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Brief article

Where music meets space: Children's sensitivity to pitch intervals is related to their mental spatial transformation skills

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ABSTRACT

Relations have been found among various continuous dimensions, including space and musical pitch. To probe the nature and development of space-pitch mappings, we tested 5- to 7-year-olds and adults ($N = 69$), who heard pitch intervals and were asked to choose the corresponding spatial representation. Results showed that children and adults both mapped pitches continuously onto space, although effects were stronger in older than younger children. Additionally, children's spatial and numerical skills were tested, showing a relation between children's spatial and pitch-matching skills, and between their spatial and numerical skills. However, pitch and number were not related, suggesting spatial underpinnings for pitch and number.

1. Introduction

In Western cultures, we map auditory pitch onto vertical space, as shown by our musical notation system and use of spatial metaphors to describe musical concepts. Adults also *think* about pitches in spatial terms, responding faster for congruent pairings such as high-frequency pitches and higher spatial positions (Ben-Artzi & Marks, 1995; Melara & O'Brien, 1987). Similar congruence effects are found when adults respond to higher pitches with a higher response key and to lower pitches with a lower response key (Lidji, Kolinsky, Lochy, & Morais, 2007; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). Such findings are strengthened by studies showing adults' continuous space-pitch mappings (Casasanto, 2010; Dolscheid, Shayan, Majid, & Casasanto, 2013).

One possible explanation for this connection is that continuities are processed within a single neural mechanism (Walsh, 2003). Support for this general magnitude system comes from neuroimaging data showing that different types of comparisons are processed within overlapping neural areas (Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Pinel, Piazza, Le Bihan, & Dehaene, 2004). Accordingly, adults' processing of various magnitudes share distinctive characteristics: adults are faster and more accurate at differentiating magnitudes when the difference between them increases (i.e., the distance effect; Pinel et al., 2004).

What are the origins of space-pitch mappings? Research suggests that a general magnitude system emerges early in life. Nine-month-olds showed cross-dimensional transfer between numerical and spatial magnitudes (e.g., Lourenco & Longo, 2010). Infants also showed space-pitch connections, looking longer at congruent space-pitch mappings than incongruent pairings (Dolscheid, Hunnius, Casasanto, & Majid, 2014; Walker et al., 2010). Similarly, kindergarteners pointed more often to lower quadrants for lower pitches and higher quadrants for higher pitches when asked to point to the quadrant from which a centrally-presented pitch came (Roffler & Butler, 1968). Another study found that preschoolers matched pitches with sizes, associating higher pitches with smaller sizes (Mondloch & Maurer, 2004; see Eitan & Timmers, 2009, for similar results with adults).

Although these studies indicate an early space-pitch connection, the precise nature of this correspondence remains unclear. Space-pitch mappings were typically tested with events in which *dichotomous* spatial information was combined with pitch information. Therefore, it is unknown whether children's space-pitch transfer is solely categorical or based on a *continuous* mapping. The present study aimed to investigate children's processing of various pitch intervals and their relation to spatial information.

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Five- to 7-year-olds heard a pitch interval and were asked to choose the correct spatial counterpart from two visual displays (see Fig. 1). We measured children's response times (RTs) and percentage of correct trials (accuracy), expecting performance to exceed chance only if they could accurately map pitch intervals onto space. Additionally, we investigated whether children's pitch processing showed a distance effect similar to adults' pitch discrimination (Cohen Kadosh, Brodsky, Levin, & Henik, 2008) and other magnitudes (Holloway & Ansari, 2008).

We also explored two stronger implications of a space-pitch relationship. First, we asked whether children with better spatial skills may map *pitch intervals* more accurately onto corresponding *spatial magnitudes*. Second, we asked whether children's mathematical knowledge may relate to children's pitch-matching skills. Previous studies indicated that spatial and mathematical reasoning are closely linked (for a review, see Mix & Cheng, 2012). Thus, a similar connection might exist between number and pitch, consistent with the view that continuous dimensions are coded in a common framework. Contrariwise, spatial thinking may underlie each, resulting in a weaker connection between number and pitch, because spatial thinking may not account for enough shared variance to support a reliable connection.

2. Methods

2.1. Participants

Fifty-three 5- to 7-year-olds served as participants[2] (see Table 1). Three additional children were excluded from the final sample for experimenter error. No child had music training[3]. Sixteen adults were tested to obtain a mature reference for the pitch-matching task. Their music experience ranged from 0 to 7 years. Thus, no adult met the criterion for being a musician (having at least 8 years of music training, cf. Lidji et al., 2007).

