Ithaca Conference '96
Music as Intelligence

A Sourcebook

Verna Brummett, editor

Published by Ithaca College
Ithaca, New York '97

A Cognitive Basis for the Facilitation of Spatial-Temporal Cognition Through Music Instruction

Frances H. Rauscher
Department of Psychology, University of Wisconsin, Oshkosh

A child picks out a simple melody on a piano. Another child pieces together a puzzle. While these children might seem to be involved in disparate activities, notable similarities exist between musical and spatial-temporal cognition. Playing a melody involves reconstructing a spatial-temporal pattern in which the elements are not puzzle pieces but notes of high and low pitches of long and short duration. Indeed, it is impossible to describe the structure of a melody, much less a symphony, without resorting to spatial and temporal terms.

Converging theoretical and empirical evidence suggests that music and spatial-temporal reasoning are linked by more than a convenient analogy. This monograph explores this link. I suggest that music and spatial intelligence, while unique, share common cognitive features such that musical experiences can influence spatial reasoning.

Psychologists have made a great deal of progress in the last decade toward understanding the partial independence of different intellectual abilities (Gardner, 1983). Although this view of intelligence as a collection of relatively autonomous skills serves as an important correction to the notion of a single general intelligence, it may be time to examine the links between intellectual abilities, including how development in one sphere might influence the development of related processes in another sphere. I begin this endeavor with a definition of my use of the term "spatial reasoning," followed by a review of the relevant literature and a brief description of a study that demonstrates the existence of a causal relationship between music and spatial-temporal reasoning.

What is Spatial Reasoning?

In general, the term "spatial" appears to be used in a relatively global fashion and is somewhat misleading. Spatial cognition is often used to refer to the type of mental processing involved in an apparently diverse group of tasks. As neurologists examining spatial deficits in adults have shown, the spatial factor is not a unidimensional concept, but includes spatial perception, attention, memory, operations (e.g., rotation or reflection of spatial representations), and construction (putting the parts of an object together to create a whole) (Kritchevsky, 1988; Linn and Petersen, 1985). For example, remembering the location of an armchair in a room does not tap the same skills as visualizing how one would have to rotate the armchair to move it through the door frame.

Psychologists distinguish several categories of spatial skills (Nicolopoulou, 1988; Stiles-Davis, Kritchevsky, and Bellugi, 1988). For clarity, I will contrast two broad classes, spatial-temporal processes and spatial recognition.

Spatial-temporal processes are responsible for combining separate elements of an object into a single whole by arranging objects in a specific spatial order. The fundamental aspect of spatial-temporal reasoning is the ability to establish spatial-temporal continuity among the elements. This type of reasoning requires successive steps, each step somewhat dependent upon previous ones. The temporal order in which these steps are carried out is crucial to the successful performance of spatial-temporal tasks. Examples would be putting together a jigsaw puzzle, or solving a topological problem.

This skill is distinguished from *spatial recognition*, which requires recognition of similarities or differences among objects, and is generally a single-step process. Order is not relevant for success in tasks relying solely on spatial recognition. For example, the child asked to classify objects according to their color would be performing a spatial recognition task.

Knowledge gained from musical training seems to be relevant to spatial-temporal processes (Rauscher, Shaw, Levine, and Wright, 1993; Rauscher, Shaw, Levine, Ky, and Wright, 1994; Rauscher, Shaw, Levine, Wright, Dennis, and Newcomb, in press). As in spatial-temporal problems, the elements of a musical piece are organized both spatially and temporally (e.g., evolving patterns of distance and closeness between pitches, rhythmic patterns, etc.). Playing a melody involves reconstructing a spatial-temporal pattern in which the elements, the notes, are organized in a highly specialized spatial-temporal code. Even recognizing a previously-heard melody relies on processing spatial-temporal relationships among pitches.

In considering the link between music and spatial intelligence, a further distinction needs to be made: one must distinguish between "correlation" and "causality." Correlation simply refers to a non-random relationship between two things; they "go together" but one does not necessarily cause the other. In short, one cannot legitimately infer causes from correlations. A causal relationship also consists of some systematic relationship between two items, events, or the like. However, causality also requires that there be a link in time between the two related things, that is, the alleged cause precedes its alleged effect. Moreover, if the hypothesized cause is provided, then the hypothesized result should occur. Thus, while studies that report correlations between music and spatial intelligence are of great interest, they yield little insight into causality, although they may lead to new and important lines of inquiry, ultimately including questions of causality. I will therefore review the correlational and causal studies separately, so that the reader can easily distinguish between the types of information that they provide.

