Mental Rotation in Visual and Musical Space:

Comparing Pattern Recognition in Different Modalities

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Abstract

The phenomenal space of music is formed by two main dimensions: temporal and tonal. Together, these two intertwined dimensions constitute the tonal chronotope. Musicians, such as classical pianists and conductors, routinely perform structural analysis of musical form that requires thinking in quasi-spatial terms. During this process of structural analysis, the sound stream of musical composition is transformed into tonal architectonics. In this musical space, melodic objects are shaped by a tonal force field. The melodic objects can be mirrored, enlarged, diminished, and reoriented in tonal space. It is plausible that spatial abilities—such as the mental rotation of visual shapes—are related to certain kinds of musical abilities such as the mental manipulation of musical shapes in the virtual musical space of pitch and time. We found a correlation between the visuo-spatial and quasi-spatial melodic transformation tasks. We also included a non-spatial musical task, timbre judgment, which correlated with visual mental rotation for women but not for men. The results confirmed men's advantage in performing mental rotation, and also showed that men perform better than women on the melodic transformation and timbre-change tasks. The pattern of correlations for men and women suggests involvement of specific cognitive mechanisms for spatial and melodic transformations for men, and of more general cognitive mechanisms for women.

Key words: music perception, amodal processing, mental rotation, melodic transformation, sex differences

It seems very likely that the processing of musical patterns and of shapes in visual space shares brain resources. For example, Hassler (1992) found that musicians performed better than non-musicians on tests of spatial perception. Zatorre, Mondor, and Evans (1999) found evidence that a network of right-hemisphere cortical regions is involved in the processing of both pitch and spatial location for sounds. And Douglas and Bilkey (2007) showed that amusical participants experienced less interference than normal controls when performing simultaneous pitch discrimination and visual spatial rotation tasks. Listening to melodic transformations involving transposition (Foster and Zatorre, 2009) and retrograde (Zatorre, Halpern, & Bouffar, 2009) generates activation in parietal areas known to be important for processing spatial information. It is thus plausible that performance of a musical task involving the manipulation of melodic shapes should be correlated with performance in visual spatial rotation.

The possibility of a close relationship between melodic and visual shape processing becomes all the more likely when we consider that musicians typically think in terms of melodic shapes, and that the pervasiveness of that way of thinking is supported by psychological theory and experiment. To a first approximation, melodic phrases are remembered in terms of their overall shape or contour (Dowling, 1978). Kubovy and Van Valkenburg (2001) argue persuasively that melodic shapes in music are perceived as existing in a virtual space of pitch and time in the way analogous to the perception of visual shapes in physical space.

Shepard and Cooper’s (1982) list of types of visual object transformation includes, among others, a translation, a dilation, and a reflection. Each of these types of visual object transformation has an analogue in music, where a musical theme can be transposed in pitch (translated), augmented and diminished in time (slowed down or speeded up), inverted (reflected), or be subjected to some combination of these transformations. Indeed, composers like J. S. Bach have exploited the possibilities of such melodic transformations in achieving a balance of similarity and difference in their art (see Fig. 1). Listeners' ability to recognize transformations of melodic shapes has been documented (Dowling, 1971, 1972; Krumhansl, Sandell, & Sergeant, 1987).

Fig. 1. J. S. Bach, *Two-Part Invention in C.* The musical theme is "translated" white arrows), "mirrored" (black arrows), and its fragment is "augmented" (striped arrows).

Studies involving brain imaging suggest that professional musicians process visuo-spatial information differently than non-musicians. Musicians have a different pattern of brain activation during the classical Shepard and Metzler (1971) task on mental rotation (Bhattacharya & Petsche, 2005), and the brains of professional male keyboard players show increase in gray matter volume in several areas of the cortex including the superior parietal lobule (Brodmann Area 7, Gaser & Schlaug, 2003). The superior parietal lobule is involved in propioception and in visuo-spatial processing, including mental rotation (Jordan, Heinze, Lutz, Kanowski & Jancke, 2001; Harris & Miniussi, 2003). Other experience-dependent structural changes in the brain of the musicians are related to tonal processing (Schneider, Scherg, Dosch, et al, 2002; Gaab & Schlaug, 2003; Bermudez & Zatorre, 2005) and motor skills (Hyde, Lerch, Norton et al, 2009). The effects of intensive motor training in musicians results in differences in white matter organization in the corona radiata and internal capsule (Schmithorst & Wilke, 2002), and the significantly larger anterior part of the corpus callosum that contains many fibers from frontal motor-related regions and prefrontal regions (Schlaug, 2001). Studies investigating physiological correlates of musical syntax with event-related brain potential (ERAN) show that musical expertise influences pattern of brain activation in perception of violation of tonal expectation (Koelsch, Schmidt, & Kansok, 2002; Regnault, Bigand, & Besson 2001). Listening to classical music generates leftward temporal activation in musicians as compared to rightward temporal activation in non-musicians (Ohnishi, Matsuda, Asada et al, 2001), which is explained as an expertise-dependent change in music perception in musicians. Musicians also differ in psychometric performance (Brandler & Rammsayer, 2003).