2.2. Tasks

Participants were tested individually in a laboratory room. Children completed the pitch-matching, numerical, spatial, and verbal task in this order. The pitch-matching task was completed first to avoid any influences of the other tasks. Adults completed the pitch-matching task only.

2.2.1. Pitch-matching task

Stimuli were presented on a laptop using Cedrus SuperLab 4.5 software. First, participants were familiarized with every pitch. They saw a piano keyboard presented centrally on a 15-in. computer display and heard eight pitches on a C-major scale using laptop speakers. Each pitch was simultaneously represented by a blue circle on the matching key of the keyboard. Pitches were played from lowest to highest and vice versa. Afterwards, the lowest and highest pitches were played twice to highlight auditory boundaries.

Then, participants were presented with test trials in which they saw pictures of two keyboards presented side-by-side (see Fig. 1). Each of these keyboards had two marked keys and participants were asked to choose the keyboard with the markings corresponding to the simultaneously played pitch interval. Pitches in intervals were played consecutively (1 s each) with the first pitch remaining the same (C4, frequency = 261.63 Hz). Adults completed 50 trials, comprised of unisons, fourths, fifths, sixths, and octaves as targets and unisons, thirds, fourths, fifths, sixths, and octaves as foils, omitting trials with equal intervals on both keyboards. For each combination, the target keyboard was located once on the left and once on the right side.

Based on piloting, children saw 25 randomly presented test trials, receiving the same pairings of targets and foils as adults. Side of the target keyboard was counterbalanced. Participants were told that the interval could be repeated by the experimenter, at which point the trial would be restarted. Children were instructed to point to the keyboard that corresponded to the pitch interval and the experimenter recorded their response. If there was ambiguity, the child was probed to point again; however, this was rarely the case. For adults, two keys on the computer keyboard were marked with "L" for left and "R" for right and they were told to press the correct matching key. We measured accuracy and RTs from trial onset (the interval covered the first 4 s). Raw data of this and the following measures can be found among the supplementary materials.

To investigate a distance effect, we computed the interval distance in semitones between both keyboards for each trial. For example, a trial with a fifth and a sixth interval had a distance of 2 semitones. The design yielded distances from 1 to 12 semitones. As the number of trials for each distance was not equal, we grouped distances into five categories that had roughly the same number of trials and averaged distance: 1 and 2 (very small), 3 and 4 (small), 5 (mid), 7 and 8 (large), and 9 and 12 (very large).

2.2.2. Number line estimations

Children were presented with target numbers (2, 3, 6, 25, 67, 86), and asked to indicate their locations using a small peg on a 25-cm continuous number line (range: 0–100, Siegler & Opfer, 2003). The experimenter marked their responses. Children's percent absolute errors (PAE, Booth & Siegler, 2006) from the target position served as an index for their estimations.

2.2.3. Children's Mental Transformation Task (CMTT)

Children's spatial skills were measured using the CMTT (Levine, Huttenlocher, Taylor, & Langrock, 1999). Children saw pictures of two separated puzzle pieces and were asked to find the shape from four choices that the pieces would form if put together. Thirty-two trials tapped mental rotation or translation skills on a horizontal or diagonal dimension. The resulting four transformation types were counterbalanced using four forms and two orders, randomly assigned to participants. We measured percentages of correct responses. As children's performances during rotation and translation were related ($r = .60$, $p < .001$), we combined them to one index of children's spatial skills.

2.2.4. Woodcock–Johnson III-R picture vocabulary task

Vocabulary knowledge has been shown to indicate children's general intelligence (Horn & Cattell, 1966). Thus, we assessed children's expressive vocabulary (Woodcock, McGrew, Mather, & Schrank, 2003). Here, children verbally identified pictures (maximum of 38 items). Scores were calculated using the standard scoring system.

[2] Our sample size is close to the suggested size of 58, based on an a priori power analyses using G*Power 3.1, to yield significant effects within a two-tailed correlation using a bivariate normal model, with $p < .05$, expecting a medium-sized correlation.

[3] Even though none of the children had professional music training, it is possible that children's prior experience with toy pianos and xylophones might have influenced their pitch-matching performance, and this experience may be assessed in future research. However, pilot data from our pitch-matching task revealed that the influence of such prior experience may be limited as the pitch-matching performance from 11 music-trained children (with 8 of them receiving piano lessons, $M = 66.91$, $SE = 4.95$), revealed no differences to performance of an age- and gender-matched control group who did not receive music training ($M = 69.46$, $SE = 3.82$), $F(1,20) = 0.17$, $p = .69$.

