LEARNING, ARTS, AND THE BRAIN

The Dana Consortium Report on Arts and Cognition

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Learning, Arts, and the Brain

The Dana Consortium Report on Arts and Cognition

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Arts and Cognition
Findings Hint at Relationships

Michael S. Gazzaniga, Ph.D.

University of California at Santa Barbara

In 2004, the Dana Arts and Cognition Consortium brought together cognitive neuroscientists from seven universities across the United States to grapple with the question of why arts training has been associated with higher academic performance. Is it simply that smart people are drawn to "do" art—to study and perform music, dance, drama—or does early arts training cause changes in the brain that enhance other important aspects of cognition?

The consortium can now report findings that allow for a deeper understanding of how to define and evaluate the possible causal relationships between arts training and the ability of the brain to learn in other cognitive domains.

The research includes new data about the effects of arts training that should stimulate future investigation. The preliminary conclusions we have reached may soon lead to trustworthy assumptions about the impact of arts study on the brain; this should be helpful to parents, students, educators, neuroscientists, and policymakers in making personal, institutional, and policy decisions.

Specifics of each participating scientist's research program are detailed in the appended reports that can be downloaded from www.dana.org. Here is a summary of what the group has learned:

1. An interest in a performing art leads to a high state of motivation that produces the sustained attention necessary to improve performance and the training of attention that leads to improvement in other domains of cognition.
2. Genetic studies have begun to yield candidate genes that may help explain individual differences in interest in the arts.
3. Specific links exist between high levels of music training and the ability to manipulate information in both working and long-term memory; these links extend beyond the domain of music training.

4. In children, there appear to be specific links between the practice of music and skills in geometrical representation, though not in other forms of numerical representation.
5. Correlations exist between music training and both reading acquisition and sequence learning. One of the central predictors of early literacy, phonological awareness, is correlated with both music training and the development of a specific brain pathway.
6. Training in acting appears to lead to memory improvement through the learning of general skills for manipulating semantic information.
7. Adult self-reported interest in aesthetics is related to a temperamental factor of openness, which in turn is influenced by dopamine-related genes.
8. Learning to dance by effective observation is closely related to learning by physical practice, both in the level of achievement and also the neural substrates that support the organization of complex actions. Effective observational learning may transfer to other cognitive skills.

The foregoing advances our knowledge about the relationship between arts and cognition. These advances constitute a first round of a neuroscientific attack on the question of whether arts training changes the brain to enhance general cognitive capacities. The question is of such wide interest that, as with some organic diseases, insupportable answers gain fast traction and then ultimately boomerang.

This is the particular difficulty of correlations; the weakness and even spuriousness of some correlational studies led to the creation of the consortium. Correlation accompanies, parallels, complements or reciprocates, and is interesting to observe, but only an understanding of mechanisms drives action and change.

Although scientists must constantly warn of the need to distinguish between correlation and causation, it is important to realize that neuroscience often begins with correlations—usually, the discovery that a certain kind of brain activity works in concert with a certain kind of behavior. But in deciding what research will be most productive, it matters whether these correlations are loose or tight. Many of the studies cited here tighten up correlations that have been noted before, thereby laying the groundwork for unearthing true causal explanations through understanding biological and brain mechanisms that may underlie those relationships.

Moreover, just as correlations may be tight or loose, causation may also be strong or weak. Theoretically, we could claim a broad causation, akin to “smoking causes cancer,” with randomized prospective trials showing that children taking arts training can improve certain cognitive scores. Yet, even such a clear-cut result would be weak causation, because we would not have found even one brain mechanism of learning that could suggest progress in understanding such mechanisms to guide optimal arts exposure. Nor would we have found by what mechanisms the brain generalizes that learning, nor anything about developmental periods where the brain is particularly sensitive to growth from specific types of experience.

A vast area of valuable research lies between tight correlation and hard evidence based causal explanations. Theory-driven questions using cognitive neuroscience methods can go beyond efficacy-of-outcome measures by framing experiments that demonstrate how changes in the brain, as a result of arts training, enrich a person’s life, and how this experience is transferred to domains that enhance academic learning. Such mid-ground studies would significantly advance our knowledge even though they are not at the level of cellular or molecular explanations.

The consortium work on dance is a good example. Our research indicates that dance training can enable students to become highly successful observers. We found that learning to dance by watching alone can be highly successful and that the success is sustained at the neural level by a strong overlap between brain areas that are used for observing actions and also for making actual movements. These shared neural substrates are critical for organizing complex actions into sequential structure. In the future we can test if this skill in effective observation will transfer to other academic domains.

Nailing down causal mechanisms in the complex circuitry of the brain is a tall order. The arts and cognition studies by the Dana consortium during the past three years lay a foundation for understanding the mechanisms needed for action; we believe they offer the validity essential for the future studies that will build on them.

A life-affirming dimension is opening up in neuroscience; to discover how the performance and appreciation of the arts enlarge cognitive capacities will be a long step forward in learning how better to learn and more enjoyably and productively to live. We offer several suggestions for extensions of the research reported herein:

1. Previous work has established that different neural networks are involved in various forms of the arts such as music, visual arts, drama and dance. Future studies should examine the degree to which these networks are separate and overlap.
2. We also require evidence of how high motivation to pursue an art form will lead to more rapid changes in that network and must find out to what degree such changes may influence other forms of cognition.
3. The links between music and visual arts training and specific aspects of mathematics such as geometry need to be more profoundly explored with advanced imaging methods.
4. The link between intrinsic motivation for a specific art (e.g. music and visual arts) and sustained attention to tasks involving that art needs to be followed up with increased behavioral evidence and imaging methods that can demonstrate that changes in specific pathways are greater for higher levels of motivation.
5. The search for individual indicators of interest in and influence by training in the arts should continue to be examined by a combination of appropriate questionnaire research, use of candidate genes already identified and whole genome scans.
6. Further research also should pose these questions:
    a. To what degree is the link between music training, reading and sequence learning causative? If it is causative, does it involve shaping of connectivity between areas of the brain network involved?
    b. Is the link between music and drama training and memory methods a causative one? If so, can we use brain imaging to determine the mechanism?
    c. What is the role of careful observation and imitation in the performing arts? Can we prepare our motor system for complex dance movements by simply observing or imagining desired movements? Does the discipline and cognitive skill to achieve this goal transfer?

The consortium's accomplishments to date have included bringing together some of the

leading cognitive neuroscientists in the world to sort out correlative observations on the arts and cognition, and to begin the analysis of whether these relationships are causal. The consortium's new findings and conceptual advances have clarified what now needs to be done. The specific suggestions noted above grow out of the project's efforts—and surely others are possible as well. These suggestions represent a further deepening of a newly accessible field of investigation. Fresh results as well as new ideas are presented herein on how to continue to research this topic.

In my judgment, this project has identified candidate genes involved in the predisposition to the arts and has also shown that cognitive improvements can be made to specific mental capacities such as geometric reasoning; that specific pathways in the brain can be identified and potentially changed during training; that sometimes it is not structural brain changes but rather changes in cognitive strategy that help solve a problem; and that early targeted music training may lead to better cognition through an as yet unknown neural mechanism. That is all rather remarkable and challenging.

How Arts Training Influences Cognition

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University of Oregon

Summary

In our research, we studied how training in the arts can influence other cognitive processes through the underlying mechanism of attention. We also identified the neural network (system of connections between brain areas) from among the several involved in attention that is most likely to be influenced by arts training. Finally, we explored how individual differences in genes and temperament relate to the amount of improvement achieved, through attention training.

We developed a theory about how arts training might work in which we hypothesized that: 1) there are specific brain networks for different art forms; 2) there is a general factor of interest or openness to the arts; 3) children with high interest in the arts, and with training in those arts, develop high motivation; 4) motivation sustains attention; and 5) high sustained motivation, while engaging in conflict-related tasks, improves cognition.

The first two elements were tested through a questionnaire administered to adults. We found a statistically significant association between having an interest in a specific art form and producing that type of art. The questionnaire analyses also revealed that a general aesthetic interest, or openness to the arts, was correlated with an appreciation of all of the art forms except dance. In our study, dance was confused between the art form and the social activity.

We tested whether motivation sustains attention by randomly assigning children into a control group, which performed a speeded task, or to an experimental group, in which the children performed tasks under motivating conditions of either reward or knowledge of their results. We found that high levels of motivation led to strong improvements in task performance, particularly when motivation was sustained for longer periods of time. The findings support the idea that interest in the arts allows for sustained attention,

providing an increased opportunity for the training to be effective.

We also studied training of an executive attentional network that is related to the self-regulation of cognition and emotion. We assessed whether engaging in tasks designed to teach children how to resolve conflict improves cognition. We randomly assigned children to a control or intervention group. The intervention consisted of five days of training on computerized exercises of conflict resolution, under highly motivating conditions.

Children receiving attention training in conflict resolution under motivating conditions, compared to controls, showed significantly greater improvement on intelligence test scores. This suggests that the effects of attention training generalized to a measure of cognitive processing that extended far beyond the training exercises. Brain imaging using EEG (electroencephalophy, which records the brain's electrical activity) also showed that during executive attention tasks, trained children had patterns of activity similar to those found in adults, while untrained children (control group) did not.

Our genetics studies suggest that specific forms of several genes involved in the transmission of the neurotransmitter dopamine from one brain cell to another may be related to differences among children and among adults in how efficiently they resolve conflict. We are continuing these genetic studies.

In our work, we used specific training exercises designed to be engaging and motivating to improve attention. However, we believe that any training that truly engages the interest of the child and motivates the child can serve to help train attention. Our findings indicate that arts training could work through the training of attention to improve cognition for those with an interest and ability in the arts.

Introduction

We have been investigating an executive attentional network of connections between brain areas that appears to be an important underlying foundation of cognitive improvements related to arts training. This executive attention network is related to the self-regulation of cognition and emotion (Posner and Rothbart, 2007a,b; Rothbart and Rueda, 2005; Rueda, Posner, and Rothbart, 2004). The network involves specific brain areas, including the midline and lateral frontal areas (Fan, McCandliss et al 2005a). We have shown that the efficiency of executive attention is related to a higher order factor in parental reports about their children called effortful control (Rothbart and Rueda, 2005). Thus executive attention plays an important role in the child's everyday control of thoughts, feelings, and behavior that can be observed and reported by their parents.

… executive attention plays an important role in the child's everyday control of thoughts, feelings and behavior…

…this attentional brain network is related to self-regulation of cognition and emotion.

The ability to study the executive attentional network is enhanced by progress in neuroimaging (Posner and Rothbart, 2007a) and in sequencing the human genome (Posner, Rothbart, and Sheese, 2007; Venter et al, 2002). These two scientific fields make it possible to consider high level cognitive skills in terms of experiential and genetic

factors that shape the development of underlying brain networks (systems of connections between brain areas).

Our previous extensive studies on the processes of attention used by infants and children have established that this attentional brain network is related to self-regulation of cognition and emotion. It is involved in attending to high level skills, including making word associations. For instance, during the act of attending to one language while suppressing related responses in another language, the executive attentional network is the one most likely to be active.

… individual differences in the development of the executive attentional network are related to differences in … brain areas that are involved in high level skills.

In this research, we studied the network's development in children ranging from two-and-one-half to seven years of age (Rueda et al., 2004). Additionally, we asked parents of the children enrolled in our study to fill out a self-report questionnaire. We examined children's abilities to self-regulate cognition and emotion. The children were tested on a number of conflict tasks (Fan, Flombaum et al., 2003), which have been shown to activate the executive attentional network.

Individual differences among children in development of this network were related to parents' reports of the degree to which their children were able to regulate their own behavior (Rothbart and Rueda, 2005) and to their ability to delay rewards. Additionally, through imaging studies, it was found that individual differences in the development of the executive attentional network are related to differences in the activation of brain areas that are involved in high-level skills (Posner and Rothbart, 2007b).

Through genetic studies, it has been shown that specific forms of several dopamine and serotonin genes were related to differences in the efficiency with which conflict is resolved. Two of these genes have also been related to activation of the part of the executive attention network located in the brain's cingulate gyrus (Fan, Fossella et al., 2005).

Based on these findings, we had adapted a set of exercises, developed from animal studies, to train developmentally healthy four and six year olds to focus their attention. We randomized the children into two groups: an attention training group (experimental group) and a "control" group who interacted with videos not designed to improve attention.

Children in the experimental group, compared to those in the control group, showed greater improvement in IQ measures, showing generalization beyond the direct measures of attention (Rueda, Rothbart, Saccamanno, and Posner, 2005; 2007).

Our Hypotheses

We considered it as important to have an explanation of how the arts influence cognition, as it is to have evidence that arts training influences cognition. We hypothesized, therefore, that the brain network involved in executive attention and effortful control can be strengthened by specific learning. Moreover, we hypothesized that the enthusiasm that many young people have for music, art, and performance could provide a context for paying close attention. This motivation could, in turn, lead to improvement in the attention network, which would then generalize to a range of cognitive skills.