Males advantage in performance on mental rotation task is explained by regional morphological differences between male and female brains (Koscik, O'Leary, Moser, Andreasen, & Nopoulos, 2009), and by involvement of sex hormones (Hassler & Nieschlag, 1989; Hausmann, Slabbekoorn, Van Goozen, Cohen-Kettenis, & Gunturkun, 2000; Hooven, Chabris, Ellison, & Kosslyn, 2004; Peters, Manning, & Reimers, 2007). The sex differences include a greater hemispheric asymmetry in men as compared to women (Amunts, Schleicher, Burgel, et al, 1999; Good, Johnstrude, Ashburner et al, 2001) and the thicker corpus callosum in women (Steinmetz, Staiger, Schlaug et al, 1995). Measures of event-related brain potential (ERAN) show developmental sex differences in music perception: a bilateral responsiveness in girls and a predominantly left-hemispheric response in boys (Koelsch, Grossmann, Gunter et al, 2003), as compared to a continued bilateral responsiveness with age in women but a transition to a right-hemispheric dominance in men (Koelsch, Maess et al, 2002). When compared to males, females show heightened responses to musical stimuli in electrophysiological measures (Nater, Abbruzzese et al, 2006), finger-temperature measures (McFarlan & Kadish, 1991), and a greater sensitivity to modal (major vs. minor) condition in musical stimuli (Webster & Weir, 2005).

Whereas the general principles of music cognition work independently of musical experience and training (Hevner, 1935, 1936; Holleran, Jones & Butler, 1995; Krumhansl, 2005; Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005; Dalla Bella, Giguère, & Peretz, 2007), there is a real possibility that perceptual learning in musicians and their facility in manipulation of melodic shapes are related to visual spatial abilities. In contrast, tone-deaf individuals (Cuddy, Balkwill, Peretz, & Holden, 2005) show a significantly poorer performance on the mental rotation task than musicians and non-musicians (Douglas & Bilkey, 2007). Tone deafness or amusia, which affects 4-5% of the population (Kalmus & Fry, 1980), can be explained as a result of a failure to generate a mental representation of the tonal system of reference. Music perception is a process of pattern recognition within the tonal space. Whereas visual space can be explained in basic terms with Cartesian coordinates and the force of gravity, the tonal space of music is defined by differences in tonal attraction of tones to a tonal center (Krumhansl & Shepard, 1979; Krumhansl & Kessler, 1982) (See Figure 2).

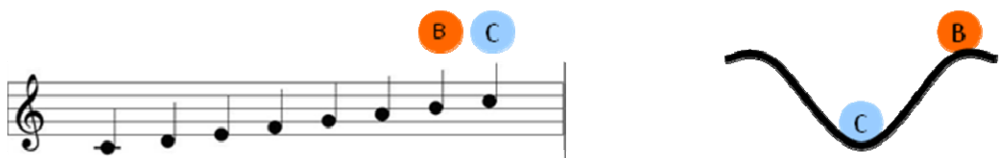

Fig. 2. In diatonic scale, tones differ in their pitch (as defined by frequency) and in degree of tonal attraction to tonal center

In the European tradition, the tonal scale consists of whole steps (melodic intervals of a major second) and half steps (melodic intervals of a minor second). On a keyboard, a half step (minor second) is a shortest distance between any two keys. Amusic individuals lack the ability to discriminate tones of a minor second (Peretz, Ayotte, Zatorre, Mehler, et al, 2002). This poor pitch discrimination most likely prevents the generation of a mental representation of the tonal system of reference which is a precondition for music perception, and thus deprives amusics of the ability to navigate in tonal space.

A musical sound becomes a tone when it enters into relationships with other musical sounds and thus acquires a status in the tonal scale. The perceived arrangement of tonal relationships creates the surface of melodic objects. Conceptually this is similar to conceiving of material objects as the “wrinkles and ripples of space” (Florensky, 1925/1993). In music, a source of production is secondary to tonal relationships between musical sounds (Scruton, 1997). For example, a melody can be started by one person in one room and finished by a musical instrument in another room. Whether this person is a child or an elderly, a male or a female, and whether the musical instrument is a piano or oboe are secondary to the image of a familiar melody.

The tonal hierarchy generates mental system of reference that guides our perception of music. Differences in tonal attraction, which can be explained as a tonal force field, shape sequence of musical sounds into a coherent image, such as a melody. Listening to music can be compared to navigation in the visual world, where our mind streams-out separate images within visual scene. An explanation of the conventional visual space in mathematical terms involves Cartesian coordinates, which are the accepted system of reference for perception of visual objects, and a force of gravity that identifies the direction for "falling down." In music, it is tonal attraction that identifies direction for "falling down" to a tonal center or tonic. The word "cadence," that translates as "falling," means several things in music; in general terms, cadence is a concluding part of a melodic phrase. Cadence brings our tonal expectations to an equivalent of a punctuation mark at the end of a linguistic phrase. Similar to a process of reaching a stable position by a visual object, conventional authentic cadence is a process of achieving stability in a tonal force field. The stability is felt as a release from tonal tension. Research in tonal modulation, a reorientation in tonal space, connects tonal distance (key proximity) to perceived tension (Bigand, Parncutt, & Lerdahl, 1996; Toiviainen & Krumhansl; 2003; Korsakova-Kreyn, 2009). This suggests a link between perceived tension and tonal relationships.