Correlational Studies

A scan of the research literature suggests the variable pursuit of a correlation between music and spatial reasoning over the years, rather than a systematic body of research. Many of the correlational approaches rely on the work of Jean Piaget. For example, preschool children unable to perform concrete operational tasks involving number are also unable to combine musical sounds in memory. Conversely, children who exhibited concrete operations were more successful at the tasks requiring musical cognition (Serafine, 1981). Moreover, children's understanding of meter in music becomes increasingly sophisticated as they progress through the Piagetian stages of cognitive development (Jones, 1976). Other developmentalists have also found positive correlations. Using a different theoretical approach, Hassler, Birbaumer, and Feil (1985) found that creative musical ability was significantly related to spatial orientation skills.

Causal Studies

If music and spatial reasoning are *causally* related, music training should improve spatial reasoning skills. However, a causal relationship can be difficult to demonstrate (Carstens, Huskins and Hounshell, 1995; Stough, Kerkin, Bates and Mangan, 1994) without a careful consideration of the complexity of spatial cognition (Rauscher and Shaw, 1997; Rideout and Lauback, 1996). Failed attempts to find a relationship between music and spatial reasoning neglected to distinguish the cognitive demands that differentiate complex spatial tasks from simpler spatial tasks. It may be that complex spatial processes are related to music cognition, but that simpler spatial processes are not. The distinction between spatial-temporal reasoning and spatial recognition is therefore central to understanding the relationship between music and spatial cognition. Spatial-temporal operations seem to be especially relevant to musical reasoning, chess, engineering, and higher mathematics.

The studies that do report a causal relationship are intriguing. For example, Parente and O'Malley (1975) explored how rhythm affects the spatial dimension of field-independence. Field-independent people tend to perceive their physical environments as consisting of distinct objects separate from the surrounding background, whereas field-dependent people perceive the objects in their environments as being more affected by the surroundings. Parente and O'Malley found that four weeks of twice weekly rhythm performance training sessions significantly improved the performance of 40 six- to nine-year-old children on two tasks designed to measure field-independence. Their findings parallel research indicating that field independence improves with perceptual-motor training (e.g., Gill, Herdtner, and Lough, 1968).

As with many of the studies exploring correlations between music and spatial reasoning, Piaget's (1981) theories have inspired some causal studies as well. Botvin (1974) demonstrated that training in conservation of musical concepts facilitates development of conservation with nonmusical concepts, and Foley (1975) found that music training can improve a child's ability to use Piagetian conservation skills on tonal and rhythmic patterns. The literature suggests that cognitive skills of classification, seriation, spatial understanding, and temporal relations can also be improved through guided music listening (Parker, 1973). Hurwitz, Wolff, Bortnick, and Kokas (1975) found that six-year-old boys improved on tests of spatial cognition after they had training in the Kodály music curriculum, which stresses the development of rhythmical skills. Similarly, Kalmár (1982) found that Kodály music education facilitates abstract-conceptual thinking as it relates to creativity. More recently, my colleagues and I (Rauscher, Shaw and Ky, 1993; 1995) found that listening to a Mozart sonata can temporarily increase scores on the Stanford-Binet paper folding and cutting task, as compared to various control conditions or silence, and that this enhancement is not due to mood effects (Rauscher, Hughes and Miller, 1996). We also reported that middle-income preschoolers improved significantly on spatial-temporal tasks following music training, whereas children who received computer lessons or no special training did not (Rauscher, Shaw, Levine, Ky and Wright, 1994; Rauscher, Shaw, Levine, Wright, Dennis, and Newcomb, in press). And finally, Gardiner, Knowles, and Jeffrey (1996) reported that kindergarten children who received seven months of extra music and arts training improved significantly on mathematics achievement tests, whereas a control group of children who did not receive the special training did not improve.

Neurobiological Insights

Research on the neural representations of musical functioning clarifies the spatial-temporal qualities of music. An increasing amount of research supports the theory that the brain is specialized for the building blocks of music, and that these building blocks include separate spatial (melodic) and temporal (rhythmic) components. There are individual brain cells that process melodic contour, the pattern of increasing and decreasing notes in music (Weinberger and McKenna, 1988). Cells have been found in the auditory cortex that process specific harmonic relationships, such as the simultaneous presentation of the second and third harmonics of a note (Espinoza and Gerstein, 1988). Temporal, including rhythmic, aspects of sound streams also seem to be handled by certain cells in particular parts of the auditory cortex (Buchfellner, Lepplesack, Klump, and Hausler, 1989; Hose, Langner, and Scheich, 1987; Ison, O'Connon, Bowen, and Bocirnea, 1991).