Our training study supported this proposed theory about the mechanisms by which training in

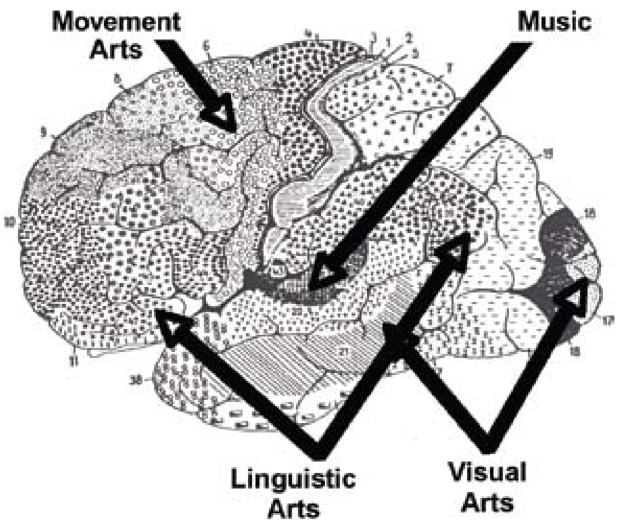

Figure 1

the arts can have a persistent effect on a wide variety of cognitive processes.

The theory is based on the idea that each individual art form involves separate brain networks. In Figure 1, we summarize some of the specific brain areas involved in different art forms.

The theory is … that each individual art form involves separate brain networks.

The results from the parents' questionnaire suggest that there is some variation in a child's degree of interest in different art forms. In addition, interest in each of the arts indicated in Figure 1 is correlated with a General Arts Interest factor.

This General Arts Interest factor was itself correlated with a temperamental characteristic called "Orienting Sensitivity" (Rothbart, Ahadi, and Evans, 2000; Evans and Rothbart, 2008). Orienting Sensitivity is, in turn, strongly related to the Big Five-personality factor of openness. Therefore, we related the degree of general arts interest with the personality factor of openness.

Interest in aesthetics, or openness to an interest in the arts, has been found in studies of adults to be related to specific forms of genes that direct the production of the neurotransmitter dopamine. Some of these same genes have also been related to the efficiency of executive attention, which in turn is modulated by dopamine.

Elements of the Arts Theory

Our theory of how interest and training in the arts leads to improved general cognition generally, involves five elements. They are listed below, and then discussed.

1. There are specific brain networks for different art forms.
2. There is a general factor of interest in the arts.
3. When this general factor of interest in the arts is high, training in an appropriate specific art form produces high interest or motivation.
4. This interest or motivation sustains attention.
5. High sustained attention in conflict-related tasks, of the type used in our attention–training studies improves cognition.

Study Design and Results

To explore the first three elements of our theory, we constructed a questionnaire based on the Evans and Rothbart's Adult Temperament Scale (ATQ) (Evans and Rothbart, 2007). We also added a number of aesthetics questions listed below that were developed by Victor, Rothbart, and Baker (in preparation). The questionnaire was administered to samples of University of Oregon undergraduates and to a sample of adult residents of the community of Bend, Oregon.

General Aesthetic Activity	Perception Items	Production Items
I show a lot of imagination.	I like to look at art.	I like to paint or draw. I like making sculptures or ceramics.
I am creative.	I enjoy listening to music.	I would enjoy playing a musical instrument.
I am artistic.	I like watching plays.	I enjoy photography or filmmaking. I like to write.
		I like dancing.

Table 1: Structure of the Aesthetics Questionnaire

Element 1: Appreciation of Art Relates to Pleasure in Producing that Art

We tested the hypothesis that an appreciation of a specific type of art was related to pleasure in producing that type of art. We correlated responses to questionnaire items that assessed interest in perceiving and producing specific art forms.

Interest in looking at art was correlated with interest in painting/drawing r=.48. The correlation, termed "r" reflects the relation between observing arts and producing the art. This correlation was significant statistically, meaning that it was unlikely to be present by chance alone. Similarly, interest in making ceramics or sculptures was statistically correlated with pleasure in producing that type of art ($r = .42$, $p < .01$). Interest in listening to music was correlated with interest in playing a musical instrument ($r = .31$, $p < .01$). Interest in watching plays was correlated with interest in photography or filmmaking ($r = .33$, $p < .01$) and interest in writing ($r = .28$, $p < .01$).

Element 2: Appreciation of an Art Form Relates to General Aesthetic Interest

We tested the hypothesis that appreciation of specific types of art is related to general aesthetic interest. We computed a score for "general aesthetic interest" by calculating the average ("mean") of non-specific artistic items ("I am creative," "I am artistic," "I show a lot of imagination"). We looked for correlations between this average score and each item that assessed interest in a specific art form.

All of the specific art form items were significantly ($p < .05$) correlated with the score on general aesthetic interest, except "I like dancing." The median correlation was r=.35 for all of the items except dancing.

These results also showed that the general aesthetics factor (Table 1, Row 1) was highly correlated with the temperament factor of orienting sensitivity (openness).

Element 3: High Interest is Linked to High Motivation

This element links training in appropriate arts with motivation. The link between arts training and motivation, though plausible, remains speculative, and needs to be tested through experimental research. We postulate that children who have a high level of orienting sensitivity (openness) and at least normal interest in a particular art will have high motivation to receive training in that art.

Our research has provided evidence that motivation sustains attention.

Element 4: Motivation Sustains Attention

Our research has provided evidence that motivation sustains attention. We found, in children aged four-and-one-half and seven years old, that high levels of motivation, as induced by reward and feedback, led to strong improvements in sustained attention (Kieras, 2006). When feedback and reward were used to heighten motivation, children showed improved levels of alerting during a task. We found that children performing the task under motivating conditions sustained their attention over longer periods of time compared to children who performed the task in the absence of such motivating conditions.

We propose, based on these findings, that arts training for those with a high level of interest would allow for sustained attention, thereby increasing the opportunity for training to be effective.

Element 5: High Sustained Attention on Conflict Tasks Improves Cognition

We have published evidence that one form of attention training does, in fact, improve the underlying network that is involved in executive attention for effortful control of cognition and emotion (Rueda, et al, 2005). To examine the role of experience on the executive attentional network, we developed and tested a five-day training intervention that uses computerized exercises. The exercises were designed to be interesting and motivating to young children in just the way that we assume arts training to be for children with the appropriate interests.

We tested the effect of this training intervention during the period of major development of executive attention, in children between the ages of four and seven (Rueda, Posner, Rothbart, and Davis-Stober, 2004). We hypothesized that children trained in attention related to effortful control of cognition and emotion would show improvement in conflict resolution by changes in the underlying executive attentional network; and we hypothesized that this effect would be generalized to other aspects of cognition.

To test this hypothesis, we used EEGs (electroencephalograms), electrodes that are placed on the scalp and record electrical activity of the brain. Our EEG data showed clear evidence that training improved the efficiency of the executive attentional network in resolving conflict.

The technical explanation is that the "N2" component of the scalp-recorded ERP (event-related potential, which is an electrical response to a specific stimulus) has been shown to arise in the brain's anterior "cingulate" region, and is related to the resolution of conflict (Rueda, et al, 2004; van Veen and Carter, 2002). We found N2 differences between congruent (matched) and incongruent trials of the Attentional Network Test in six year olds trained in attention. The differences in the attentional network seen in the trained six year olds resembled those found in adults.

In four year olds, training appeared to influence patterns of electrical activity measured by electrodes placed above the anterior part of the brain, which is related to emotional control areas of the brain's

anterior cingulate region (Bush, Luu and Posner, 2000). Taken together, the data on the four and six-year-old children suggest that attention training altered the network involved in the resolution of conflict, and that the alteration was more like the network efficiency seen in adults.

... attention training altered the network involved in the resolution of conflict ...

We also found a significantly greater improvement in intelligence test scores in the group of children who received attention training, compared to the control group of children. This finding suggests that the effects of attention training generalized to a measure of cognitive processing that extended far beyond the training exercises. We did not observe changes in the children's temperament over the course of the training, but the inability to observe such changes was expected, since such a short time elapsed between assessment sessions.

Genes Involved in Attention

Our findings indicate that not all children need or benefit from attention training. This may be one reason why variability in children's performance following attention training is so high. In some of our studies, for instance, children with the most initial difficulty in resolving conflict showed the greatest overall improvement in this task following attention training. Our research also suggests that genetic markers may exist that help explain differences seen in children's abilities to selectively focus attention for effortful control of cognition and emotion.

We obtained genetic information on most of the six-year-old children who participated in our research. Children were divided into two groups according to which of two forms they carried of the gene called the dopamine transporter gene ("DAT1"). The dopamine transporter gene is responsible for conveying the neurotransmitter dopamine from one brain cell to another. This neurotransmitter has been shown to be involved in attention, arousal, and problem solving, along with other cognitive functions such as learning and memory.

Since we found that children differed in their ability to selectively focus attention in effortful control of cognition and emotion ("attentional ability"), and that this difference rested, in part, on which of the two forms of the dopamine transporter gene each had (Posner, Sheese and Rothbart, 2007), we decided to examine how this attentional network system develops from infancy and how genes may influence the network's development. To accomplish this, we obtained genetic information on 70 children. We then measured attention and temperament from experimental studies and parental reports. We found evidence that executive attention is present in infancy, and that it can be measured in infants and young children by assessing their anticipatory looks.

We are beginning to explore the origin in infancy of the executive attention network, as measured in childhood. To do so, we are examining a larger cohort of children in a longitudinal study, in which we follow seven-month-old infants until they reach age four. During this time, we characterize the development of their executive attention network, and correlate children's performance in selective attention and control at age four with characteristics of their network's development.

A major interest, beyond healthy abilities in effortful control and selective attention, is to determine how these abilities are altered in attention deficit hyperactivity disorder (ADHD). We have approached this question through our genetic studies. We found that during the early years of life, individual differences in attention and effortful control are related to the CHRNA4 gene. In adults, this gene has been shown to be related to

tasks that involve orienting. We also found that the presence of the seven-repeat form of the dopamine 4 receptor gene (DRD4), interacted with the quality of parenting skills to influence several related aspects of temperament. These aspects include level of activity (such as hyperactivity), sensation seeking, and impulsivity. These characteristics are frequently seen in children with ADHD.

Children with the seven-repeat form of the DRD4 gene show more moderate levels of activity and impulsivity when parenting is of high quality. Children who do not have the seven-repeat form of the DRD4 gene, in contrast, are relatively uninfluenced by parenting (Sheese, Voelker, Rothbart and Posner, 2007).

Genetic studies have shown that the seven-repeat form of the DRD4 gene is under positive selective pressure (it tends to be passed on—inherited—over other forms of the gene). We suggest, therefore, that the seven-repeat form of DRD4 gene is being genetically selected because it increases the influence of parenting on child behavior. This raises the possibility that positive selection of genetic variation, in general, is related to the degree to which a particular form of a gene makes behavior subject to cultural influences, including parenting (Posner, in press).

Although most of these genetic findings are not directly related to aesthetics, we found that the presence of the seven-repeat form of the DRD4 gene, in the parents of the children we studied, was related to parents' self-reported lower levels of interest in specific arts, such as music, the visual arts, or theater. We do not know if this finding differs as a function of the exposure of these parents during their childhood. This is a possibility, however, given our findings about the relationship between the seven-repeat form of the DRD4 gene and the influence of parenting skills on children's behavior.

No other genes showed a significant relationship to the composite measure of enjoyment of specific art forms. However, one dopamine gene (DBH) and one serotonin gene (TPH2), both of which have been shown to be related to executive attention, were also related to our more general "interest in aesthetics" as measured by questionnaire items.

We believe that success in arts training rests in part on the temperament of the child being trained.

Future Study Directions

We believe that success in arts training rests in part on the temperament of the child being trained. Temperament in turn is determined by genes in interaction with the environment. Since it is so important to study the role of genes and the interaction of genes and environment in influencing attention to the arts, we plan to conduct a full genome scan to determine the range of genetic variation that might influence aspects of executive attention, effortful control, and aesthetic preference. We have pooled data from our adult participants according to whether they scored high or low in aesthetics preference, and plan to determine which of the 30,000 genes in the human genome might differ between the two groups. We plan a similar investigation of possible genes involved in executive attention, effortful control, and positive and negative affect in our children.

Conclusion

Our three-year research has led to a general framework for viewing how arts training changes cognition. Our theory stresses that there are individual differences in interest and motivation toward the arts. Our theory suggests that arts training works through the training of attention to improve cognition for children with interests and abilities in the arts.

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Musical Skill and Cognition

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Summary

We explored the effects that training in music and in acting have on memory skills. Our studies to date suggest that the benefits of enhanced memory skills conferred by training in these two art forms result from strategic changes on the cognitive system used to maintain and store retrievable memories.

Our behavioral studies on memory were undertaken in a group of college-aged participants who had been extensively trained in music, and in a similar group (in terms of gender, age, and education) of non-musician controls. We tested the two groups' long-term verbal memory. We found that the musically trained participants had better scores compared to the controls, but this difference disappeared when the musicians were prevented from rehearsing.

These results suggest that people trained in music apply strategies of rehearsal to maintain information in memory more effectively.

We used functional magnetic resonance imaging (fMRI) to visualize brain activity involved in long-term verbal memory, and to determine whether the musicians' better scores, compared to non-musicians, were accompanied by more extensive activation in brain regions that have been implicated in rehearsal processes. While undergoing fMRI imaging, 11 trained musicians and 11 non-musician demographically similar control participants were instructed to rehearse and remember groups of three words. All participants first were instructed to use simple repetition to rehearse the words, and then they were instructed to use "elaborative" rehearsal (creating an emotionally aroused context) for remembering the words.

The musicians showed more brain activation using rote rehearsal, while the non-musicians showed more brain activation using elaborative rehearsal. The results

suggest that the musicians, through rote rehearsal, are able to bind the remembered items to the context in which they occur.

Our studies in 21 actors trained in theater performance, compared to 24 demographically similar control participants, revealed that actors do not have better verbatim verbal memory. Instead, they are better able to extract the general idea from the verbal material, and this skill is transferable to other verbal cognitive skills.