Perception of a melodic phrase involves expectations that are defined by the logic of tonal relationships (Schenker, 1954; Schoenberg, 1954; Meyer, 1956, Lerdahl, 2001). Conceptually, these expectations are akin to the representational momentum (Freyd & Finke, 1984) that involves an image of a final position and implies velocity of motion. Confirmation of auditory momentum (Freyd, Kelly & DeKay, 1990) strengthens the argument for the possibility of bypassing real-time duration of a given melodic phrase during recall (Dalla Bella, Peretz, & Aronoff, 2003). The navigation in tonal space can involve reorientation from one tonal center to another (tonal modulation). The shortened time-estimates for reorientation to distant keys as compared to reorientation to the close tonalities (Firmino, Bueno, & Bigand, 2009) demonstrates "velocity of motion" in tonal expectations.

A coherent melody can be explained as a melodic object shaped by tonal forces. Once grasped in its entirety, a melodic object can be recognized even if there are pronounced distortions of the melodic intervals that comprise it, as it was demonstrated in studies of melodic contour (Dowling, 1971, 1972, 1978; Dowling & Fujitani, 1971). Making judgment during melodic congruency task implies the presence of a stored standard melodic phrase in working memory; this melodic template is then compared with its unfolding-in-time version. Whereas melodic images are explicitly temporal in their nature, mental rotation of 3D objects involves temporal aspect implicitly via an angle of rotation. The greater is an angle of rotation, the longer time it takes to make judgment on visuo-spatial congruency (Shepard & Metzler, 1971).

Jordan and Shepard (1987) believe that the tonal scale underlies the comparison of auditory objects. In their research with a distorted musical scale, Jordan and Shepard made a conceptual comparison between perceptual schemata in the visual domain and the tonal scale in music perception. This comparison connects navigation in visual space with navigation in the tonal space of music. Implied in this approach is the possibility of a complementary influence of musical training on visuo-spatial skills, or the possibility of the coupled proficiency in both modalities.

A study by Cupchik, Phillips, and Hill (2001) compared accuracy on Shepard and Metzler's mental rotation task with accuracy in a music perception task that involved two melodic transformations: inversion (changes in direction of melodic intervals, turning them all upside down) and retrograde (playing the melodic phrase backwards, note for note). Essentially these were melodic contour transformation tasks. Cupchik et al had participants distinguish between more or less precise inversions and retrogrades (that preserved both the contour and note-to-note diatonic intervals of the targets) and patently imprecise transformations (that did not preserve diatonic intervals). They found that a multiple regression analysis of performance on the musical tasks predicted spatial rotation performance, but the pattern was complicated. Cupchik et al found that accurate discrimination of retrograde transformations predicted accuracy on the mental rotation task. However, the correct rejection of imprecise inversions was *negatively* correlated with the spatial task, and the positive recognition of inverted targets was unrelated to spatial rotation.. So whereas performance on the musical tasks predicted performance on the spatial task, it was not generally true that better musical performance was associated with better spatial performance.

The puzzling pattern of results obtained by Cupchik et al (2001) may be due to their choice of melodic transformations and the particular way in which they implemented the task. Retrograde transformations are not common in music, apart from such *tours de force* as J. S. Bach's famous retrograde canons and the use of retrograde in serial compositions. The way the retrograde task was implemented by Cupchik et al leaves doubts concerning whether its solution actually required mental manipulation of patterns in musical space. In general precise retrogrades share all their pitches with the target phrase, and imprecise retrogrades do not. Discriminating precise from imprecise retrogrades can be thus be done in their task simply on the basis of pitch content and need not involve transformations of melodic shapes in musical space. This perhaps explains Cupchik et al's findings of superior performance with retrogrades than with inversions, the reverse of what is found when pitch repetitions are controlled (Dowling, 1972).

There were several additional problems with Cupchik et al study. First, recognition of retrogrades is notoriously difficult (Dowling, 1972), so it is not an optimal task for exploring pattern-manipulation abilities in music. Second, their "correct" inversions were not exact inversions in the sense of preserving exact interval sizes, so that the participants had to make judgments concerning *degree* of precision of interval sizes in the transformations. Third, the study was missing a critical control task. The authors found that a task involving musical shapes predicted performance with visual shapes. However, how do we know that other, non-spatial musical tasks would not correlate with the visual spatial task as well?

In our study we used melodic transformation tasks of only moderate difficulty. In addition, our study included a control task, since it is possible that the Cupchik et al (2001) results are due to general processing abilities contributing to both tasks, and not to specific underlying spatial abilities for visual space and music. For the non-spatial task we used a musical task involving recognition of changes in timbre.