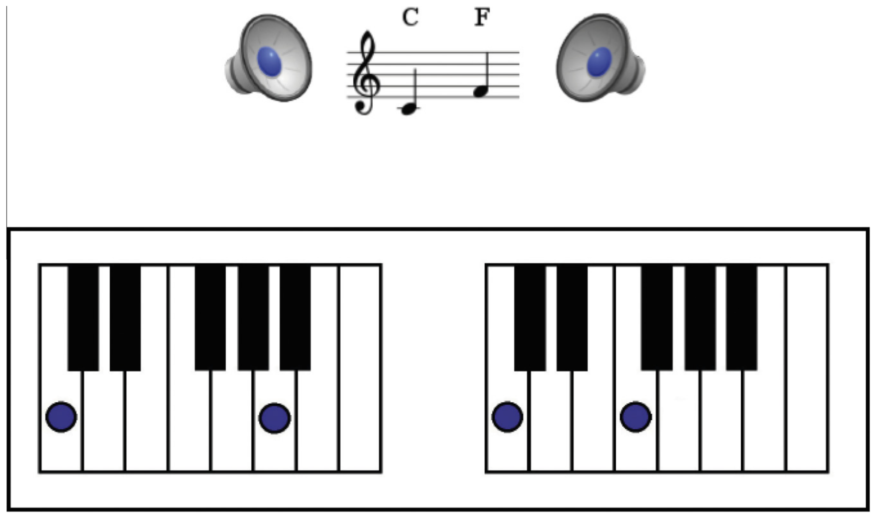

Fig. 1. Example of stimuli in the pitch-matching task. Participants heard two consecutively played pitches and were asked to indicate the keyboard with the marked keys that matched the pitch interval they heard.

Table 1
Participant numbers, mean ages, and the percentage of female participants per each age group. Standard deviations (*SD*) are presented in parentheses.

	n	Mean_{age} (*SD*)	% Female participants
Age group			
5-year-olds	19	66 months (3)	42.1
6-year-olds	18	77 months (4)	50.0
7-year-olds	16	91 months (3)	50.0
Adults	16	31.6 years (10)	50.0

2.2.5. Parent-reported data

Spatial play seems to predict children's spatial development (Jirout & Newcombe, 2015; Terlecki, Newcombe, & Little, 2008). Therefore, we asked parents how many hours per week their child plays with puzzles, blocks, or Tetris and similar computer games. Additionally, we used parent-reported maternal education as a proxy for socioeconomic status (SES).

3. Results

3.1. Pitch-matching performance

An analysis of variance (ANOVA) with pitch-matching accuracy as dependent variable and age (5-, 6-, 7-year-olds, adults) and sex as between-participants variables yielded a significant age effect, $F(3,61) = 15.23$, $p < .001$, $\eta_P^2 = .43$. Follow-up comparisons (Bonferroni-corrected here and throughout) revealed that adults differed from 5- and 6-year-olds (*ps* < .001; see Table 2 for means and *SD*s) and 7-year-olds differed from 5-year-olds ($p < .01$), but no more differences ($p > .08$). There were no further effects (*ps* > .18). Separate *t*-tests with participants' mean accuracies showed that participants performed significantly higher than chance (5-year-olds: $t(18) = 2.81$, $p < .05$, $d = 1.32$; 6-year-olds: $t(17) = 6.40$, $p < .001$, $d = 3.10$; 7-year-olds: $t(15) = 8.02$, $p < .001$, $d = 4.14$; adults: $t(15) = 18.98$, $p < .001$, $d = 9.80$).

To determine a potential distance effect, separate ANOVAs with RTs and accuracies were computed. The ANOVAs with distance (5) as within-participant variable, sex and age (5-, 6-, 7-year-olds, adults) as between-participants variables yielded significant distance effects[4] on participants' RTs, $F(4,244) = 11.12$, $p < .001$, $\eta_P^2 = .15$, and accuracies, $F(4,244) = 21.41$, $p < .001$, $\eta_P^2 = .26$. Participants were faster and more accurate with increased distance between the intervals (see Figs. 2A and B).