In aggregate, our results to date indicate that the process of rehearsal, used in music and acting training, implements a strategy for focusing attention that enhances memory, and that this skill transfers to other cognitive functions involving memory. Rehearsal is an implementation of an attentional strategy, or "executive attention" as defined by Michael Posner.

Rehearsal is a way to implement an attentional strategy...

Introduction and Conclusions

Most final reports about research programs begin with a summary of the empirical studies and the resulting findings. We begin, by contrast, with a summary of our conclusions and then move on to the findings that support these conclusions. We do this as a way of giving the reader a sense of the destination that this research has reached before reviewing the journey that led to this destination.

What we seem to be learning from the study of the effects of two arts (music and acting) on cognition is that the benefits of each are not a result of structural changes that they produce in the cognitive system; rather, the benefits are the result of strategic changes on the cognitive system. In an important way, this is consistent with Michael Posner's work on the effect of arts training on "executive attention."

He summarizes his work by arguing that the mediational path between arts training and cognitive performance goes through changes in motivation, which lead to changes in attentional focus. It is this change in attentional focus, he argues, that heightens performance in a variety of cognitive tasks, because most cognitive tasks require the kind of cognitive control that is needed to overcome prepotent responses when there is conflict present in the environment.

Our work focuses on this general theme within the context of memory processes. What we have found for musicians is that it is not that their memory is better; rather, it is that they apply strategies of rehearsal to maintain information in memory more effectively. Rehearsal is a way to implement an attentional strategy, in the sense defined by Posner as "executive attention."

Similarly, what we have found for actors is not that their memory for verbal material is better; it is that they apply strategies for extracting semantic themes from verbal material, and these strategies result in better memory for the material in question. Again, this is a matter of strategy, and a matter of applying attention to semantic extraction rather than verbatim memorization.

Overall, then, what is emerging is a picture in which there is a mediational path that governs the now amply documented effects of arts training on memory. The path goes from skill in the arts, to heightened use of effective strategies for memorization, to better memory. We do not yet understand the mechanisms at work in learning in the various arts domains that lead to this path, but the tentative conclusion that the mediational path governs the effects of arts training on memory opens up the field for studying how training in the arts, and in other domains, can have such beneficial effects.

The Studies and their Results

The empirical work that leads us to this overall view comes from our studies of music and memory on the one hand, and from the study of acting and memory on the other hand. Let us summarize our findings.

Music and Memory

Study 1: Comparing Groups on Verbal Memory

We have completed a program of behavioral research that examined the relationship of musical skill and memory. The results of this work are reported in Franklin (in press).

In brief, we selected a cohort of college-aged participants who were well-matched demographically, but differed substantially in musical experience. Specifically, one-half of the study participants had at least 10 years of musical experience, and practiced at least 10 hours of music per week. The other half had played an instrument for less than a year in their entire lives and did not play music currently. The two groups were similar in terms of demographics, including gender, age, education, grade point average, SAT scores, and performance on the Raven's Test of Advanced Progressive Matrices.

We found that musicians scored better compared to the non-musicians on a test of long-term verbal memory, but this advantage disappeared when we prevented the musicians from rehearsing the material. We also found evidence that the musicians had a greater span of verbal working memory compared to the non-musicians. We attribute both of these effects to the enhanced use of rehearsal skills in musicians, rather than to a "hard-wired" difference in verbal memory capacity. This result suggests that musical training has the added benefit of training another cognitive skill, rehearsal, which has spillover effects onto cognitive tasks that engage verbal memory.

Study 2: Functional Neuroimaging of Verbal Memory

Our results from studies of the effects of musical training on verbal memory were sufficiently promising to prompt us to conduct a study using functional MRI (fMRI, functional magnetic resonance imaging) of the brain in 11 trained musicians and 11 matched "control" (non-musician) participants, to delve into the neural mechanisms involved. We searched for a long-term verbal memory model test that would yield robust activation in the brain's medial temporal region, and in other regions of the brain's cortex. Our search led to a model developed by Davachi and Wagner (2002).

These authors were kind enough to provide us with the stimuli they used for their experiment, and we used those stimuli to construct our study of the musicians and their "matched controls" (demongraphically similar non-musicians). The study design involved having participants undergo fMRI imaging while they encoded (stored in memory in a retrievable way) triplets of words in one of two instruction conditions. One instruction condition involved simple repetition rehearsal, and the other involved "elaborative" rehearsal (constructing a plausible relationship among the words) in order to make a quality judgment on the stimuli.

The interesting feature of this paradigm is that it compared these two rehearsal conditions, since the results of our first study (described above) implicate rehearsal skill as the critical outcome of musical training. After participants encoded all the stimuli while being scanned, they later were tested on their memory of all the individual words, in a recognition test.

We then took a retrospective review of the data ("back-sorted" the data), comparing participants' performance on the word-recognition test with an examination of brain activations, seen on imaging,

that had resulted in successful versus unsuccessful encoding of the words. This allowed us to compare brain activation profiles for musicians versus control participants, to see whether the advantage shown in our first study for musicians behaviorally, is accompanied by a more extensive activation profile in brain regions that have been implicated in rehearsal.

Although all of our data have been collected and we are just at the beginning stages of analysis, our first pass at analyzing the data shows some interesting features. First of all, as with the findings of Davachi and Wagner, we also find that engagement of the brain's medial temporal lobe occurs with both elaborative and rote encoding instructions. This demonstrates the robustness of this brain activation effect, and that the effect is replicable.

Even more interesting, however, is the pattern of brain activations for rote versus elaborative encoding in musicians compared to non-musicians. The musicians showed more engagement of the brain's medial temporal lobe for rote than for elaborative encoding, while the non-musicians showed exactly the reverse.

We need to explore this finding in greater detail, and we certainly need to conduct analyses to determine whether these brain activation patterns were associated with whether or not the participants later correctly recognized each word. Nonetheless, this preliminary imaging finding seems to be consistent with our behavioral finding of enhanced verbal memory in musicians as a function of a strategic allocation of rehearsal. The musicians appear to be more able to rehearse the verbal memory, and this is what causes greater engagement of the brain's medial temporal lobe structures, as a mechanism to bind the items to the context in which they occur. As we noted, it is yet premature to draw any firm conclusions from these data, and we shall continue our analyses, including a potential collaboration with Mark D'Esposito to conduct some multivariate analyses of the data.

Acting Skill and Memory

Our results with musicians led us to ponder the effects of training in other art forms on memory skill. One seemingly obvious domain in which to address this has to do with training in acting. On the face of it, training in acting would seem a natural place to examine its benefits on verbal memory. Surprisingly, our review of the literature unearthed remarkably little insight about this issue.

… what does seem to differentiate the actor and non-actor groups is how well they can extract gist from verbal material.

Study Design and Results

Consequently, we devised a behavioral study in which we tested 21 actors skilled in live theater, and compared them to 24 demographically matched control participants who had not had acting training. We tested for both long-term and short-term verbal memory skills. We found, contrary to what popular lore may suggest, that actors do not differ from control participants in their verbatim memory for verbal material. It is verbatim memory that one might suppose would be a skill that would be enhanced by training in acting, because actors (at least for live theater) need to memorize long corpora of lines.

Instead, what does seem to differentiate the actor and non-actor groups is how well they can extract gist from verbal material. Perhaps the most interesting implementation of this result comes from the research design used by Roediger and McDermott (1995). In this task, participants receive a set of lists to memorize. Each list is built around a theme. For example, subjects may see the

words, "nap, bed, pillow, rest, night, snooze," etc. They then later have to recall the list. The paradigm distinguishes itself because the theme word around which each list is constructed (in this example, "sleep") is not actually included in the list. Yet in many cases, study participants mistakenly "recall" that this word was part of the list.

We have found that this false recall is much more pronounced among actors than among non-actors. This result suggests to us that what acting confers is a generally enhanced skill to extract gist from verbal material, a skill that is transferrable to other verbal cognitive tasks. It is this skill, we also suggest, that leads to actors being able to assume the roles of their parts. We are currently preparing a manuscript based on these results to submit for publication.

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Effects of Music Instruction on Developing Cognitive Systems at the Foundations of Mathematics and Science

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Summary

Our research examined the relationship between cognitive systems that underlie music and mathematical abilities. Specifically, we undertook studies to determine whether, when children or adolescents produce music—comparing and operating on melodies, harmonies, and rhythms—they activate brain systems that also enable them to compare and operate on representations of number and geometry.

Prior research has established three core systems at the foundation of mathematical reasoning. These are: 1) a system for representing small exact numbers of objects (up to three); 2) a system for representing large, approximate numerical magnitudes; and 3) a system for representing geometric properties and relationships (especially Euclidean distance and angle). Each system emerges in infancy, continues into adulthood, and is malleable by specific experiences.

Children use object representations to learn the meaning of words for numbers and the logic of verbal counting. They use approximation of large numbers to learn arithmetic and its logical properties (such as the inverse relation of addition to subtraction). They use geometric representation to learn and use symbolic maps. Students' mastery of formal mathematics depends, in part, on these three systems.

If music training fosters mathematical ability, it could do so by activating and enhancing one or more of these systems. In addition, music training could activate and enhance processes that connect these systems. We examined, therefore, whether instruction in music is associated with higher performance on tasks that tap each of the three core systems and their connections.

We conducted three experiments in children and adolescents. All three experiments assessed participants' performance on a total of six tests. Three of the tests assessed the

function of each of the core systems underlying math capabilities. Three further tests measured abilities to connect pairs of systems to one another.

The first experiment compared test performance of participants who had moderate training in music or sports. This experiment involved 85 children and adolescents, aged 5-17. The second experiment compared performance of participants who had intense music training to those who had little such training. This experiment involved 32 children, aged 8-13, with high intensity music training and 29 same-aged children with low intensity music training. The third experiment compared the effects of intensive training in music, dance, theater, creative writing, and visual arts. Participants were 80 students, aged 13-18, attending a private school for arts.

Our results show that intensive music training is associated with improved performance in the core mathematical system for representing abstract geometry. Controlling for an array of other variables (such as IQ, academic performance, social and economic factors), we found that intensively music-trained students outperformed students with little or no music training at detecting geometric properties of visual forms, relating Euclidean distance to numerical magnitude, and using geometric relationships between forms on a map to locate objects in a larger spatial layout. While this association was found for participants who received intensive music training, our sample size might have been too small to detect more subtle improvements that may occur from less intensive music training. That possibility needs to be explored in future studies.

Our findings are consistent with recent studies that suggest that sequences of tones spontaneously activate representations of space in the brain. We are now beginning to use behavioral and brain imaging methods to explore the nature and development of this relationship in infants and young children.

Introduction

Music is universal across human cultures and is a source of pleasure to people of all ages, but its place in humans' cognitive landscape is poorly understood. The present research investigates the relation between the cognitive systems at the foundations of music (and possibly other arts) and those at the foundations of mathematics and science. When children or adults produce or actively listen to music, comparing and operating on melodies, harmonies, and rhythms, do they activate brain systems that also allow them to compare and operate on representations of number and geometry? We explore this question by investigating whether instruction in music is associated with higher core abilities in the numerical and spatial domains.

... we test for fundamental associations between musical and mathematical cognition.

Many studies have documented that musically trained children and adults outperform their untrained peers on tests of academic aptitude, especially in mathematics (see Schellenberg, 2005, for discussion). These studies are consistent with the possibility that musical training enhances children's core cognitive capacities. The studies are not conclusive, however, because they focus on complex measures of higher cognitive function, such as IQ scores (e.g. Schellenberg, 2004), that depend on multiple, diverse cognitive abilities. If music instruction enhances particular core cognitive functions, however, its effects should be evident in tasks that tap those core functions more directly.

This report describes three experiments that were conducted to investigate associations between music training and performance on each of the core systems at the foundations of higher cognition in

mathematics and the sciences. The experiments focus on children in three age groups (from kindergarten to high school) and on music instruction at three levels of intensity (from mild extracurricular interest to principal discipline). In different studies, we compare effects of music training to a no-instruction control, to sports training, or to training in other arts disciplines. By these diverse approaches, we test for fundamental associations between musical and mathematical cognition.

neuroscience provides evidence for three core systems at the foundations of mathematics and science

Core Systems of Number and Geometry

Formal mathematics and science are recent achievements in human history: recursive natural number systems emerged only several thousand years ago and are not universal among humans today (Everett, 2005; Pica, Lemer, Izard & Dehaene, 2004). Geometric map-making is even more recent, and the formal unification of number and geometry is less than 400 years old (see Dehaene, 1997, for discussion). Thus, the human brain cannot have been shaped, by natural selection, to perform symbolic mathematics. When children learn mathematics, they harness brain systems that evolved for other purposes.

What are those systems and purposes? Research in cognitive neuroscience provides evidence for three core systems at the foundations of mathematics and science: a system for representing small, exact numbers of objects (up to 3); a system for representing large, approximate numerical magnitudes (e.g., about 20); and a system for representing geometric properties and relationships (especially Euclidean distance and angle) (Feigenson, Dehaene & Spelke, 2004; Wang & Spelke, 2002). Each of these systems emerges in human infancy and continues to function in adults.

Each of the systems, moreover, is malleable by specific experiences (e.g., Green & Bavelier, 2003; Baenninger & Newcombe, 1989; Dehaene et al., 2006; Newcombe & Uttal, 2006). Behavioral experiments provide evidence that these systems guide adults' intuitive reasoning about object mechanics (e.g., McCloskey, 1983), mental arithmetic (e.g., Gallistel & Gelman, 1992), and spatial relationships (e.g., Shepard & Metzler, 1971). Studies using functional brain imaging provide evidence that the systems are activated when adults or children solve problems in symbolic mathematics (e.g., Piazza, Pinel, & Dehaene, 2006; Temple & Posner, 1998). Moreover, impairment of these systems is associated with impaired mathematical and spatial performance (e.g., Lemer, Dehaene, Spelke, & Cohen, 2003; Cappelletti, Barth, Fregni, Spelke, & Pascual-Leone, 2007).