Findings from humans who have suffered damage to the auditory cortex by stroke or by surgery to correct intractable epilepsy are particularly fascinating.

For example, damage to the right hemisphere selectively impairs the ability to process timbre (Samson and Zatorre, 1994). Also, the processing of melody and rhythm can be separated by specific brain lesions. Some patients show impaired discrimination of melodies while they have normal discrimination of rhythms, and vice versa for lesions in different regions (Peretz, 1990). And even different aspects of the processing of temporal information seem to be handled by different parts of the auditory cortex, rhythm by the left hemisphere and beat (meter) by the right hemisphere (Peretz and Morais, 1993).

The data from intact people support and complement these neuropsychological findings. It is possible to determine which areas of the brain are active during various tasks, including listening to music. One powerful method is to measure increases in the regional distribution of blood flow to parts of the cerebral cortex, because these reflect the increased metabolic needs of brain cells that are active.

In a recent study, healthy people were tested in two passive listening conditions, noise bursts or music matched for sound frequencies, and two active judgment conditions, comparing the pitch of the first two notes of melodies or the first and last notes of melodies (Zatorre, Evans, and Meyer, 1994). Listening to melodies produced an activation of the right temporal (auditory) hemisphere relative to the left ("language") hemisphere. Comparing notes, which also involves short-term memory, also showed a preferential activation of the right auditory cortical system, plus other areas of the right hemisphere. These findings indicate that there are specialized neural substrates in the auditory cortex of the right hemisphere that process melodies versus other non-melodic sounds.

And finally, that infants can detect differences in frequency (Olsho, 1984), melodic contour (Trehub, Bull, and Thorpe, 1984), rhythm (Thorpe and Trehub, 1989; Trehub and Thorpe, 1989), phrase structure (Krumhansl and Jusczyk, 1990), and musical scale (Lynch, Eilers, Oller and Urbano, 1990) suggests that music may be neurally represented from birth.

These studies highlight the many types of evidence, from animals, the neurologically impaired and the healthy human, that the brain contains an organization that is specialized to process the individual spatial and temporal elements of music.

The hypothesis that there is a causal connection between music cognition and spatial ability is supported by a structured neuronal model of the cortex developed by Shaw and his colleagues (Leng and Shaw, 1991; McGrann, Shaw, Shenoy, Leng, and Mathews, 1994; Shenoy, Kaufman, McGrann, and Shaw, 1993). This model, called the "trion model," proposes that musical activity strengthens neural firing patterns that are organized in a spatial-temporal code over large regions of the cortex. These firing patterns are also exploited by spatial reasoning tasks. Leng and Shaw (1991) predicted that music training provided to young children, whose cortices are plastic, could strengthen these common neural firing patterns through Hebbian learning principles (Hebb, 1949), resulting in enhanced spatial task performance.

Supporting this model, a pilot study found that electroencephalogram (EEG) electrode coherence values for adults who listened to music were similar to the EEG coherence values obtained when they performed a spatial-temporal task. Both activities yielded significant increases from baseline in the high beta frequency band (18.5–31.5 Hz) in the parietal and frontal cortex of both hemispheres (Sarnthein, von Stein, Shaw, Rauscher, Rappelsberger, and Petsche, 1996).

Behavioral studies motivated by this model have found a causal relationship between music and spatial-temporal reasoning. College students scored significantly higher on a spatial-temporal reasoning task after listening to a Mozart sonata, but not after listening to silence or to minimalist music (Rauscher, Shaw, and Ky, 1993, 1995). And finally, a highly significant improvement of spatial-temporal reasoning was found for middle-income preschoolers who received six months of keyboard lessons, as compared to preschoolers who received computer lessons or no lessons (Rauscher et al., in press). This study is described more fully below.