Experiment

METHOD

Participants

Two-hundred-thirty-one undergraduates of the University of Texas at Dallas, 163 females (ages 18 – 54 with a mean of 24.64, SD = 6.44) and 68 males (ages 18 – 65 with a mean 25.99, SD = 8.34) participated in the experiment in partial fulfillment their course requirements in psychology. All 231 participants performed the melodic contour transformation and visuo-spatial tests, while 114 of them (82 females and 32 males, ages 18 – 38 with a mean of 24.75, SD = 5.74) performed additionally the control task on timbre change recognition. Each of the participants completed a brief questionnaire that asked about their gender, age, and musical experience. Participants who had 4 or more years of musical experience were characterized as musically experienced: 98 of the entire group of 231 and 48 in the subgroup of 114.

Stimuli and Apparatus

The visuo-spatial task was a brief replica of the classic Shepard and Metzler's experiment on mental rotation, and was composed of 122 pairs of images of three-dimensional geometric objects (Figure 3). They were presented to the participants as a PowerPoint slide presentation. The auditory tasks included the main task on melodic contour transformation and the control task on timbre change. The main task was designed as a musical counterpart of the mental rotation task and consisted of a series of 27 melodies in their standard and altered form that presented melodically congruent and non-congruent transforms.

These melodic stimuli were designed as auditory analogues to the three-dimensional geometric objects from the Shepard and Metzler's (1971) study on mental rotation. The principal investigator collected 27 melodies and their transformations (one transform for each melody) from keyboard compositions by J. S. Bach, and recorded them in a CD quality with a freshly tuned grand piano. The melodies were 7 to 16 notes long, relatively balanced on mode (major-minor), balanced on meter (duple versus triple), and differed in tempo and character. Their duration was within the “sliding window” of music perception (Tillmann, Bigand & Pineau, 1998; Bigand, Vieillard, Madurell et al, 2005) determined by the properties of the immediate auditory memory buffer. On each trial, a melody was followed by its transformed version. Melodic contour transformation was represented by three categories: Bent, Mirrored, and Composite (Figures 4 & 5). Bent transforms preserved contour, but were shifted along the scale so that details of their pitch intervals were altered. Mirrored transforms were diatonic inversions in which all melodic intervals of a contour reverse their direction. Composite transforms had some of the melodic intervals of their contours reversed. Our design did not include manipulation of temporal aspect of the melodic stimuli, so that the temporal organization of a melodic model and of its corresponding transform was identical.

The same 27 original melodies were used in the control task where participants were asked to say how many tones in a sequence were different in timbre from other tones: 1, 2, or 3. Cakewalk software was used to control the change of timbre from piano to harpsichord and to play the timbre-change series of melodies that were recorded with a Yamaha TG-500 synthesizer. This auditory task did not ask for an integrated perception of a melodic object but demanded attention to individual musical sounds. In this way it was possible to compare the quasi-spatial perception of the melodic objects in the main task with the acoustically-oriented (non-spatial) perception of individual tones in the control task. Employing the same standard melodies in the main task on melodic congruency and in the control timbral-change task provided commonality of stimuli. The standard melodies were recorded on a grand piano, whereas the timbral changes were represented by a harpsichord, that is, by another keyboard instrument. The mild timbral change demanded a focused attention to the melodies.

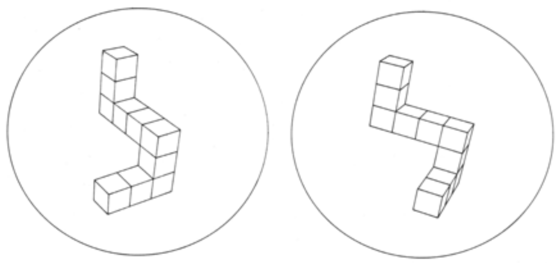

Fig. 3. Sample of three-dimensional congruent geometric objects (Shepard & Metzler, 1971)

Fig. 4. Melodic contour of a theme from the *Two-Part Invention in C* by J. S. Bach (1), Mirrored contour (2), Bent contour (3).

Fig. 5. Melodic contour of a theme from the *Prelude and Fugue in A* from *WTCII* by J. S. Bach (1), Composite contour (2).

Procedure

First the participants were introduced to the concept of a melodic contour (pattern of ups and downs) and its transformation with the help of graphs and familiar musical samples like “Twinkle, Twinkle, Little Star,” “Happy Birthday to You,” and “Minuet” (the latter from the *Notebook for Anna-Magdalena Bach*). To explain the tonal space and tonal force field of music to the participants, the concept of tonal attraction was illustrated with such simple melodic examples as a scale and the dissonant versus consonant melodic intervals, and with two short harmonic progressions: one resolving into stability of a tonic triad, and the second ending on apparently dissonant chord, away from the tonal stability. Also, the participants were presented with an explanation of the similarities and differences between the division of a plane—where an image is perceived “at once,” and the division of time—when a musical image arrives to perception step by step, as a sequence of events. This explanation aimed to elucidate the main auditory task that demanded grasping each melody as a complete object and as a template for the matching task of mental auditory “rotation.”