The same ANOVAs yielded a significant age effect for participants' RTs, $F(3,61) = 5.66$, $p < .01$, $\eta_P^2 = .22$. Adults responded faster than children (*ps* < .05, see Table 2), but no other differences emerged (*ps* = 1). A similar age effect occurred for participants' accuracies $F(3,61) = 14.86$, $p < .001$, $\eta_P^2 = .42$ (refer to the analysis above for comparisons). Additionally, there was a significant interaction between distance and age for participants' accuracies, $F(12,244) = 2.24$, $p < .05$, $\eta_P^2 = .10$, but no further effects (*ps* > .25). To explore this interaction, separate ANOVAs were computed for each age group with distance (5) as within-participant variable. The ANOVAs revealed significant distance effects for 5-year-olds, $F(4,72) = 2.55$, $p < .05$, $\eta_P^2 = .12$; 6-year-olds: $F(4,68) = 3.35$, $p < .05$, $\eta_P^2 = .17$; 7-year-olds: $F(4,60) = 12.67$, $p < .001$, $\eta_P^2 = .46$; and adults: $F(4,60) = 23.23$, $p < .001$, $\eta_P^2 = .61$.

To investigate developmental changes, we subtracted accuracies during very small distances from accuracies during very large distances. An ANOVA with this dependent variable and age as a between-participants variable revealed a significant age effect, $F(3,65) = 2.96$, $p < .05$, $\eta_P^2 = .12$. Follow-up comparisons showed that 7-year-olds showed larger distance effects ($M = 45.3$, $SE = 7.6$) than 5-year-olds ($M = 15.8$, $SE = 7.0$; $p < .05$), but no further effects (*ps* > .28).

3.2. Mental spatial transformations (CMTT)

An ANOVA with age (5-, 6-, 7-year-olds), sex, form (4), and order (2) as between-participants variables and percent correct as dependent variable revealed a significant age effect, $F(2,45) = 8.50$, $p < .01$, $\eta_P^2 = .27$, but no further effects (*ps* > .06). Comparisons revealed that 7-year-olds outperformed 5-year-olds ($p < .01$), but no other differences (*ps* > .06, see Table 2).

3.3. Number line estimations

An ANOVA with age (5-, 6-, 7-year-olds) and sex as between-participants variables and PAE as dependent variable revealed a significant age effect, $F(2,47) = 4.60$, $p < .05$, $\eta_P^2 = .16$. Children's accuracies in our number line task (see Table 2) matched scores found in previous studies (cf. Booth & Siegler, 2006; 5-year-olds:

[4] The same ANOVAs with every distance tested (9) yielded similar distance effects on participants' accuracies, $F(8,488) = 13.75$, $p < .001$, $\eta_P^2 = .18$, and RTs, $F(8,488) = 6.92$, $p < .001$, $\eta_P^2 = .10$. Again, adults and children responded faster and more accurate with increased distance between pitch intervals.

Table 2
Mean RTs (in ms) and percentage of correct trials (accuracy) during the pitch-matching task, the spatial transformation task, and percentage absolute errors during the number line task per age group. Standard deviations (*SD*) are presented in parentheses.

	Pitch-matching		Number line estimations	Spatial transformations
	% Correct Mean (*SD*)	RT Mean (*SD*)	% Absolute error Mean (*SD*)	% Correct Mean (*SD*)
Age group				
5-year-olds	60.0 (15.5)	6912 (1037)	18.5 (8.0)	57.4 (19.4)
6-year-olds	68.7 (12.4)	6878 (1079)	14.7 (5.7)	69.8 (15.8)
7-year-olds	76.5 (13.2)	6702 (1754)	12.1 (6.1)	78.3 (9.8)
Adults	87.9 (8.0)	5311 (1183)	–	–

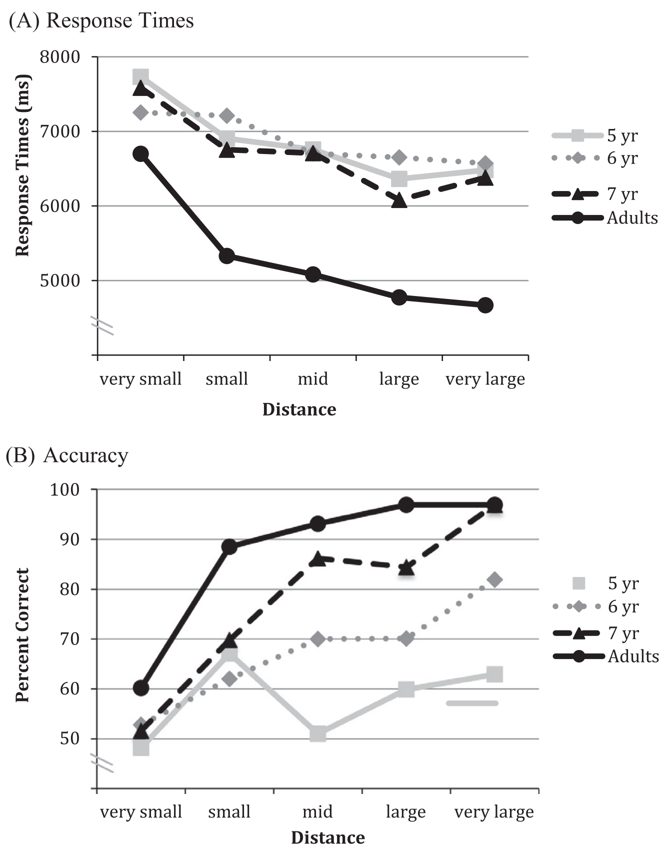

Fig. 2. Children's and adults' response times and percent correct (accuracy) as a function of the distance between presented pitch intervals.

