that are non synesthetes. However, as suggested, unlike controls, synesthetes' associations

are explicitly reported and are more consistent over time (see Experiment 1). Furthermore, our findings suggest that unlike the spatial musical associations in the control group, synesthetic associations are automatically elicited, impossible to suppress even under more rigid experimental conditions (e.g., cue detection task, Experiment 2) and are elicited even in the absence of an auditory tone (see the visual task of Experiment 3). Taken together, the above mentioned reasons suggest that the associations between musical notations and spatial positions represent a genuine demonstration of synesthesia in which auditory pitch tones and musical notes elicit explicit spatial locations. The present study also demonstrates weaker associations between music and space for non-synesthete control participants.Cross-modal associations between pitch and other non-musical dimensions are well documented in the literature (Marks, 1987). Furthermore, the association between space and auditory tones was suggested in several studies. In 2006, Rusconi and her colleagues demonstrated the association between spatial response codes and auditory tones. This was replicated a year later by Lidji and colleagues (Lidji et al., 2007). The authors suggested that auditory tones are mentally represented in a spatial array similar to the mental number line (Dehaene, 1992), with a vertical spatial representation of musical pitches in the general population, and an additional horizontal representation of pitches in musicians. Unlike these suggestions, in the present study a diagonal pitch representation rising from left to right was found both for synesthetes and controls. This diagonal organization of the pitches could be related to the musical notation system, which is a combination of the left-to-right reading system, together with the vertical organization of pitches on the musical staff, with lower pitches at lower positions of the staff and high pitches at higher positions.

Writing direction has already been proven to be a crucial factor in mental representations of other ordinal stimuli (i.e., numbers – Dehaene, Bossini, & Giraux, 1993; Shaki & Fischer, 2008; Zebian, 2005; months – Gevers, Reynvoet, & Fias, 2003). In the musical domain, Stewart, Walsh, and Frith (2004) suggested that the automaticity of music reading involves the building of a spatial representation of music and its extension outside the music reading context. In a recent study, Grégoire et al. (2013) demonstrated that the association between pitch and spatial position is inherent to the music reading system. Accordingly, the codification of spatial position of musical notes on a staff is automatic and irrepressible. Taken together, it is possible to suggest that the cross-modal associations between these two seemingly independent dimensions (e.g., pitch and space) are based on previous experience (music reading). Accordingly, the organization of the reading system and musical training could affect spatial representation in musically trained participants. Hence, it is not surprising to find a diagonal representation of the musical pitches also in musically trained participants who are not synesthetes.

In the cue detection task, the validity effect was significant only for synesthetes in the diagonal task but not in the vertical task, suggesting that auditory pitch tones automatically oriented attention to an external spatial position. There are two interesting points about these results. First, the validity effect was present although no relative pitch anchor was given in order to enhance absolute identification of the auditory cues. Participants were all non-absolute-pitch (AP) possessors; hence, they were unable to recognize auditory pitch tones without an external reference point. Second, although four different auditory cues were presented (two high pitches and two low pitches), the target could appear only in two possible locations on the screen (high and low position), suggesting that attentional orientation is related to a relative position of the pitch tone in space and not to the specific spatial location, associating high pitches to upper right spatial positions and low pitches to lower left spatial positions. In fact, Eagleman (2009) highlighted the importance of the simple ordinality of the inducers in sequence-space synesthesia and emphasized that adjacent elements maintain close relationships also on the spatial array. According to this view, it is possible to suggest that the associations between pitch and space in music–space synesthesia are based on the relations between pitches and not on the absolute identity of the pitch. Hence, in order to associate pitch with space, relative pitch ability is necessary; thus, it is not surprising to find auditory associations in synesthetes and control participants who are not AP possessors.

The Stroop-like task results demonstrated the spatial representation of auditory pitch tones both for synesthetes and controls. The associations were made between four pitches and four different specific spatial positions. Furthermore, the auditory pitch tones had a closer interval, they were distributed along inner positions of the musical scale, and four orienting chords were presented at the beginning of each task in order to give a relative pitch anchor. In contrast, in the cue detection task, the four auditory pitch tones where taken from the lowest and highest parts of the musical scale and the visual target could appear only at one of two extreme spatial positions of the diagonal (lower left or higher right). Taken together, it seems that the Stroop-like task was more sensitive and revealed the implicit association between musical pitch tones and space in non-synesthete musicians. Cohen Kadosh and Henik (2007) suggested that at least to some extent, synesthetic and normal processes are identical and differ only in the level of awareness. The present results suggest that the controls' auditory compatibility effect reflects an implicit mental pitch line that is identical to that of the synesthetes. This means that the spatial representations of pitch tones that are explicit and spontaneously reported by synesthetes exist also in non-synesthete musicians but are manifested only under specific experimental conditions.

Unlike in the auditory task, in the visual task musical pitch tones were presented as written notes. In this task only synesthetes presented a significant compatibility effect. Here, pitch identity was inherent to the stimulus and musical–space associations were created on a semantic level, without involvement of a direct auditory stimulation. This type of association characterizes *higher* synesthesia. Hubbard and Ramachandran (2005) theorized that synesthetic connections of such synesthetes occur at a late stage of perception and involve parietal areas. Results of Experiment 3 herein support the temporal aspect of *higher* synesthesia––synesthetes exhibited a greater compatibility effect for longer SOAs (Fig. 8), meaning that post perceptual elaboration (or possible identification of the musical note) increased the difficulty to ignore the irrelevant musical note. Further corroboration was provided in a recent study by Teuscher, Brang, Ramachandran, and Coulson (2010) demonstrating electrophysiological differences between time–space synesthetes and a control group only in post perceptual stages.

Teuscher et al. did not report a localization of the aberrant components (i.e., p3b and pSW) but these components were previously presumed to originate from the temporo-parietal cortices. Another possible anatomical location that may be involved in M–S synesthesia is the posterior parietal cortex, based on prior works tracing space and ordinal sequences to this area (Cohen Kadosh & Gertner, 2012).

To summarize the main implications of our study, M–S synesthesia is a genuine phenomenon. Taken together, our results suggest that musicians, synesthetes and non-synesthetes associate ascending musical pitch tones to an ascending diagonal spatial array. Synesthetes' associations are explicitly reported and are based on both auditory and semantic levels. In contrast, for non-synesthetes the associations are implicit and are related to an auditory level. Future research should replicate current findings using larger samples and possibly using a different way to verify the identification of auditory pitch tones. Employing vertical and horizontal alignments in a Stroop-like task would allow checking for the existence of other possible spatial representations of pitch tones. Imaging studies of M–S synesthetes are another promising line of future research since they could shed light on the involvement of specific posterior parietal regions in spatial aspects of music perception.

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