During the main auditory task, the participants responded on each of 27 trials by making a forced choice judgment between the three response categories—Mirrored, Composite, and Bent**.** A single answer sheet was arranged in three columns of squares, each square containing a letter: **M** for Mirrored, **C** for Composite, and **B** for Bent. During the control auditory task, the participants listened to the same 27 melodies in their standard version only, each melody having 1 to 3 tones changed in timbre from piano to harpsichord. The participants were asked to identify the number of tones changed in timbre in each melody. An answer sheet was similar to one used for the main auditory task on melodic contour transform, except that the letters **M**, **C**, and **B** were replaced with numbers 1, 2, and 3. In the visual part of the experiment, the participants were asked to make judgments on congruency of the 122 pairs of drawings depicting three-dimensional objects. On each trial, the participants identified a pair of images as either congruent or non-congruent by filling an appropriate circle on a single answer sheet. The 122 pairs of empty circles were arranged in two columns, one for "congruent" (CON) answers and another for "non-congruent" (NON) answers.

RESULTS

For all 231 participants, the visuo-spatial and melodic transformation tasks were correlated, $r =.40$, $p < .001$, as well as musical experience and the melodic transformation task, $r = .40$, $p < .001$, but not musical experience and the visual-spatial task. A similar pattern of correlations was obtained for men and women independently (Table 1).

For those 114 participants who performed all three tasks (including timbre change) the visuo-spatial and melodic transformation tasks were correlated, $r = .32$, $p < .001$, as were the visuo-spatial and timbral tasks, $r = .26$, $p < .05$, and the melodic transformation and timbral tasks, $r = .22$, $p < .05$ (see Table 2). Performance on the melodic transformation task correlated with musical experience, $r = .43$, $p < .001$, but neither the timbral task nor the visuo-spatial task correlated with musical experience. Separate analyses for males and females revealed a significant correlation between the visuo-spatial and melodic transformation tasks for males, $r = .46$, $p < .05$, and females, $r = .28$, $p < .05$. However the visual and timbral tasks correlated significantly for females only, $r = .30$, $p < .05$. While for females there was no significant correlation between performance in the visual task and musical experience, for males this correlation approached significance, $r = .34$, $p < .06$. Musical experience and melodic transformation task correlated for females only, $r = .48$, $p < .001$. None of the tasks correlated with age in either analysis.

TABLE 1

Correlation matrix for the visual and melodic tasks and musical experience for all 231 participants

All participants	Experience	Visual	Melody
Experience		0.12	0.40***
Visual			0.40***
Melody			

Male participants	Experience	Visual	Melody
Experience		0.07	0.33**
Visual			0.28***
Melody			

Female participants	Experience	Visual	Melody
Experience		0.10	0.42**
Visual			0.39***
Melody			

*** $p < .001$; ** $p < .01$; * $p < .05$

TABLE 2

Correlation matrix for the visual, melodic, and timbre tasks and musical experience for the subgroup of 114 participants

All participants	Visual	Melody	Timbre
Experience	0.16	0.43***	0.18
Visual		0.32***	0.26***
Melody			

Male participants	Visual	Melody	Timbre
Experience	0.12	0.48***	0.20
Visual		0.28*	0.30***
Melody			0.24*

Female participants	Visual	Melody	Timbre
Experience	0.34	0.30	0.08
Visual		0.46***	0.10
Melody			0.20

*** $p < .001$; ** $p < .01$; * $p < .05$

Subgroup: Participants in the subgroup performed all three tasks including the timbre change task

Because of the strong effect of gender, we calculated partial correlations among the three tasks while controlling for the effects of gender. There were significant partial correlations between the visual and melodic transformation tasks, $r = .32$, $p < .001$, the visual and timbral tasks, $r = .26$, $p < .05$, and the melodic transformation and timbral tasks, $r = .22$, $p < .05$. There was also a partial correlation between the melodic transformation task and musical experience, $r = .43$, $p < .001$. A two-sample *t*-test showed that males performed better than females on both the mental rotation, $t\ (229) = 4.92$, $p < .01$ and melodic transformation, $t\ (229) = 3.24$, $p < .01$, tasks. This was in agreement with other studies that show that males in average perform better on visuo-spatial tasks than females (Voyer, Voyer & Bryden, 1995).

DISCUSSION

The main hypothesis of this study relied on the supposition that perception of transformation of objects in visual space and in musical space involves common underlying brain processing.

To test this hypothesis, we had the participants to perform a visual mental rotation task and an analogous auditory task on congruency of melodic contour transformations. The results demonstrated a significant correlation between the melodic and the visuo-spatial tasks both for females and males. However, the timbre and visuo-spatial tasks correlated for females only. First, these results suggest gender-dependent differences in cognition of visual mental rotation and melodic transformation. Second, the results do not allow either confirming or rejecting with certainty the hypothesis that there is a special relationship between visual spatial and musical quasi-spatial abilities.

The starting point in comparing accuracy in visual and musical congruency tasks was an assumption that Shepard and Meltzer's (1971) collection of visual images offers visual analogues of melodic contour transformation in the tonal field. A rotated object might appear at first sight as if its proportions are distorted (Fig. 6). The three-dimensionality of the images in Shepard and Meltzer's study was produced by constructing the shapes from cubes. This added dimensionality in the visual mode provides a strong analog of the effect of the melodic interval changes within the “bent” melodic contours in tonal music (Fig. 2 & 3). If the system of tonal reference (tonal schema) can be compared conceptually to linear perspective, then a “bent” melodic contour would be like an object that is observed from a different angle. For example, in M. C. Escher’s “Another World” an image of a bird is presented from three different points of view and hence appears to the eye as “reshaped” for each position. Similarly, a melody, when shifted along a given scale, can sound differently because of changes of melodic intervals within its contour, yet this “bent” melodic contour is congruent with the model.