Most importantly, each of these systems supports young children's learning of formal mathematics and science. Children use the system of object representation to learn the meanings of number words and the logic of the system of verbal counting (Lipton & Spelke, 2006). Children also use this system to organize their learning about the mechanical properties of objects (Kim & Spelke, 1999; Huntley-Fenner, Carey, & Solimando, 2002). Children use the system of large, approximate numbers to learn symbolic arithmetic (Gilmore, McCarthy, & Spelke, 2007) and to master logical properties of arithmetic such as the inverse relation between addition and subtraction (Gilmore & Spelke, in press). Finally, children as young as two years of age use the system of geometric representation to make sense of symbolic maps (Winkler-Rhoades, Carey, & Spelke, 2007).

Although the three systems at the core of number and geometry are relatively independent of one another at the start of human life, they

become linked over the course of human cognitive development, and the most important linkages emerge before children begin their formal education. When children master verbal counting, at about 4 years of age, they connect their representations of small, exact numbers and large, approximate numbers to construct new concepts of natural number (Spelke, 2003).

By the time children enter kindergarten, they have come to relate their representations of number to their representations of space and construct the "number lines" that will become central to their mastery of measurement and higher mathematics (Siegler & Opfer, 2003; de Hevia & Spelke, in review). Even earlier, children begin to link their representations of objects and geometry: they detect the geometric relations among a set of objects and use those relations to understand maps (Shusterman, Lee & Spelke, in press: Winker-Rhoades, et al., 2007). These linkages provide kindergarten children with highly useful and versatile tools for mastering mathematics and science in school (see Gelman, 1991; Griffin & Case, 1996).

If music training enhances mathematical ability, therefore, it could act in either of two general ways. First, musical processing may specifically activate one or more of the core systems, and so music training may enhance processing of small exact numbers, large approximate numbers, or geometric relationships. Second, musical processing may specifically activate processes that connect different systems together in the construction of natural number, number lines, or symbolic maps.

Our consortium research investigates the first suite of possibilities by testing whether children and adolescents with more musical experience show enhanced representations of small exact numbers, of large approximate numbers, or of geometric relationships in small-scale visual arrays or large-scale spatial layouts. It investigates the second suite of possibilities by testing whether children with more musical experience show enhanced abilities to represent and operate on symbolic natural numbers, number lines, and maps.

The Experiments

We conducted three experiments comparing children and adolescents with training in music to those with (a) no specific training, (b) training in sports, or (c) training in other art forms. Separate experiments tested for effects of mild to moderate training in children and adolescents (Experiment 1), moderate to intense training in children (Experiment 2) and highly intense training in adolescents (Experiment 3).

In Experiment 1, we studied 5- to 17-year-old children and adolescents from an affluent suburban Massachusetts community who attended either a music school offering Saturday music lessons, or a soccer program offering Saturday sports lessons. Both programs offered lessons to all interested children, and both were attended primarily by children with only a mild to moderate interest in music or sports. In Experiment 2, we compared a group of 8- to 13-year-old children receiving intense music training, mostly recruited from music schools in the Boston area to which they were admitted by audition, to a group of control children with little or no music training. In Experiment 3, we studied 13- to 18-year-old students attending a private and selective high school for the arts, and we compared those majoring in different arts disciplines: music, dance, theater, writing, or visual arts.

Methods and Measures

Participants were given six behavioral tests of mathematical and spatial abilities: three tests tapping core systems of numerical and spatial representations and three tests tapping abilities to link those systems. Because all of the abilities emerge in preschool children, we were able to use the same tests on participants ranging in age

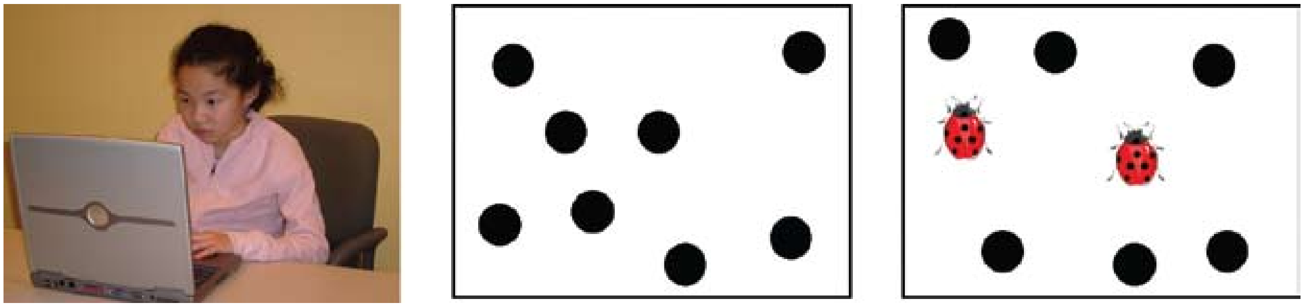


Fig. 1a. Multiple object tracking ("which is your ladybug?")

from 6 to 18 years. On each test, participants were tested at a wide range of difficulty levels so as to reveal patterns of variation both across age and across individuals.

In addition to these tests (described below), each participant was given a test of verbal ability (the vocabulary sub-test of the Wechsler Intelligence Scale for Children), and a questionnaire assessment of his or her history of lessons and practice in music, other arts, and sports. The vocabulary test was started at different levels for the elementary school and high school students. The questionnaire was answered by the participants themselves in the high school sample and by the participants' parents in the younger samples.

Small exact number: Multiple Object Tracking

To investigate whether music training enhances the ability to represent small, exact numbers of objects, we created a child-friendly version of the Multiple Object Tracking (MOT) task (Pylyshyn & Storm, 1988). In our version of the task, children saw an array of white dots described as ladybug eggs, and they were instructed to keep track of a subset of the eggs in the array while all the eggs moved independently around the screen. After 10 seconds of motion, the eggs stopped moving, two eggs turned into ladybugs, and the child indicated which of the two ladybugs was in her tracked set (Figure 1a). The number of eggs tracked varied across trials (from 2 to 6; 10 trials at each number); on each trial, one of the two ladybugs was a member of the tracked set.

This task was selected, because a wealth of research provides evidence that the same signature limits characterize adults' performance on this task and infants' performance in tests assessing small-number representations (see Scholl, 2001, and Carey & Xu, 2001, for review). Moreover, task performance has been shown to be highly malleable by experience (Green & Bavelier, 2003) yet little affected by verbal or symbolic object knowledge (Scholl, 2001). If music training enhances representations of small numbers of objects, then children and adolescents with a history of music training should track objects more accurately.

Large, approximate number: comparison

To investigate whether music training enhances the ability to represent the approximate cardinal values of large sets of objects, we used a variant of the method of Barth, La Mont, Lipton, & Spelke (2005) to assess children's and adolescents' abilities to compare two visual arrays of elements on the basis of number over variation in continuous quantities. In our version of the task, participants saw an array of blue dots and an array of red dots side by side, and they indicated which array had more dots (Fig. 1b).

The ratio of the two numbers varied across trials, as did the continuous quantitative variables of dot size, position, density, and array area. Each participant received 48 trials, 8 per ratio, with arrays

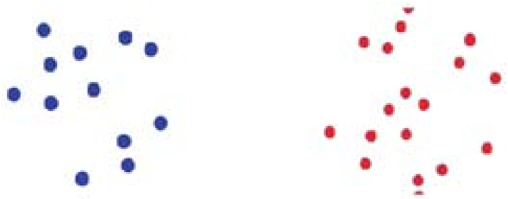


Figure 1b. Numerical comparison ("are there more blue or red dots?")

differing in number at each of 6 ratios: 2:3, 3:4, 4:5, 5:6, 7:8, and 9:10. For each participant, we computed the proportion of correct comparisons at each of these ratios (chance=.50) and tested for associations with music training both overall and at each ratio. If music training enhances representations of large, approximate numerical magnitudes, then children with music training should choose the array with the larger number more accurately, especially at the more difficult ratios.

Geometry: Detecting invariants

To investigate whether music training enhances the ability to represent geometric properties in visual forms, we used a task developed by Dehaene, Izard, Pica & Spelke (2006) for studies of sensitivity to geometry in adults and children. On each trial, children viewed six geometric figures that differed in size and orientation. Five of the figures shared a single property not shared by the sixth figure; children were instructed to find the deviant figure (Fig. 1c).

Participants received a total of 45 trials testing for properties in 7 categories: topological properties, Euclidean properties of points and lines, Euclidean properties of figures, symmetry, chirality, proportionality, and geometrical transformations. Their performance was assessed both overall and within each category (chance=.167). If music training enhances sensitivity to geometry in visual arrays, then children with music training should detect more reliably the geometric properties that unite 5 of the 6 figures in each trial, and they therefore should choose the deviant figure with higher accuracy.

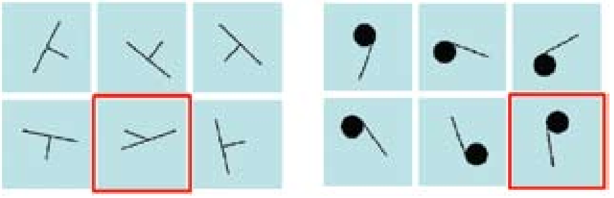


Figure 1c. Detecting geometric invariants ("which one is different?")

Linking small and large numbers: verbal estimation

We used a verbal estimation task to assess participants' command of the system of number words and sensitivity to their numerical reference. On each trial, participants saw an array of dots, presented too briefly for counting, and gave a verbal estimate of their number (Fig. 1d). Participants were tested with 3 arrays at each of 15 numerosities (10 through 150, increasing by multiples of 10). At each numerosity, the sizes and distributions of elements varied across trials. From the verbal estimates, we calculated a measure of the accuracy of estimation performance, by taking the average of the distance of each estimate point from the true number. If musical training enhances the link between approximate number and language that underpins knowledge of number words and verbal counting, then participants with music training may perform more accurately on this test.

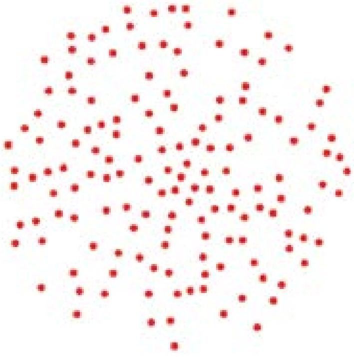


Figure 1d. Numerical estimation ("guess how many dots are on the screen.")

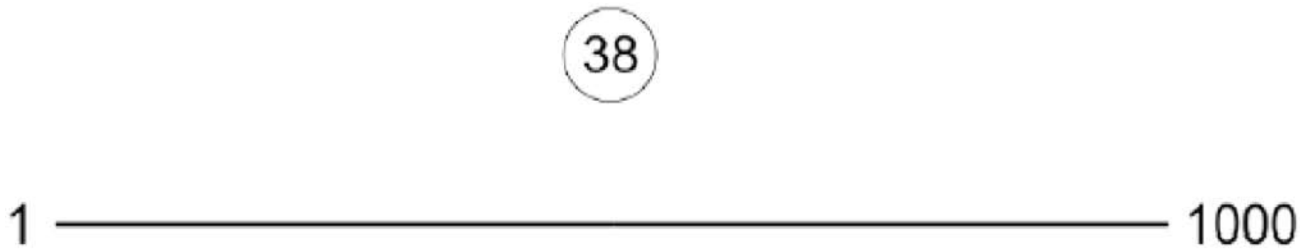


Figure 1e. Number line task ("Draw a mark on the line where the number in the circle belongs.")

Linking number and space: Number lines

We used a task developed by Siegler and Opfer (2003) to investigate participants' command over the relationship between numerical and spatial magnitudes. On each trial, participants were presented with a line, the left endpoint was marked "1" and the right endpoint was marked with a higher number (e.g., "100"). Above this line was a third number between those extremes (e.g., "38"; Fig. 1e). Subjects' task was to mark the location on the line where that number belonged. The task was presented to subjects in paper and pencil form. Each participant received 12 trials at each of 3 number line scales from 1 to 100, 1000, or 1,000,000. Performance was analyzed by recording the location of each point and calculating its accuracy by means of the same accuracy measure as for the estimation task, after transforming the numerical magnitudes so that errors at each of the magnitude ranges were computed on a common scale.

Linking geometry and objects: Maps

Our final task used a method developed by Dehaene et al. (2006) to assess the ability to represent geometric properties of the surrounding environment in maps. On each of 18-28 trials (with more trials for the older students), children viewed a simple map depicting three geometric forms in a triangular arrangement, while facing away from an array of three containers forming a similar triangle but 12 times larger and at a different orientation. The experimenter pointed to a single location on the map and instructed the child to place an object in the corresponding container (Fig. 1f).

Across trials, the nature of the triangle (isosceles or right triangle) and its orientation were varied. On half the trials, one form on the map and one container in the room were distinct in color and served as a landmark. Children's performance was analyzed separately for trials with and without the landmark. If music training enhances sensitivity to the geometry of the spatial layout, then children with music training should perform better on the map task.