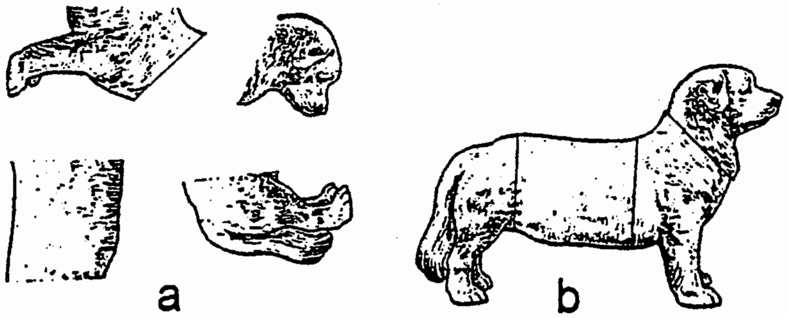
Music Training Enhances Spatial-Temporal Reasoning

To test the hypothesis that music training enhances spatial reasoning skills, we compared the spatial reasoning scores of 78 preschool children (42 boys, 36 girls) who were provided with six months of keyboard lessons, singing lessons, computer lessons, or no lessons. All children were of normal intelligence (IQ > 80).

The children were randomly assigned to one of four groups — 34 children received keyboard training coupled with singing sessions, 10 children participated in singing sessions alone, 20 children received computer lessons, and 14 children did not receive any special training. All lessons were provided by professional instructors. The keyboard and computer lessons lasted approximately 15 minutes and were given twice a week. The singing sessions were given for 30 minutes each day. Songs included popular children's tunes and folk melodies.

Dependent Measures

The children's spatial reasoning was tested using four tasks from the performance subtest of the Wechsler Preschool and Primary Scale of Intelligence-Revised (WPPSI-R). One task, object assembly, measures spatial-temporal skill. This task requires the child to arrange pieces of a puzzle to form a meaningful whole (figure 1a and 1b). Three other tasks were chosen to measure spatial recognition: (1) geometric design consists of a visual recognition task and a igure drawing task (2) block design requires the child to match depicted patterns ising flat, two-colored blocks, and (3) animal pegs requires the child to place orrect colored pegs in holes below a series of pictured animals.



Figures 1a and b. Example of the Object Assembly task. After placing a shield in front of the child blocking his/her view, the puzzle pieces were arranged according to a specified configuration (a). The shield was then removed, and the child was told that the pieces will "make something," and to put them together as quickly as possible. The experimenter started a stopwatch as soon as the child's hand touched a piece, and stopped it when the child indicated that the task was completed (shown assembled correctly in (b)).

Procedure

All children were tested individually before beginning the training. Testing sessions lasted between 1 hour and 1 hour 15 minutes, depending on the child's attention span, and were performed in the mornings over the course of several weeks. Testing procedures followed those demanded by the test manual (Wechsler, 1989), although task order was randomized for each child. Children from all groups were retested after six months.

The children who received the keyboard training were taught the names of the white and black keys of the keyboard, proper hand position, music notation, rhythm, intervals, and basic musical concepts such as fast vs. slow, loud vs. soft, and so on. After six months of lessons most children could perform simple pieces in the first position. The computer instructor taught the children the keys of the computer keyboard, proper typing position, letter and number notation, and simple DOS commands using age-appropriate animated software. The mouse was not used, nor were programs that centrally featured music. The singing sessions provided to the singing and keyboard groups were informal group sing-alongs accompanied by the piano. Each child was given the opportunity to "lead" the group in a song of his or her choice. The no-lessons group did not receive special training.

Scoring

Raw scores were based on the number of errors the child made within a specified time period, which varied from task-to-task, as given by the WPPSI-R manual. Bonus points were awarded for accuracy and speed for the object assembly, block design, and animal pegs tasks. Scaled scores were obtained from the manuals' tables for children at three-month age internals (M=10, sd=3).

Results

Figure 2 shows the effect of music training on spatial-temporal abilities by comparing the OA scores of the keyboard group before and after training to the OA scores of the other groups. After music training, the mean standard age scores (SAS) of the keyboard group had increased from 9.79 to 13.41 (Fig. 2a). A two (testing period: before vs. after) by four (group: keyboard, singing, computer, no lessons) analysis of variance (ANOVA) performed on the object assembly task showed significant main effects for testing period and group ($F_{(3,74)} = 11.97$, $p < .001$ and $F_{(3,74)} = 3.26$, $p < .02$), and a significant interaction effect between testing period and group ($F_{(3,74)}$=8.83, $p < .001$). ANOVAs performed on the other dependent variables (geometric design, block design, and animal pegs) were not significant, indicating that the children's scores on the items that measured spatial recognition did not increase significantly after lessons (fig. 2b). The object assembly scores of the singing, computer, and no-lessons groups did not improve significantly, nor did their scores on the spatial recognition tasks (fig. 2b).