24%, 6-year-olds: 12%, 7-year-olds: 10%). Comparisons yielded significant differences between 5- and 7-year-olds ($p < .05$), but no further differences ($ps > .21$). Additionally, there was a significant sex effect, $F(1, 47) = 5.34$, $p < .05$, $\eta_P^2 = .10$, with boys ($M = 13.09$, $SE = 1.24$) locating numbers more accurately than girls ($M = 17.25$, $SE = 1.30$), but no further effects ($ps > .47$).

3.4. The relation between pitch-matching, spatial, and mathematical skills

Spearman correlations were calculated because Kolmogorov–Smirnov tests indicated that spatial and pitch-matching performances were not normally distributed. Children's accuracy at pitch-matching was related to higher spatial skill ($r = .58$, $p < .001$), even after accounting for age, verbal intelligence, spatial play, and SES ($r = .47$, $p < .01$). By contrast, children's pitch-matching and errors on the mathematical task were not related (with controls; $r = -.17$, $p = .26$), even though mathematical and spatial skills were significantly related (with controls; $r = -.31$, $p < .05$).

The same pattern of results was revealed when correlating the size of the distance effect and children's spatial and mathematical skills. Again, larger distance effects in the pitch-matching task were related to higher spatial skill (with controls; $r = .33$, $p < .05$), whereas size of the distance effect was not related to mathematical ability (with controls; $r = -.05$, $p = .72$).

4. Discussion

The present results show that even 5-year-olds are capable of mapping pitch intervals onto their spatial counterparts. Nevertheless, there was rapid development between 5 and 7 years of age. Our results support previous findings of early space-pitch connections (Dolscheid et al., 2014; Mondloch & Maurer, 2004; Roffler & Butler, 1968; Walker et al., 2010); however, they qualify and extend these findings by showing robust space-pitch connections in childhood above and beyond a dichotomous categorization process. Furthermore, children's pitch processing resembles their processing of other magnitudes (Holloway & Ansari, 2008). They responded faster and more accurately with increased difference between presented pitches, supporting the notion of a common system that processes various magnitudes (Walsh, 2003). The distance effect typically indicates a rather coarse mapping between internal and external magnitude representations. Thus, it seems that internal representations of nearby pitches share more mental representational attributes than those farther apart, resulting in more incorrect answers and longer RTs. Indeed, children performed at chance when responding to very small distant intervals, but increased their accuracies with larger distances. The age-related progress of children's pitch-matching accuracy indicates that internal representations of pitches become more precise, supporting the idea of a domain-general comparison process that improves with age (cf. Holloway & Ansari, 2008).

Similar improvements were found for children's mental spatial transformation skills and number line placements between 5 and 7 years of age. Importantly, we found that higher accuracies at pitch-matching were related to higher spatial skills, even after controlling for several control measures. By contrast, pitch-matching and number line performance were not related, although number and space were connected. It is possible that another number task would have revealed a connection, although we purposely chose one that is linked to mathematical proficiency (Siegler & Booth, 2004) and spatial thinking (Gunderson, Ramirez, Beilock, & Levine, 2012).

A potential mechanism for these associations is that mental visualization skills enable children to more easily imagine the pitch interval in space or numbers on a line. Even though children's spatial skills were associated with their pitch-matching performance and number line estimations, pitch and number were not related. These asymmetrical relations point to the idea that space is a primary dimension on which pitch and number are mapped (cf. Shepard, 1987). Corroborative research has indicated asymmetrical relationships between space, number, and luminance (deHevia, Vanderslice, & Spelke, 2012; Pinel et al., 2004), and space, time, and pitch (Casasanto, 2010). This basic role of space may exist because space is a concrete dimension that can be simultaneously grasped by sensorimotor and perceptual experience, making it an ideal foundation for mapping other dimensions. Overall, our results contrast the idea that any perceivable dimensions can be universally mapped, and instead highlight the basic and privileged role of spatial thought for pitch and number.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.02.016.

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