In this study, the Bent and Mirrored transforms present melodic congruency. The Bent transform preserves melodic contour, though some of melodic intervals that comprise this contour can slightly differ in size. The Mirrored transform (systematic inversion) has all its melodic intervals changed in direction. In comparison, the Composite transform (partial inversion) produces melodic non-congruency. Conceptually, Composite transform gives an auditory analog of non-congruency of visual objects when no angle of rotation can produce a match. Similar to the apparent changes in direction and size of sides of cubes that comprise a rotated visual object in the Shepard and Meltzer collection, a melodic shape displays changes in the direction and size of melodic intervals that comprise its contour. The sequencing of cubes in a given 3-D object can be compared to temporal sequencing of melodic intervals in a given melodic contour. The design of our study assumes that the listener is able to grasp a melodic phrase as an object in tonal space (or tonal system of reference) to encode this object in its entirety, and then use it as a template during the melodic congruency task. This process of comparing a melodic template with a transformed version implies the bypassing the real-time duration of a melodic phrase.

The control timbre-change task in this study was considerably easier than the auditory congruency task because it only demanded attention to the sound-quality of individual tones and did not impose the heavy load on memory that the melodic contour transformation task did. Therefore, it is not surprising that the participants performed much better on the control task as compared to the melodic transformation task. Whereas the correlations between the timbre change and visual tasks and between the timbre change and melodic tasks can be interpreted as a sign of consistency of attentive concentration for the female group, the advantage of males in processing the highly complex visuo-spatial and melodic tasks and the lack of correlation between either of these difficult tasks with the cognitively undemanding timbral task suggests a more automated processing that seems to transcend modality and thus is more abstract in nature.

The results of the analysis of false positives revealed an influence of octave equivalence on incorrect recognition of Composite transforms as Bent transforms. These false positives occurred when inversions of melodic intervals within a Composite transform were mentally adjusted in relation to the octave. In common practice, when singing, people switch their voice octave up or down when a melody is too high or too low in tessitura. That is, to the ear the octave equivalence in a familiar melody can be perceived as a part of the same melody. It seems that octave equivalence (which reflects a cyclical organization of the tonal scale) caused the participants to ignore the change in direction of some melodic intervals in the Composite transforms. This phenomenon underlines differences between the 3D space and the cyclically organized tonal space of music.

There is an essential difference between our understanding of the idea of a melodic object rotation in a tonal space and an approach by Shepard & Cooper (1982) to the idea of an auditory object in an auditory space. In their important book “Mental Images and Their Transformations,” Shepard & Cooper suggest a study case that would look upon the auditory rotation in terms of physical sources of varying-in-timbre sounds within the Cartesian coordinates. Such approach concerns, first of all, a perception of an auditory signal in a 3-D space and thus is limited to the field of acoustics; in other words, this approach does not reach cognitive level of object-recognition that is presented in Shepard & Metzler (1971) mental rotation model.

The main premise of the presented research, that navigation in tonal space is akin to navigation in visual 3-D space and involves the same neural substrate, specifically Brodmann 7 (Korsakova-Kreyn, 2005), has been recently supported by results of the imaging studies in perception of transposed melodies (Foster & Zatorre, 2009) and temporally reversed melodies (Zatorre, Halpern, & Bouffard, 2009). Foster & Zatorre found that the activity in the intraparietal sulcus “predicts relative pitch ability,” which is the main ability in melodic perception. Whereas the authors compare melodic transformation with object-rotation, the choice of transposition in their study is somewhat unfortunate: melodic transposition is conceptually equivalent to visual translation, which is a relocation of an object in space without spatial transformation, and as such it was not included in the set of images in Shepard- Metzler (1971) study in mental rotation. By introducing alterations in transposed and non-transposed melodies, Foster and Zatorre created melodic analogues to rotated objects in their study (comparable to our "bent" transform). Historically, it was melodic transposition, or rather the demand of the invariant melodic intervals in transposition, that boosted the tempering of tonal space and made the practice of polyphonic music, and thus melodic transformation, available for general musical practice.