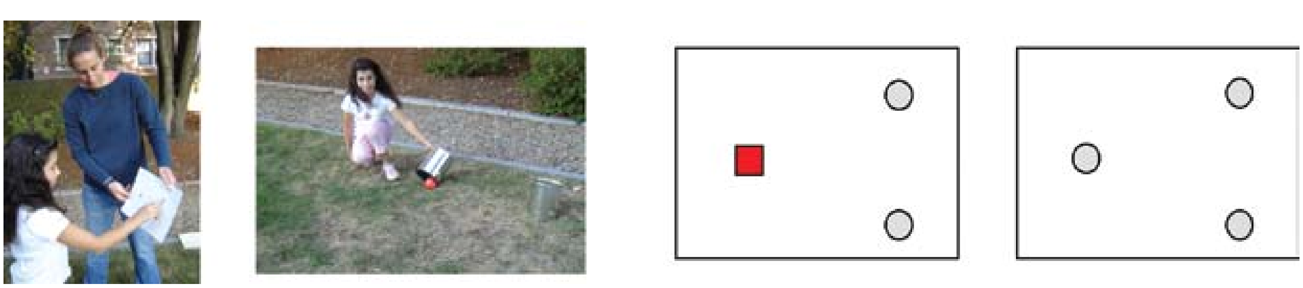


Figure 1f. Map task ("Put the toy in this can (pointing to asterisk)")

Experiment 1: Effects of mild to moderate music training, relative to sports training, at 5-17 years of age.

Participants

Participants were 85 students aged 5 to 17 years (mean 10.4 years) in grades ranging from pre-school to 11 (mean 4th grade). Participants and their parents were recruited through their participation in one of two Saturday programs in the same suburban community in Massachusetts: a music program and a soccer program.

Measures

Music and sports training each were calculated as weeks of training, derived from the start date of training in each area and the end date. In most cases, the training was ongoing and the date of test was used as the end date. Other measures were as described above.

Analyses

Preliminary analyses of students' experience with music and sports revealed high overlap between the profiles of children recruited from the music school and those recruited from the soccer program. For this reason, the two groups were collapsed together. Associations between music training, sports training, and performance on the 6 numerical and spatial tasks were analyzed by hierarchical regressions that tested and controlled for effects of age, sex, socioeconomic status, and verbal IQ. Regressions on each task proceeded by entering age, sex, parental SES, and verbal IQ scores simultaneously as the first set of predictors, followed by music and sports training entered simultaneously as the second set of predictors. In this way, we were able to explore the effect of music and sports training independently of any effects of the suite of demographic variables.

Findings

Small, exact number

Performance on the Multiple Object Tracking task was high yet below ceiling (mean 87.1%, chance=50%, $t(84)>4{,}000$, $p<.001$), and it showed reasonably high variability across children (range 57-100%, s.d. 9.5) (Fig. 2a). A one-way analysis of the effect of number of items tracked (5 levels: 2, 3, 4, 5, and 6) revealed the expected linear contrast, with declining accuracy as the number tracked increased ($F(1,84)>169$, $p<.001$). Because the distribution of overall performance was both negatively skewed (z-skewness=-4.64) and kurtotic (z-kurtosis=2.59) and because mean performance was quite high, we focused our correlational and regression analyses on participants' performance on the trials with 5 or 6 targets. Performance on this subset of trials was above chance (mean 76.5%, $t(84)>3{,}000$, $p<.001$) and below ceiling, and variable across participants (range 40-100%, s.d. 13.7), and the distribution was normal.

The hierarchical regression analysis revealed that age and SES significantly predicted performance on trials with 5 or 6 targets (standardized beta of age=.475, $p<.001$; standardized beta of SES=.205, $p=.043$), but that neither music nor sports training predicted unique variation after the variation related to the suite of demographic variables was removed (R-square=.250, delta-R-square=.003, 1st step of model $p<.001$, 2nd step of model $p>.8$, n.s.).

Large-number comparison

Performance on the numerical comparison task also was above chance and below ceiling (mean 70.1%, $t(84)>6{,}800$, $p<.001$), and variable across children (range 52-83%, s.d. 6.65). A one-way ANOVA of the effect of discrimination ratio revealed the expected linear contrast ($F(1,84)>168$, $p<.001$), showing decreasing accuracy as the ratio of the two numbers approached 1 (Fig. 2b).

In the hierarchical regression analysis, age was

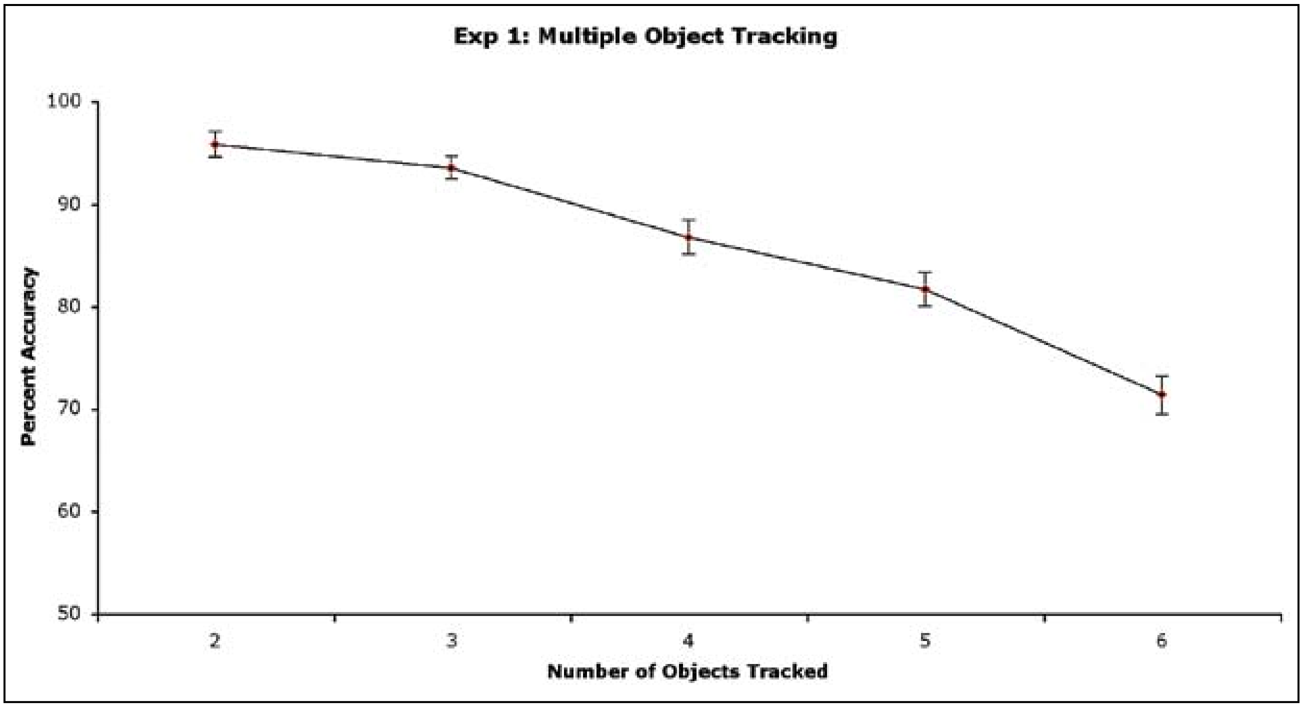


Figure 2a. Multiple object tracking performance in Experiment 1.

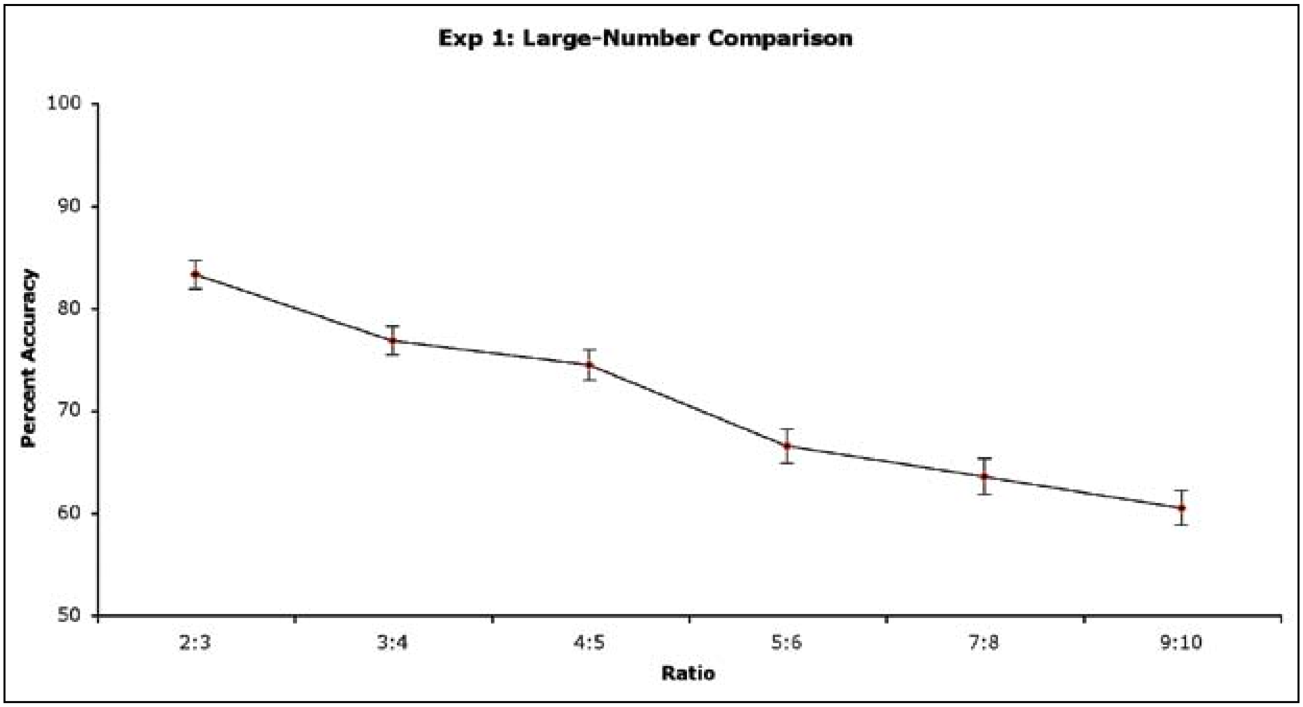


Figure 2b. Numerical comparison performance by ratio in Experiment 1.

the only significant predictor of task performance (standardized beta=.37, p=.001). Neither music nor sports training predicted unique variation in task performance after the variation related to the suite of demographic variables was removed (R-square=.143, delta-R-square=.007, 1st step of model p=.016, 2nd step of model p>.7, n.s.).

Geometrical invariants

Performance on the geometry task was above chance (mean 73.70%, t(84)>990, p<.001), below ceiling, and variable (range 33-95%, s.d.14.8). Because the distribution was negatively skewed (z-skewness=-2.96), the performance variable was transformed by taking the square root of its reflection (as was done with certain variables in Experiment 1). A one-way analysis comparing performance in the 7 different categories of trials revealed significant differences in sensitivity to the different geometric properties (Fig. 2c). Because of non-sphericity in the data, the Greenhouse-Geisser correction was used for interpreting this effect (F(4.24, 356.52)>63, p<.001).

After Bonferroni correction, post-hoc pairwise comparisons revealed that performance on the topology and Euclidean geometry categories was superior to performance on all other categories of trials (p's<.001), performance on the geometric figures category was significantly better than performance on the chiral figures, metric properties, and geometrical transformation categories (p's<.001), and performance on the symmetrical figures and metric properties categories was significantly better than on the geometrical transformations category (p=.031 and p=.007, respectively).

The hierarchical regression analysis of overall task performance revealed that age and verbal IQ predicted performance on the geometry task (standardized beta of age=-.804, p<.001; standardized beta of verbal IQ=-.264, p=.001), such that subjects who are older or of higher verbal IQ scored better on this task. However, neither music nor sports training predicted unique variation on the task, after the variation related to the suite of demographic variables was removed (R-square=.603, delta-R-square=.004, 1st step of model p<.001, 2nd step of model p>.6, n.s.).

A set of similar regression analyses tested performance on each of the sub-sets of the task. Age predicted performance on all subsets of the task, but music and sports training amounts were never significant predictors of performance after partialing out the effects of the demographic variables.

Estimation

Performance on this task showed a significant linear contrast between number of dots presented visually and the verbal estimates given (F(1,84)>851, p<.001), indicating that participants' estimates increased linearly and monotonically as the number of dots presented increased (Fig. 2d). Because the distribution of the measure of error was positively skewed (z-skewness=3.72), we transformed the variable by taking its square root.

The hierarchical regression analysis revealed that age was a significant predictor of performance on the estimation task (standardized beta=-.607, p<.001) such that older children had smaller estimation error, but that neither music training nor sports training accounted for unique variation in the task after variation related to the suite of demographic variables was removed (R-square=.116, delta-R-square=.071, 1st step of model p=.047, 2nd step of model p=.044).