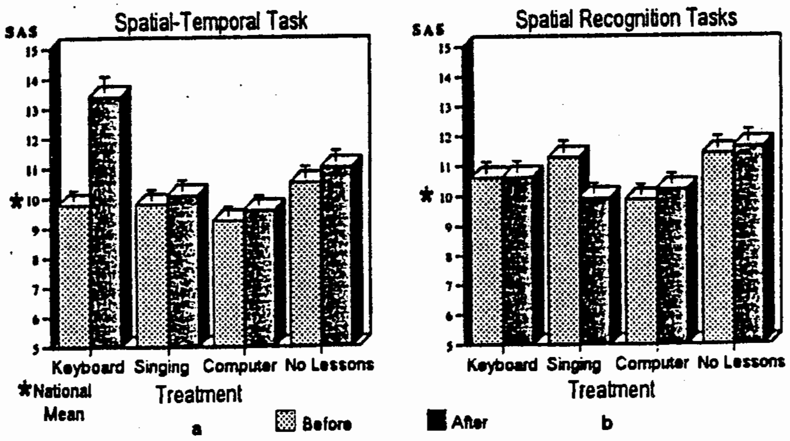


Figure 2: (a) The means for the Objects Assembly (OA) standard age scores (SAS), measuring spatial-temporal reasoning, for the keyboard, singing, computer, and no-lessons groups before and after treatment. (b) The spatial recognition SAS means for the four groups before and after treatment.

Discussion

The music group's scaled scores on the items measuring spatial-temporal ability, object assembly, were significantly higher after six months of music lessons. Those of the singing, computer, and no-lessons groups remained essentially the same. No groups improved significantly on the tasks measuring spatial recognition.

One might argue that the improvement of scores for the music group is due to a Hawthorne effect — namely, that the increased attention given to the experimental group motivated its performance on the object assembly task. We suggest that the lack of significant improvement of the *other* tasks minimizes this possibility. In addition, the failure of the computer group to improve further argues against this explanation. One might also argue that the object assembly task is more conducive to test-retest improvement than are the other tasks. This too seems unlikely, since the scores of the no-lessons group did not improve on any of the tasks when retested. The lack of significant improvement of the singing group suggests that either a more structured singing program is required, or that experience with a musical instrument, with its visual and motor representation of spatial-temporal relations between sequences of pitches, may be crucial to the effect. We are hesitant to draw firm conclusions regarding the contribution of singing based on the informal nature of these sessions.

Cognitive Analysis and Directions for Future Research

A neuronal explanation for these findings can be found in Leng and Shaw's (1991) trion model, described above. A different approach to understanding these data is to examine the common cognitive features that may be relevant to the domains of musical performance and performance on spatial-temporal tasks. This exploration may yield a better understanding of how the knowledge gained from musical training can transfer to spatial-temporal task performance. In this undertaking, one must be careful to distinguish between an "intelligence," which one can define as a potential capacity for knowledge, guided by biological and experiential factors, and a "domain," which is a set of activities upon which an intelligence is exercised. For example, spatial intelligence may govern the domains of musical performance and spatial-temporal task performance. That is, spatial intelligence may be relevant to both domains of knowledge.

Researchers have proposed several theories to describe the cognitive skills involved in music and in other abilities (Dillon and Sternberg, 1986; Perkins, 1989; Serafine, 1988). Serafine (1988) describes temporal processes (order and simultaneity) and nontemporal processes (closure, transformation, abstraction, and hierarchical levels) as the core components of musical skill. Mental imagery may also be an essential skill for musical performance. These skills are evident in the performance of the object assembly task, a spatial-temporal task. By describing the intellectual constructs involved in musical performance and in spatial-temporal reasoning, as demonstrated by the object assembly task, we can perhaps gain a better understanding of the intellectual constructs involved in musical performance and in spatial-temporal reasoning. A child performing the object assembly task must form a mental image of the completed puzzle and then must order and rotate the puzzle pieces to match the image. I suggest that it is these abstract qualities of the task that make it susceptible to enhancement through music training.

The object assembly task requires the child to arrange pieces of a puzzle to form a meaningful whole (refer to figures 1a and b). This task has several characteristics that might account for why performance improved after music lessons. First, object assembly was the only task given that required temporal operations; the nature of the task is sequential. Performance is facilitated by putting the pieces together in a particular order. Putting pieces together in the wrong order makes it more difficult to solve the puzzle correctly (e.g., children who put the two ends of the dog puzzle together first often have difficulty recognizing and correctly placing the piece that depicts the dog's middle). I expect that the object assembly task was enhanced because it involves sequential construction rather than recognition or copying skills, which are required by the other WPPSI-R tasks that we issued.