Zatorre, Halpern, and Bouffard (2009) investigated cortical activation generated by listening to the exact and inexact retrogrades of the familiar tunes. The results showed an activation in the superior parietal lobe, which was interpreted, in context of mental rotation, as a sign of amodal mental manipulation. The most important theoretical statement of Zatorre, Halpern, and Bouffard's research is located near a conclusion section: "…activity in auditory cortex likely reflects the degree to which one is able to represent the sound of the stimulus phenomenologically, which may be useful in general, but is not necessarily required to solve the mental reversal task. The manipulative requirements of the task may take precedence in this instance over the mental imagery of the sound quality itself." The idea that the listener represents "the sound of the stimulus phenomenologically," if this describes a melodic object in terms of tonal attraction, is the actual basis for comparing mental rotation and melodic transformation and is thus the main theoretical thrust of this research. This statement is the first and only instance where Zatorre, Halpern, and Bouffard give a hint of their novel theoretical approach to music cognition, which treats melodies as objects in tonal space, and which is formulated as the following: "The manipulative requirements of the task may take precedence in this instance over the mental imagery of the sound quality itself." Explanation of this sentence requires bringing in the illuminating facts from the investigation in melodic contour, and the concept of melodic object from the philosophy of music. First, it seems that the authors try to suggest that their study observed the mental disassociation of a melodic contour—which represents more general higher order information than specific pitches and specific melodic intervals—and a melodic object that is shaped by tonal attraction within phenomenal space of music. However, the postulation of this disassociation cannot be inferred from the authors' belief that mental manipulation of melodic objects takes precedence over "mental imagery of the sound quality itself," because the sound quality and source of sound are both secondary in melodic perception anyway. For example, a familiar melody can be started by a child and continued by an adult in another room, and both of them would know with certainty that they sing the same song. This concept of the primacy of melodic objecthood over the sound quality and source of production is not yet firmly accepted by music psychologists (hence the prevalence of computer-generated melodic stimuli). Without this understanding of the primary and secondary qualities of melodies, Zatorre et al investigation loses theoretical strength needed for their interpretation. When the authors write that "sound of the stimulus phenomenologically…may be useful in general," this suggests that they never *envisioned* their melodic stimuli as melodic objects. Even more revealing is their description of a process of musical composing as an "ability to manipulate as well as represent new sounds:" The named composers, Beethoven and Smetana, represented their new ideas with the conventional set of sounds, seven diatonic and five chromatic tones, arranged uniquely in tonal-temporal patterns within phenomenal space of tonal relationships that shaped melodic objects carrying these new ideas. The tonal relationships trump other qualities of sound, and this is why we recognize the “Ode of Joy” from Beethoven’s last Symphony, whether the melody is sang by a choir or played by an electric guitar. That Zatorre, Halpern, and Bouffard meant the “mental imagery of the sound quality itself” and not melodic objecthood of their stimuli is also evident in the way of describing these melodies in terms of “auditory events” and as “string of notes.” This understanding of the melodic stimuli makes their investigation conceptually similar to Cupchik et al (2001). In the latter study, the stimuli are indeed strings of notes, some just 3 note-long, and not the coherent melodies (the stimuli were “sequenced using computer software.”) Therefore, Cupchik et al compared 3-D objects from Shepard-Metzler study with melodic non-objects. In comparison, Zatorre et al investigated perception of the familiar tunes, each of which a well-defined melodic object; this choice alone sets their study apart from Cupchik et al. (Zatorre et al, similar to Forster & Zatorre, cite Cupchik' experiment as supporting a link between processing mental rotation and melodic transformation. But as it was explained before, Cupchik at al results are rather ambiguous). The use by Zatorre et al of retrograde, a temporal reversal of a melody known for its difficulty and hence rare in musical practice, is surprising, since there are other, comparatively less challenging, and thus more popular types of melodic transformation, such as tonal answer (as imprecise transposition within same tonality) and inversion. The authors write that they “devised a novel task that required mental time reversal of tunes.” Actually, retrograde belongs to the conventional polyphonic technique in music and, as such, was explored in studies in melodic contour and its transformation (Dowling, 1972), which is the main subject of the imaging research. The study by Zatorre et al made an important contribution to neuroscience of music. However, the absence of critically important information related to the music philosophy, melodic transformation, and perceptual schemata, weakens the interpretation of their results. Moreover, some of the statements even undermine the key points of the interpretation.

The results of our investigation also suggest the gender-specific differences in cognition of visual mental rotation and melodic transformation. It is possible that men possess a specific cortical network dedicated to processing mental rotation that makes this task automated, whereas women need to engage additional cognitive resources (Ecker, Brammer, David, & Williams, 2006). This advantage in performing mental rotation task is explained by neurobiological basis that involves sex hormones (Hassler & Nieschlag, 1989; Hausmann et al, 2000; Hooven et al, 2004; Peters et al, 2007). Koscik et al (2009) presented evidence for “specific adaption” for mental rotation in the parietal lobe of men as compared to women. On the mental rotation task males show principally parietal activation (particularly in superior parietal lobule, Brodmann Area 7), whereas in females there is additional involvement of inferior frontal areas responsible for categorization (Hugdahl, Thomsen, & Ersland, 2006).

Structural MRI demonstrates increase in volume of gray matter in Brodmann Area 7 (BA 7) in professional male keyboard players as compared to non-musicians (Gaser & Schlaug, 2003). These differences in structural neuroanatomy of the professional keyboard players might be explained by brain plasticity related to the consistent practicing the highly complex movements. However, considering the results of Douglas & Bilkey (2007), which suggest that processing in the virtual pitch-space and 3D visual space share the same cognitive mechanisms in people with normal music perception whereas in amusics the visual-spatial mental rotation task and pitch-discrimination task are dissociated, we cannot exclude the possibility that navigation in the tonal space of music and in the 3-D visual space involves sharing the same neural resources in men. It is possible that in men the mechanisms of pattern recognition is less tied to modality of a given system of reference—and thus is more abstract—than in women.