Number Line

Performance on the number line task showed reasonable accuracy at all three scales (Fig. 2e). One-way repeated measures ANOVAs on spatial estimates at each target number, for each scale, revealed a significant linear contrast on the hundreds scale (F(1,84)>2,600, p<.001), the thousands scale (F(1,82)>3,600, p<.001; 2 children

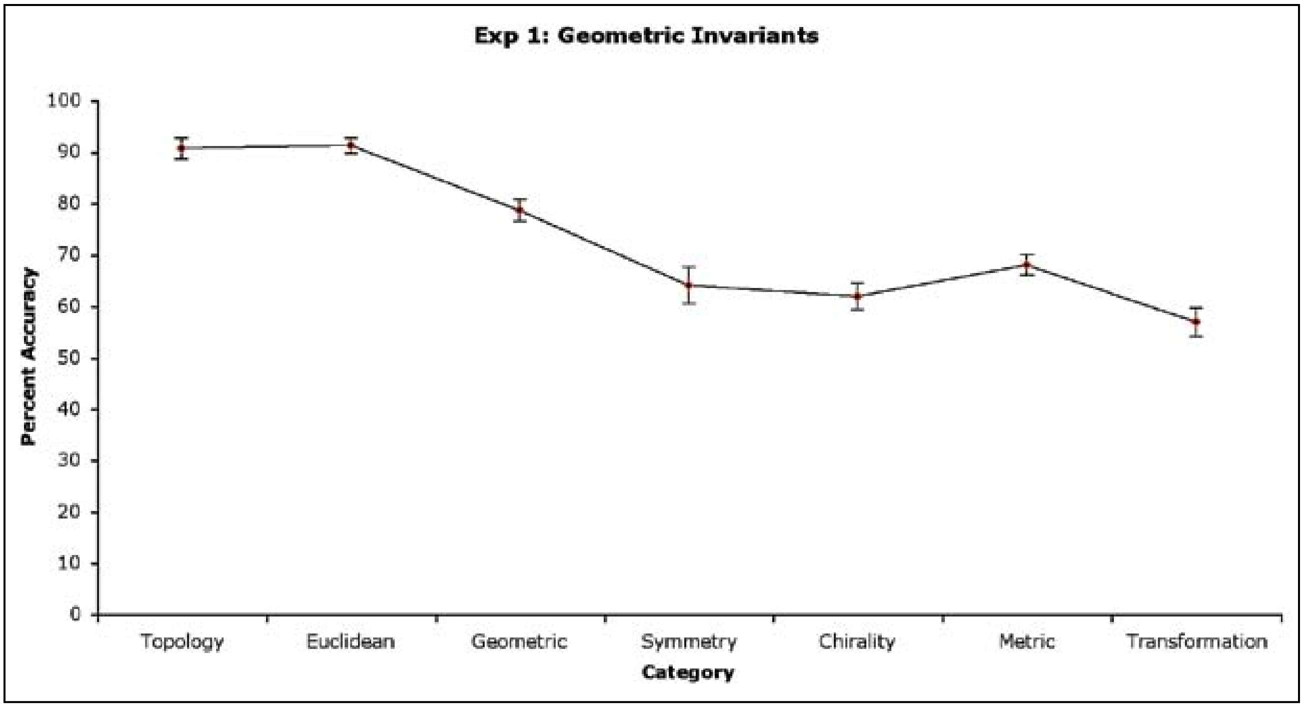


Figure 2c. Sensitivity to geometric invariants in Experiment 1.

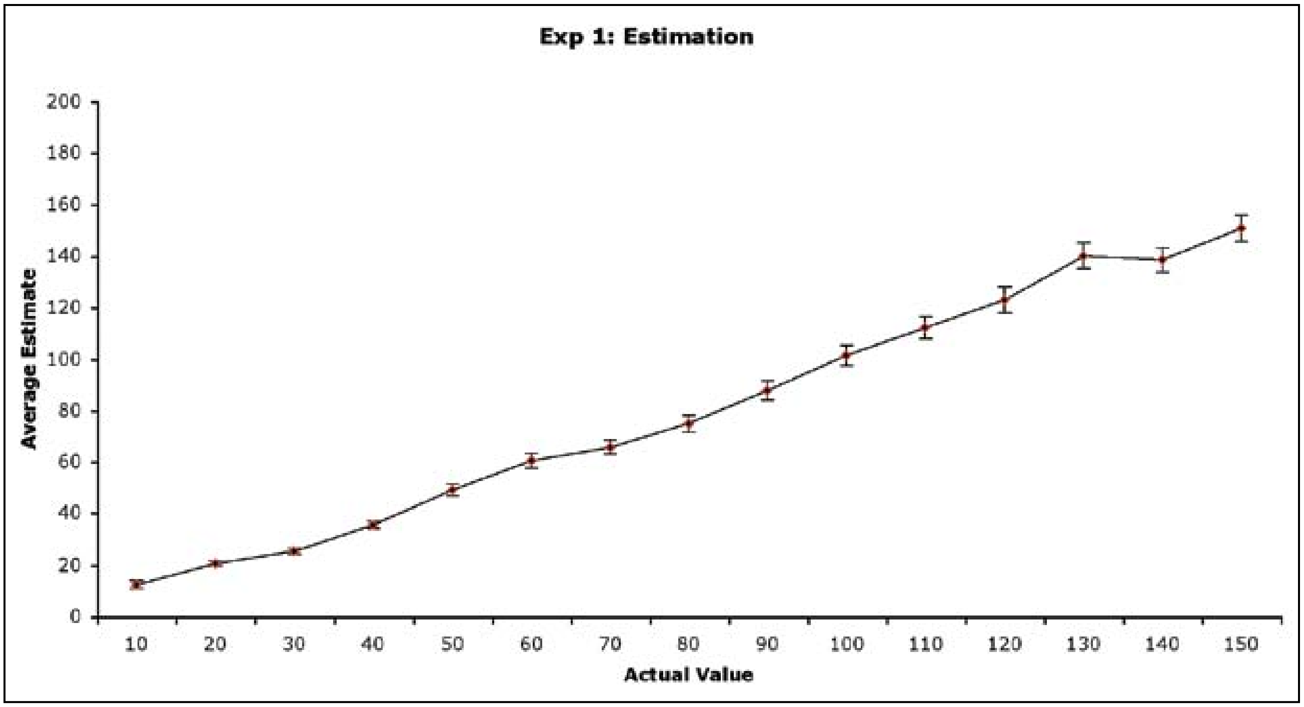


Figure 2d. Estimation performance in Experiment 1.

did not complete this scale), and the millions scale (F(1,74)>1,700, p<.001; 10 children did not complete this scale). Because error distributions at each of the three scales were both positively skewed and kurtotic (z-skewness>3, z-kurtosis>=2.57), each distribution was transformed by logarithm, to minimize skewness and kurtosis. A one-way ANOVA on log transformed performance by scale (3 levels) revealed the expected linear contrast (F(1,74)>12,000, p<.001), with greater errors on trials at the higher scales.

In order to facilitate correlational and regression analyses, we formed a composite distance score by averaging the untransformed distance scores on each of the scales, after adjusting the thousands and millions scale scores down to the same order of magnitude as the 100s distance. This was done by dividing the thousands distance by ten and the millions distance by 10,000. The distribution of this composite measure was both highly positively skewed and kurtotic, and so it was transformed by logarithm, to yield a normal distribution.

The hierarchical regression analysis on this transformed variable revealed that age, sex, and verbal IQ predicted performance on the number line task (standardized beta of age=-.669, p<.001; standardized beta of sex=-.379, p<.001; standardized beta of verbal IQ=-.244, p=.006), such that older children, boys, and children with higher verbal IQ scores performed better. However, neither music training nor sports training predicted unique variation on this task, after the variation related to the demographic variables was removed (R-square=.582, delta-R-square=.016, 1st step of model p<.001, 2nd step of model p>.2).

Map

Performance on the map task was well above chance (mean 78.58%, t(84)>2,000, p<.001) yet below ceiling and variable (range 42-100%, s.d.14.2). Because the distribution was negatively skewed (z-skewness=-2.36), we transformed the scores by reflecting them and taking the square root of the reflected scores in order to achieve a normal distribution. A preliminary one-way ANOVA on the 2 different categories of trials (with and without landmarks) revealed marginally higher performance on landmark trials (F(1,84)=3.94, p=.051; Fig. 2f).

The hierarchical regression analysis of overall task performance showed that age and sex significantly predicted performance on the map task (standardized beta of age=-.520, p<.001; standardized beta of sex=-.244, p=.012), such that older children and boys performed better on the map task. Music and sports training did not predict unique variation on the task after the variation related to the demographic variables was removed (R-square=.316, delta-R-square=.013, 1st step of model p<.001, 2nd step of model p>.4, n.s.). Similar regression analyses of the subset of trials with and without landmarks also revealed no effects of music or sports training after controlling for the demographic variables.

Summary

Experiment 1 tested for effects of mild to moderate levels of music training on a suite of numerical and spatial abilities. In this experiment, we attempted to control for motivation and extracurricular engagement by recruiting participants either from a Saturday music school or a Saturday sports program. We also controlled for effects of age, verbal IQ, and SES on children's performance. Preliminary analyses (not reported here) showed associations between music training and performance of a number of our mathematical and spatial tasks, but these relationships disappeared when we controlled for the suite of demographic variables, and verbal IQ, that correlated with music training. Age, verbal IQ, and SES predicted performance on a number of our tasks, but the amount of training in music (or sports) did not, when the effects of these variables were controlled.

These findings provide no evidence, therefore,

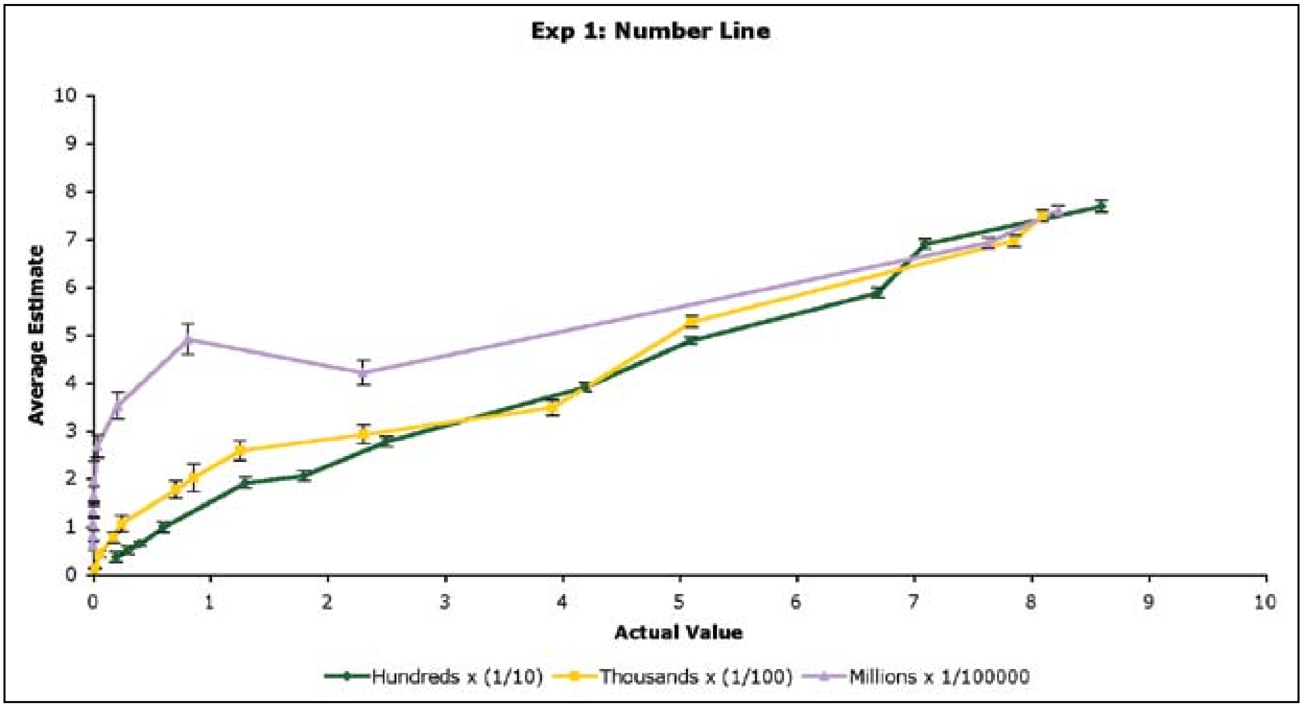


Figure 2e. Number Line placements in Experiment 1.

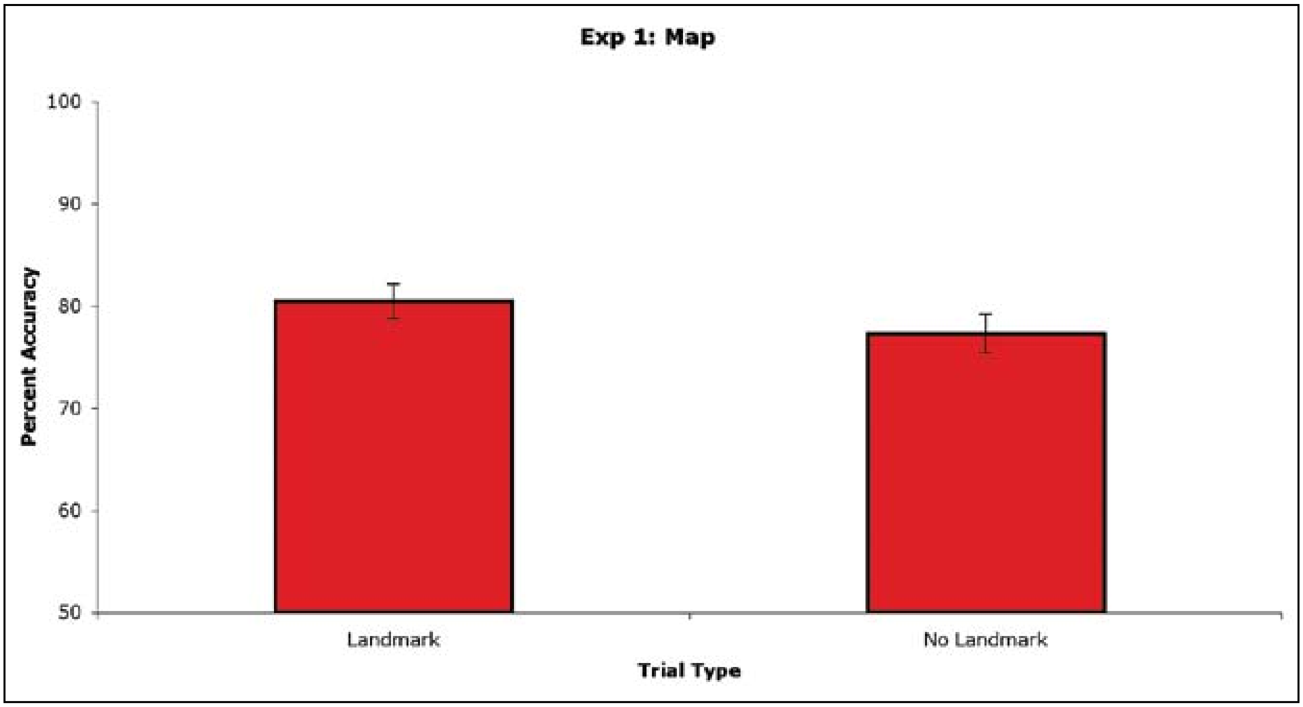


Figure 2f. Map performance on trials with and without landmarks in Experiment 1.

that low or moderate levels of music training specifically enhance any core mathematical abilities. The next experiment accordingly tested for effects of more intense music training on the same abilities.