Second, object assembly was the only task that required the child to form a mental image and then orient physical objects to reproduce that image. The child had to transform mental images without the guidance of complete physical models. Specifically, puzzle pieces must be rotated into the correct orientation and combined to match an internal representation of the complete object. In contrast, each of the other tasks provided the child with a solid object or drawing to match or copy.

In sum, the object assembly task involves (a) sequential problem-solving (b) the formation of a mental image, and (c) the transformation of mental images. If these observations are correct, performance on other tasks that draw upon these skills should also be enhanced by music training. This question remains unanswered pending further research.

Most researchers agree that musical skill, like spatial skill, is an alliance of a number of separate and relatively independent abilities (Barett and Barker, 1973; Seashore, 1938; Seashore, Lewis, and Saetveit, 1956). In our study, enhanced spatial performance was brought about through a training program that combined structured individual keyboard lessons and relatively unstructured group singing lessons. However, it may be that some musical abilities contribute more to cognitive enhancement than others. To test this it is necessary to focus music training on distinct areas of musical ability. For example, the effects of different types of music training could be examined, such as keyboard, voice, and snare drum, each of which highlights a partially non-overlapping set of musical properties. By contrasting different types of training, we can begin to explore which musical properties are important for the enhancement of spatial reasoning skills.

Conclusion

What does all this mean? I have reviewed studies that support the conclusion that musical training facilitates abstract spatial abilities. In each case there is an extramusical positive effect. I propose that spatial intelligence is relevant to the domains of musical performance and spatial-temporal task performance. A positive relationship between these two domains has strong relevance for educators, because the facilitating effect of music training on spatial-temporal task performance has implications for children's learning abilities in many areas. Spatial reasoning is required for mathematics, architecture, graphic design, and other tasks requiring an understanding of how objects fit together in space and time. Therefore, data that show how music training influences these cognitive abilities in children recommends a reevaluation of both preschool and primary school education techniques.

Although music and spatial reasoning are unique intelligences with different developmental patterns, these studies indicate that there is a great deal to be learned from analyzing the parsimonious and efficient nature of the human brain as reflected in intelligence. Neurobiologists and psychologists are only beginning to understand the importance of early experience to cognitive function. Demonstrating that music improves the cognitive performance of preschool children suggests that music education is essential for optimal cognitive development. If we do not provide adequate opportunities for our children to learn and participate in music, we are depriving them of a great opportunity.

If music is to be included in the core curriculum, administrators and politicians must be convinced of its educational as well as artistic worth. They must be convinced that musical knowledge is as essential to a satisfactory education as are English, mathematics, history, and science. It is ironic and certainly unfortunate that we are forced to resort to science to show the value of music education, and the point must be made that the data from this research do not devalue music as an art. Instead, the work reveals music's potential as an educational tool.

From a theoretical point of view, these findings will help us understand cognitive development and the role of music in human life. From a practical point of view, the argument that music education is merely a "frill" finds no objective support. Because education is probably the best and most important way to help children develop to their full intellectual potential, it is incumbent on us all to support the application of knowledge that promotes these goals. The conclusion that music education is an important and effective part of this formula can no longer be doubted.

Music education is essential for all students, not just the gifted and talented, because early musical experiences are crucial to the cognitive development of children who will never become professional musicians. Educators must understand that providing music education is a fundamental part of their responsibility.

References

Barrett, H. C. and H. R. Barker 1973. "Cognitive Pattern Perception and Musical Performance." *Perceptual and Motor Skills* 36: 1187–1193.

Botvin, G. J. 1974. "Acquiring Conservation of Melody and Cross-Model Transfer through Successive Approximation." *Journal of Research in Music Education* 22, no. 3: 226–233.

Buchfellner, E., H. J. Lepplesack, G. M. Klump, and U. Hausler 1989. "Gap Detection in the Starling (*Sternus vulgaris*): II. Coding of Gaps by Forebrain Neurons." *Journal of Comparative Physiology* 164: 539–549.

Carstens, C. B., E. Huskins, and G. W. Hounshell 1995. "Listening to Mozart May Not Enhance Performance on the Revised Minnesota Paper Form Board Test." *Psychological Reports* 77, no. 1: 111–114.