We also hypothesized that musical training would be demonstrated to have a beneficial influence on the development of visuo-spatial abilities. However, the results showed no significant correlation between musical experience and accuracy in visuo-spatial mental rotation. Musical experience did correlate with the melodic transformation task and timbre change task for females only. Observation of two highly trained female pianists participating in this study (one age 29 with 23 years of musical experience and another age 47 with 40 years of musical experience, both heterosexual) was not supportive of the hypothesis that the extensive musical training is related to enhanced performance in mental rotation and melodic transformation tasks. It is then all the more interesting that some participants with no formal musical training performed extremely well on both the quasi-spatial music perception task and visuo-spatial task, as if a difference in modality of these two systems of reference—visual and tonal—did not matter to those participants. Therefore, perhaps our study is best interpreted as an experiment on fluid intelligence (Choi, Cho, Chae, Kim, & Lee, 2005). Fluid intelligence (*gF*) is associated with the capacity of working memory (Conway, Kane, & Engle, 2003; Ackerman, Beier, & Boyle 2005). The hereditary component of *gF* is explained by the involvement of evolutionary young areas of the prefrontal and lateral parietal cortices (Gray, Chabris, & Braver, 2003). Whereas *gF* represents some processing abilities that are independent of task-specific learning, recent studies demonstrate that training working memory with the auditory-spatial exercises can improve scores on fluid intelligence test unrelated to these exercises (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). This transfer effect was explained as a consequence of training in attentional control. Additional evidence of the importance of executive processing comes from studies in the effect of playing action video games (Green & Bavelier, 2003; Boot, Kramer, Simons, Fabiani, & Gratton, 2008), which includes the lessening of gender effect in mental rotation task (Feng, Spence, & Pratt, 2007).

The puzzling average performance on the melodic transformation task by the two professional musicians, both of whom have Absolute Pitch, might have an explanation in a study by Miyazaki (2004) that demonstrated that non-AP listeners perform better in musical tasks involving relative pitch than AP listeners, who are more strongly influenced by key context. However, there is another important implication of this average performance. The entire set of the melodic stimuli in our study was collected from J. S. Bach polyphonic compositions that are broadly known to the professional classical pianists. The mediocre performance of these two highly trained musicians suggests that for them melodic transformation, unlike mental rotation, does not create the sensation of a rotated melodic object. Rather the transformation is perceived as a sequence of melodic intervals comprising a new melodic contour, a result of sequential pitch-encoding. From a historic perspective, it is probable that perception of melodic transformation was different during the times when polyphonic music flourished and the polyphonic way of thinking naturally conceived of melodic “object,” in contrast to our predominantly homophonic musical thinking today.

CONCLUSIONS

The results of the presented study demonstrated a correlation between the mental rotation task and auditory task involving transformation of melodic contours. Males showed advantage in processing both the mental rotation and melodic transformation tasks. Moreover, the non-spatial control task on timbre change correlated with quasi-spatial melodic transformation task for females only. These results corroborate the previous investigations that show gender effect in mental rotation task, and suggest that processing visual and melodic mental rotation in men involves different cognitive mechanisms than in women.

Selection of mental rotation and melodic transformation tasks in this study was determined by an assumption that melodic objects, shaped by tonal forces during melodic gestalt, can be recognized as transcending their real-time duration and perceived as wholes. This assumption suggests that the way we process contour transformations is akin to the ways in which we process visual transformations. The implied involvement of a common mechanism in pattern-recognition within different systems of reference—visual and tonal—suggests that the higher mental functioning is less tied to the modality of perceptual patterns than is often assumed. While this research was not equipped to answer the question of whether there is actual involvement of a shared neural substrate in processing mental rotations and melodic transformations, the recent imaging studies substantiate this hypothesis.

Research in melodic transformation is important for our understanding of music's perceptual system of reference and the ways our mind generates representation of melodic objects within tonal space. The experimental confirmation of the shared neural substrate in music perception and visuo-spatial processing promises important implications for the theory of mind. This confirmation hints to a phylogenetic line from the modally poorly-differentiated neural pathways, like nonclassical auditory pathways (Moller, 2000), to the modality-specific pathways and cortical areas, and from there, to the phylogenetically young neural networks in neocortex, for example in the parietal areas, that are engaged in supermodal processing. The engagement of these networks in music perception is particularly interesting, since this suggests that a relatively new musical thinking of polyphonic technique dwells on the ancient neural mechanisms intended for biological survival. Unlike the processing of visuo-spatial transformation, which is critical for the survival and as such is a phylogenetically old attribute of mental activity, the processing of melodic transformation is a recent cultural development that entered musical practice via polyphony less than 1000 ago. The motif development in the *Sonata Allegro* form, that involves extensive melodic alterations supported by the freedom of tonal reorientation in pitch-space, is an even more recent phenomenon. Since perceived tension is the main determinant of tonal hierarchy, and thus of tonal system of reference, an interesting question for the future research in music cognition is, what neural mechanism is involved in translating perceived tension into "contour of thought" (Nabokov, 1981) that music is able to communicate.

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