Experiment 2: Effects of intensive music training, relative to no training, at 8-13 years of age.

Participants

A total of 61 elementary and middle-school children aged 8 to 13 years (mean 10.97 years) participated in the experiment. Of these, 32 children had high levels of music training and 29 children had low levels. Most of the children with high music training were recruited from selective music schools in the Boston area; most of the control children were recruited from the records of the Lab for Developmental Studies at Harvard University.

Measures

Music training was measured in weeks, calculated by date of start and end of music training. In most cases, music training was ongoing at time of test, so the date of test was used as the end date. All other measures were as described above, except that the number line task was not administered.

Analyses

Preliminary analyses showed that the musicians and control group did not differ significantly by parental SES ($p=0.508$), but that the musicians were older than the control group ($t(59)=2.26$, $p=0.028$) and had higher verbal IQ scores ($t(59)=2.70$, $p=0.009$). In order to control for differences in age and verbal IQ, ANCOVAs compared performance of the music-trained and control groups on the experimental tasks, after controlling for these covariates. In addition to the group comparisons, hierarchical regressions performed on all the participants together tested for the effect of amount of music training, after controlling for the effects of age, sex, SES, and verbal IQ. Age, sex, SES, and verbal IQ were entered simultaneously as the set of predictors for the first step of each regression, followed by music training as the second step.

Findings

Small, exact number

Raw overall performance on the Multiple Object Tracking task was high yet below ceiling (mean 88.72%, $t(60)>34$, $p<.001$) and showed moderate variability across children (range 56-100%, s.d. 8.8). To correct for negative skew in the score distribution (z-skewness=-2.96), the performance scores were square-root transformed and then reflected by subtracting each score from the highest score plus 1. All subsequent analyses used the transformed scores.

A two-way ANCOVA with age and verbal IQ as covariates, crossing sub-population (musician or control) and number of items tracked (5 levels: 2, 3, 4, 5, or 6 items) revealed a significant linear contrast on the number of items tracked ($F(1,59)>158$, $p<.01$), but no effect of Group ($F(1,57)=1.20$, $p>.2$ n.s.), and no interaction (using Greenhouse-Geisser correction for non-sphericity: $F(3.50,206.45)=1.25$, $p>.2$ n.s.). Children with high and low music training showed equal object tracking performance (Fig. 3a).

Because of the high mean of overall performance on this task, we focused the regression analyses on performance on the trials with the two largest numbers of targets (mean 80.1%, range 40-100%, s.d. 13.7). This analysis tested for the effect of music training, after controlling for age, sex, parental SES, and verbal IQ. All four demographic variables were entered simultaneously in the first step of the regression, followed by music training as the variable in the second step. The regression analysis revealed that the regression model as a whole did not predict a significant amount of variance in the scores, at either the first or second

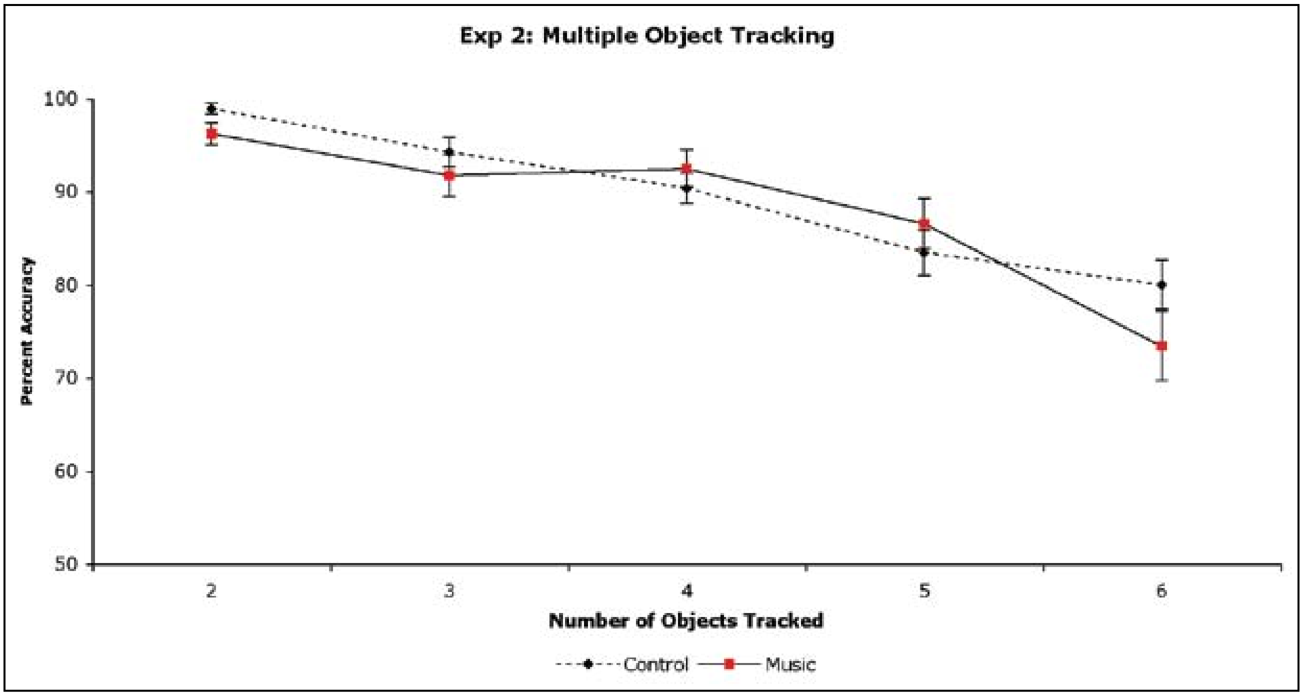


Figure 3a. Multiple object tracking performance by music-trained and control children 8-13 years.

steps of the model (R-square of first step=.03, delta-R-square=.000, 1st step of model p>.7 n.s., 2nd step of model p>.8 n.s.).

Large-number comparison

Overall performance on the numerical comparison task was above chance, below ceiling, and variable across children (46-92%, mean 75.88%, s.d. 9.90, t(60)<3,000, p<.001). Because the distribution was negatively skewed (z-skewness=-2.78), scores on this task were transformed in the same way as MOT. All subsequent analyses use the transformed scores.

A two-way ANCOVA with age and verbal IQ as covariates, crossing Group (music trained vs. untrained) and numerical ratio (6 levels) found a significant linear contrast on numerical ratio (F(1,59)>20, p<.001), no significant effect of Group (F(1,57)<1), and no interaction effect (F(5,295)=1.98, p=.08, n.s.). Children with high and low music training performed equally well on the numerical comparison task (Fig. 3b).

The hierarchical regression analysis, testing for the effect of music training after controlling for age, sex, parental SES, and verbal IQ, revealed that the regression model did not predict a significant amount of variation in performance on this task (R-square=.047, delta-R-square=.003, 1st step of model p>.5 n.s., 2nd step of model p>.6 n.s.).

Geometrical invariants

Performance on the geometry task was above chance (mean 75.52, where chance is 16.67%, t(60)=38.73, p<.001), below ceiling, and variable (range 47-95%, s.d. 11.87). An ANCOVA with age and verbal IQ as covariates, crossing Group (music training vs. control) by geometrical property (7 levels) revealed that the effects of both covariates, age and verbal IQ, were significant (F(1,57)=9.02, p=.004; F(1,57)=6.74, p=.012, respectively). In addition, there was a significant effect of geometrical property (F(6,354)>36.74, p<.001), and no effect of group (F(1,57)=1), or interaction (F(6,354)=2.00, p>.06 n.s.).

Post-hoc pairwise comparisons after Bonferroni

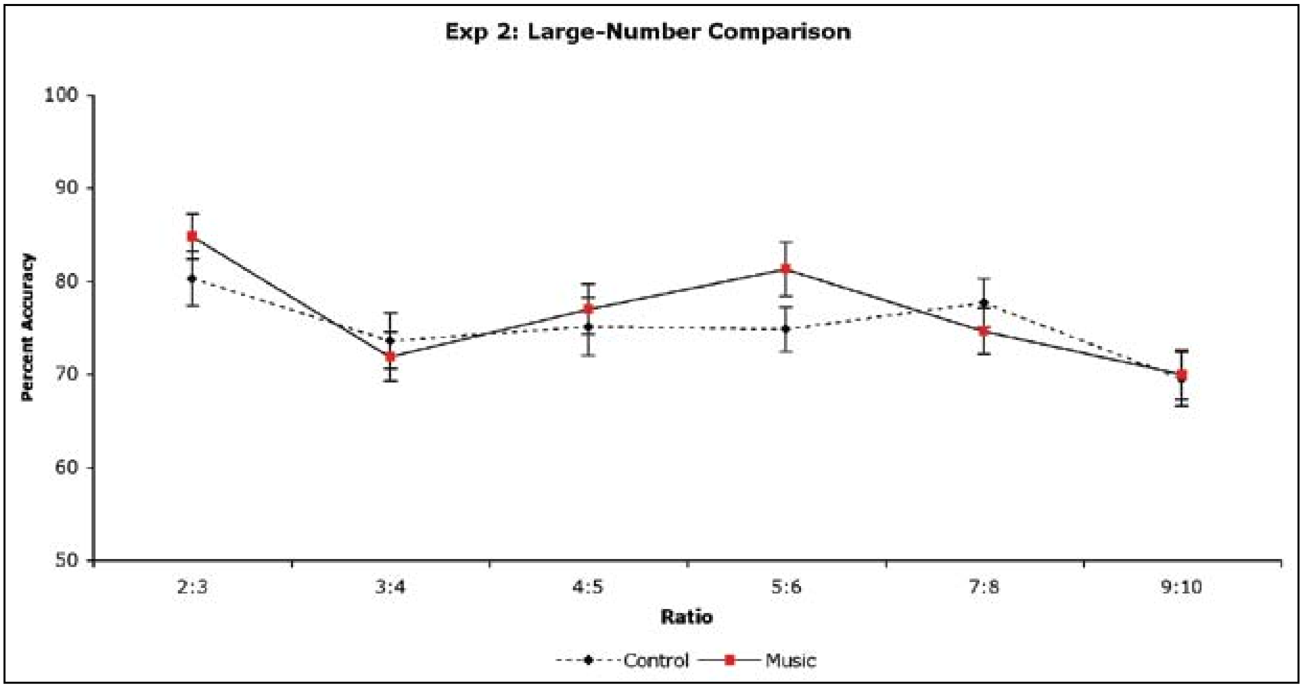


Figure 3b. Numerical comparison by music-trained and control children 8-13 years.

correction revealed that performance on the topology and Euclidean geometry categories was significantly higher than all other categories (p's<.001), performance on the geometric figures category was significantly higher than the symmetrical figures (p=.009), metric properties (p<.001), and geometrical transformation categories (p<.001), and that performance on the chiral figures and metric properties categories was significantly higher than geometrical transformations (p<.001 and p=.042, respectively).

A subsequent set of one-way ANCOVAs compared the performance of the two groups on each of the subsets of trials. When age and verbal IQ were controlled, musicians significantly outperformed non-musicians on the trials testing Euclidean geometric relationships (F(1,57)=5.90, p=.018; Fig. 3c), and they tended nonsignificantly to outperform non-musicians on all the trial subsets except for the topology subset.

Hierarchical regression analysis tested for the effect of music training, after controlling for age, sex, parental SES, and verbal IQ. The analysis revealed that age and verbal IQ were significant predictors of performance on the geometry task, but that music training did not explain unique variation in performance after the effect of those variables was removed (R-square=.315, delta-R-square=.019, 1st step of model p<.001, 2nd step of model p>.2, standardized beta of age=.392, p=.002, standardized beta of verbal IQ=.345, p=.007).

Estimation

Performance on this task, assessed by a two-way ANOVA crossing sub-population with average estimates at each target number, showed a significant linear contrast between the number of dots presented visually and the verbal estimates given (F(1,59)=383.18, p<.001), no effect of sub-population (F(1,59)=2.05, p>.1 n.s.), and no interaction effect (F(14,826)<1, p>.6 n.s.; Fig. 3d).