Dillon, R. F. and R. J. Sternberg 1986. *Cognition and Instruction*. San Diego: Academic Press.

Espinoza, I. E., and G. L. Gerstein 1988. "Cortical Auditory Neuron Interactions during Presentation of 3-Tone Sequences: Effective Connectivity." *Brain Research* 450: 39–50.

Gardiner, M. F., A. Fox, F. Knowles, and D. Jeffrey, 1996. "Learning Improved by Arts Training." *Nature* 381: 254.

Gardner, H. 1983. *Frames of Mind: The Theory of Multiple Intelligences*. New York: Basic Books.

Gill, N. T., T. J. Herdtner, and L. Lough 1968. "Perceptual and Socioeconomic Variables, Instruction in Body-Orientation, and Predicted Academic Success in Young Children." *Perceptual and Motor Skills* 26: 1175–1184.

Hassler, M., N. Birbaumer, and A. Feil 1985. "Musical Talent and Visual-Spatial Abilities: A Longitudinal Study." *Psychology of Music* 13, no. 2: 99–113.

Hebb, D. O. 1949. *The Organization of Behavior*. New York: Wiley.

Hose, B., G. Langner, and H. Scheich 1987. "Topographic Representation of Periodicities in the Forebrain of the Mynah Bird: One Map for Pitch and Rhythm?" *Brain Research* 422: 367–373.

Hurwitz, I., P. H. Wolff, B. K. Bortnick, and K. Kokas 1975. "Nonmusical Effects of the Kodály Music Curriculum in Primary Grade Children." *Journal of Learning Disabilities* 8, no. 3: 167–174.

Ison, J. R., K. O'Connon, G. P. Bowen, and A. Bocirnea 1991. "Temporal Resolution of Gaps in Noise by the Rat Is Lost with Functional Decortication." *Behavioral Neuroscience* 105: 33–40.

Jones, R. L. 1976. "The Development of the Child's Conception of Meter in Music." *Journal of Research in Music Education* 24: 142–154.

Kalmár, M. 1982. "The Effects of Music Education Based on Kodály's Directives in Nursery School Children — from a Psychologist's Point of View." Psychology of music special issue, *Proceedings of the 9th International Seminar on Research in Music Education*, 63–68.

Kritchevsky, M. 1988. "The Elementary Spatial Functions of the Brain." In *Spatial Cognition: Brain Bases and Development*, ed. J. Stiles-Davis, M. Kritchevsky, and U. Bellugi, 111–140. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Krumhansl, C. L. and P. W. Jusczyk 1990. "Infants' Perception of Phrase Structure in Music." *Psychological Science* 1, no. 1: 70–73.

Leng, X. and G. L. Shaw. 1991. "Toward a Neural Theory of Higher Brain Function Using Music as a Window." *Concepts in Neuroscience* 2: 229–258.

Linn, M. C., and A. C. Petersen 1985. "Emergence and Characterization of Sex Differences in Spatial Ability: A Meta-Analysis." *Child Development* 56: 1479–1498.

Lynch, M. P., R. E. Eilers, D. K. Oller, and R. C. Urbano 1990. "Innateness, Experience, and Music Perception." *Psychological Science* 1, no. 4: 272–276.

McGrann, J. V., G. L. Shaw, K. V. Shenoy, X. Leng, and L. Mathews 1994. "Computation by Symmetry Operations in a Structured Model of the Brain: Recognition of Rotational Invariance and Time Reversal." *Physical Review E* 49, no. 6: 5830–5839.

Nicolopoulou, A. 1988. "Interrelation of Logical and Spatial Knowledge in Preschoolers." In *Spatial Cognition: Brain Bases and Development*, ed. J. Stiles-Davis, M. Kritchevsky, and U. Bellugi. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Olsho, L. W. 1984. "Infant Frequency Discrimination." *Infant Behavior and Development* 7: 27–35.

Parente, J. A. and J. J. O'Malley 1975. "Training in Musical Rhythm and Field Dependence of Children. *Perceptual and Motor Skills* 40: 392–394.

Parker, J. J. 1973. Discriminative Listening as a Basis for Problem Solving among Four-Year-Olds." *Dissertation Abstracts International* 33, no. 8A: 4460–4461.

Peretz, I. 1990. "Processing of Local and Global Musical Information in Unilateral Brain-Damaged Patients." *Brain* 133: 1185–1205.

Peretz, I., and J. Morais 1993. "Specificity for Music." In *Handbook of Neuropsychology*, vol. 8, ed. J. Boller and J. Grafman. Amsterdam: Elsevier Science Publishers.

Perkins, D. 1989. "Art as Understanding." In *Art, Mind and Education: Research from Project Zero*, ed. H. Gardner and D. Perkins, 111–131. Urbana: University of Illinois Press.

Piaget, J. 1981. *The Psychology of Intelligence*, trans. M. Piercy and D. Berlyne. Totowa, New Jersey: Littlefield, Adams, and Co.

Rauscher, F. H., J. L. Hughes, and R. J. Miller 1996. "Music-Induced Mood Affects Spatial Task Performance." Paper presented at the meeting of the American Psychological Society, San Francisco.

Rauscher, F. H. and G. L. Shaw 1997. "Key Components of the Mozart Effect." Manuscript in preparation.

Rauscher, F. H., G. L. Shaw, and K. N. Ky 1993. "Music and Spatial Task Performance." *Nature*, *365*, 611.

Rauscher, F. H., G. L. Shaw, L. J. Levine, E. L. Wright, W. R. Dennis, and R. Newcomb. In press. "Music Training Causes Long-Term Enhancement of Preschool Children's Spatial-Temporal Reasoning Abilities." *Neurological Research*.

Rauscher, F. H., G. L. Shaw, and K. N. Ky 1995. "Listening to Mozart Enhances Spatial-Temporal Reasoning: Toward a Neurophysiological Basis." *Neuroscience Letters* 185: 44–47.

Rauscher, F. H., G. L. Shaw, L. J. Levine, K. N. Ky, and E. L. Wright 1994. "Music and Spatial Task Performance: A Causal Relationship." Paper presented at the meeting of the American Psychological Association, Los Angeles.

Rauscher, F. H., G. L. Shaw, L. J. Levine, and E. L. Wright 1993. "Pilot Study Indicates Music Training of Three-Year-Olds Enhances Specific Spatial Reasoning Skills." Paper presented at the first economic summit of the National Association of Music Merchants, Newport Beach, California.

Rideout, B. E. and C. M. Lauback 1996. "EEG Correlates of Enhanced Spatial Performance following Exposure to Music." *Perceptual and Motor Skills* 82: 427–432.

Samson, S., and R. J. Zatorre 1994. "Contribution of the Right Temporal Lobe to Musical Timbre Discrimination." *Neuropsychologia* 32: 213–240.

Sarnthein, J., A. von Stein, G. L. Shaw, F. H. Rauscher, P. Rappelsberger, and H. Petsche 1996. "EEG Investigation of the Positive Effect of Music on Spatio-Temporal Reasoning." Manuscript in preparation.

Seashore, C. E. 1938. *The Psychology of Music*. New York: McGraw Hill.

Seashore, C. E., D. Lewis, and J. Saetveit 1956. *Seashore Measures of Musical Talents*. New York: The Psychological Corporation.

Serafine, M. L. 1981. "Musical Timbre Imagery in Young Children." *Journal of Genetic Psychology* 139 no. 1: 97–108.

Shenoy, K. V., J. Kaufman, J. V. McGrann, and G. L. Shaw 1993. "Learning by Selection in the Trion Model of Cortical Organization." *Cerebral Cortex* 3: 239–248.

Stiles-Davis, J., M. Kritchevsky, and U. Bellugi 1988. *Spatial Cognition: Brain Bases and Development*. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Stough, C., B. Kerkin, T. Bates, and G. Mangan 1994. "Music and Spatial IQ." *Personality and Individual Differences* 17 no. 5: 695.

Thorpe, L. A. and S. E. Trehub 1989. "Duration Illusion and Auditory Grouping in Infancy." *Developmental Psychology* 25: 122–127.

Trehub, S. E. and L. A. Thorpe 1989. "Infants' Perception of Rhythm: Categorization of Auditory Sequences by Temporal Structure." *Canadian Journal of Psychology* 43: 217–229.

Trehub, S. E., D. Bull, and L. A. Thorpe 1984. "Infants' Perception of Melodies: The Role of Melodic Contour." *Child Development* 55: 821–830.

Weinberger, N. M., and T. M. McKenna 1988. "Sensitivity of Single Neurons in Auditory Cortex to Contour: Toward a Neurophysiology of Music Perception." *Music Perception* 5: 355–390.

Zatorre, R. J., A. C. Evans, and E. Meyer 1994. "Neural Mechanisms underlying Melodic Perception and Memory for Pitch." *Journal of Neuroscience* 14: 1980–1919.