A t-test comparing the performance of the two groups by the overall error measure revealed

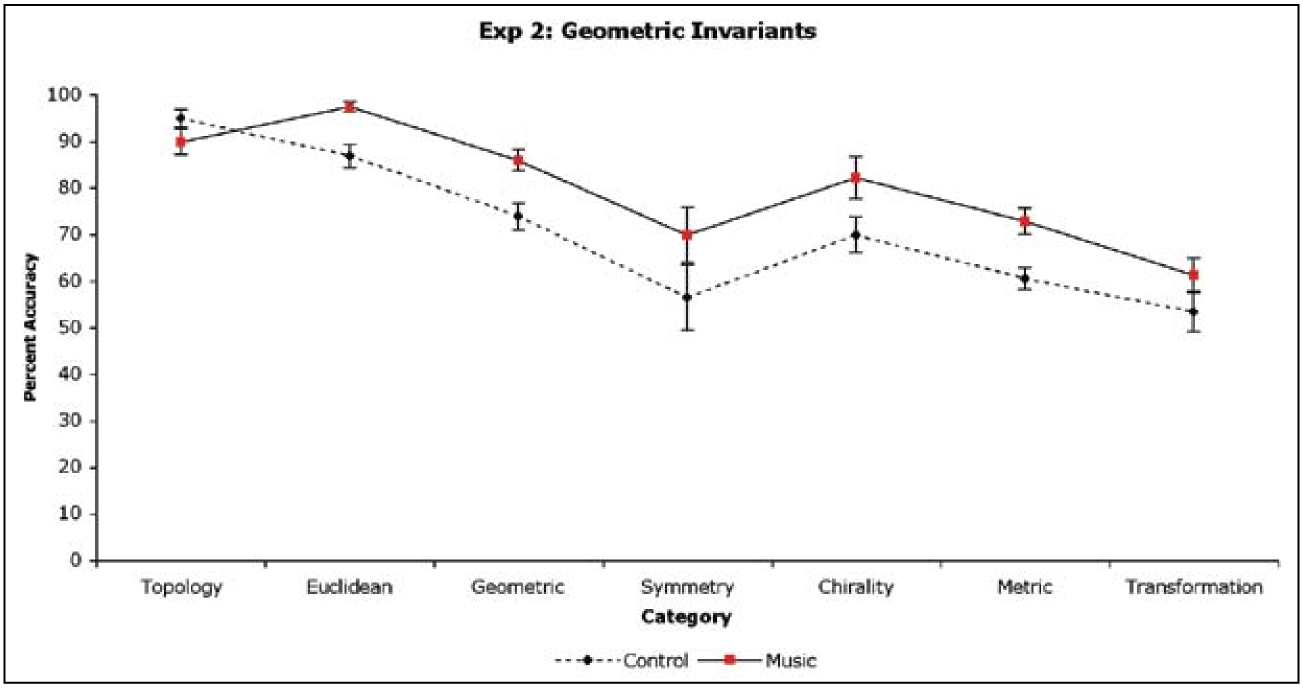


Figure 3c. Sensitivity to geometric invariants by music-trained and control children 8-13 years.

no significant difference between the musician and control groups (t(59)=0.061, p>0.9 n.s.). The hierarchical regression analysis testing for the effect of music training, after controlling for age, sex, parental SES, and verbal IQ, revealed that age was a significant predictor of performance on this task (standardized beta of age=-.371, p=.005), but that music training did not predict unique variation in the task after removing variation accounted for by the age and the other demographic variables (R-square=.151, delta-R-square=.000, 1st step of model p=.053, 2nd step of model p>.9).

Map

Performance on the map task was well above chance, below ceiling (mean 79.38%, where chance is 33%, t(60)>2,200, p<.001) and variable (range 60-100%, s.d. 10.99).

A two-way ANCOVA crossing Group (music trained vs. control) and task condition (arrays with vs. without landmarks) revealed a significant effect of task condition (F(1,57)>44, p<.001), with higher performance on trials with landmarks, and no significant effect of group (F(1,59)=1.70, p>.1 n.s.), or interaction (F(1,59)=3.27, p=.076; Fig. 3f). Separate one-way ANCOVAs comparing the sub-populations on the subsets of trials in arrays with versus. without a landmark also revealed no significant group difference (both Fs(1,57)<1).

In contrast, the hierarchical regression analysis, testing for the effect of music training, after controlling for age, sex, parental SES, and verbal IQ, revealed that music training was a significant predictor of overall performance on the map task, after removing the variation related to the suite of demographic variables (standardized beta of music training=.318, p=.009; R-square=.305, delta-R-square=.082, 1st step of model p<.001, 2nd step of model p=.009). Age was also a significant predictor of map task performance (standardized beta of age=.391, p=.002), and sex was a marginally significant predictor, with males performing slightly better than females (standardized beta of sex=.211, p=.052).

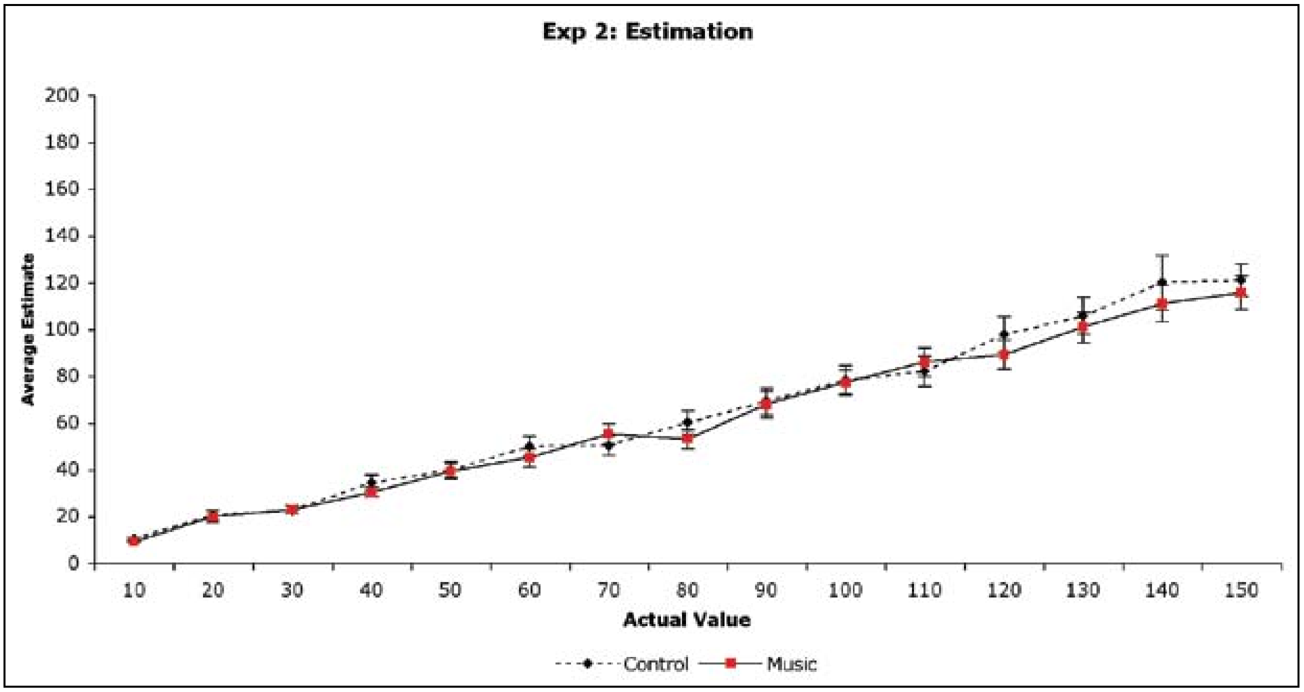


Figure 3d. Estimation by music-trained and control children 8-13 years.

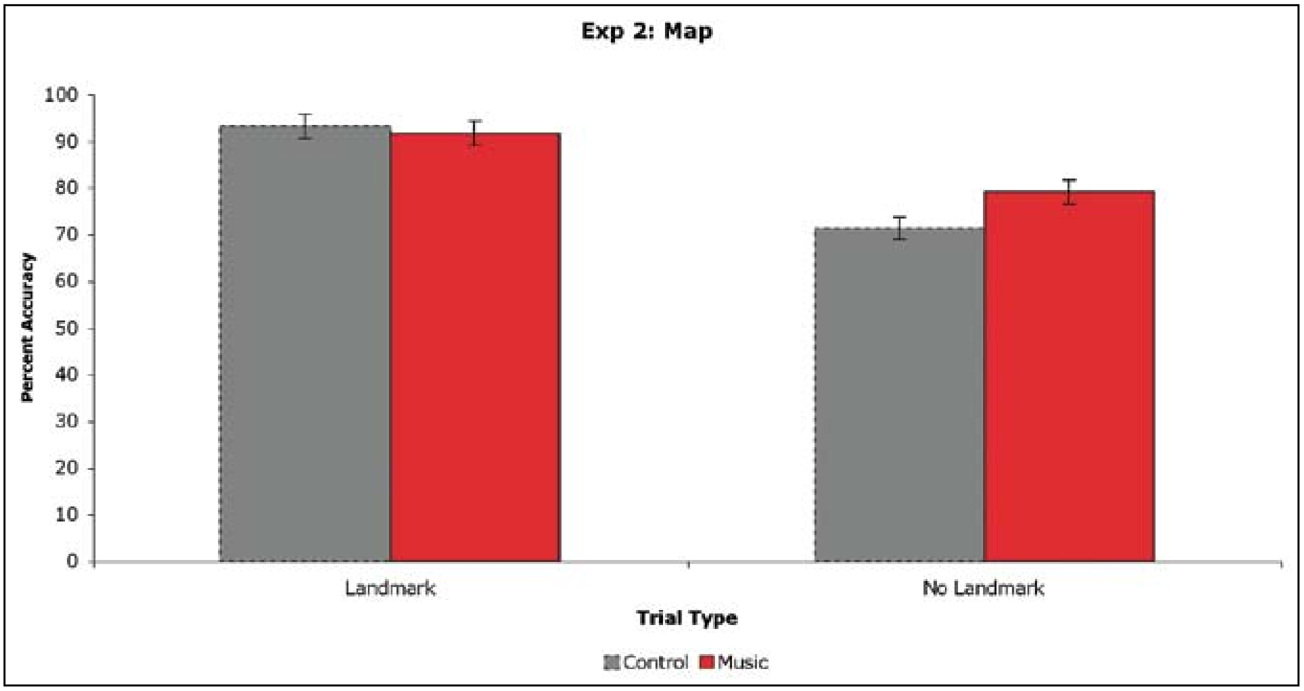


Figure 3f. Map performance by music-trained and control children aged 8-13 years.

Summary

In this second experiment, the attempt to find a specific association between music training and core systems of number and geometry clearly suffered from the strong relationships between music training, verbal IQ, and age. Numerous associations between music and mathematics disappeared when the latter relationships were controlled. Nevertheless, several findings emerged.

First, there was no hint of an association between music training and representations of small exact numbers, large approximate numbers, or number words. Second, there were associations between music training and two measures of spatial cognition: sensitivity to Euclidean geometry in visual forms and use of simple geometric maps. Music training predicted geometric map performance when the suite of demographic variables and verbal IQ were controlled. Children with extensive music training also outperformed control children on all the measures of sensitivity to geometry that involved metric geometric relationships, although the effect of music training attained conventional levels of significance only on one measure after controls for age and verbal ability.

This experiment therefore suggests a relationship between music training and spatial ability, in this moderately-to-intensively trained population of children. We return to this relationship after considering the findings from the third experiment.

Experiment 3: Effects of intensive music training, relative to intensive training in other arts disciplines, at 13-18 years of age.

Participants

In total, 80 students at a private high school for the arts in suburban Massachusetts participated in the experiment. Students ranged in age from 13.84 to 18.81 years (mean=16.35) and in grade level from 9 to 12. Most (64) of the students were female, reflecting the gender ratio of the overall school population. Students were drawn from five arts programs: music ($N=16$), dance ($N=23$), theater ($N=26$), creative writing ($N=4$), and visual arts ($N=11$). They were tested at the school in two one-hour sessions, separated by a short break.

Measures

Training experience in music, dance, visual arts, theater, writing, and sports was calculated separately for each area by multiplying the number of years of lessons the student received in the area by their self-reported intensity of focus. Intensity was reported on a scale of 1-5, where 1 indicated that the student tried the activity but didn't pursue it with intensity, 3 indicated that the student pursued the activity with some intensity but it was not the primary focus, and 5 indicated that the student pursued the activity with great intensity as the main focus of his or her work.

Analyses

Preliminary analyses of students' musical experience revealed high and overlapping values for those in the music and dance programs, and lower, overlapping values for those in the other programs. Accordingly, group comparisons of performance on each task were analyzed both by discipline and by two groups of disciplines: music and dance ($N=39$) vs. theater, writing, and visual arts ($N=41$).

A one-way ANOVA compared the 5 arts majors by age and revealed a significant difference (omnibus $F(4,75)=3.91$, $p=.006$). Post hoc pairwise comparisons corrected by Hochberg's GT2 showed that music majors were significantly older than dance majors. A similar one-way ANOVA compared the 5 arts majors on verbal IQ and found no significant difference between the arts majors ($F(4,75)$,1, $p>.4$, n.s.). Consequently, comparisons of performance by the five different arts majors on the experimental

tasks, were undertaken by ANCOVAs partialing out age, in an effort to see whether group differences emerged after statistical control for age.

T-tests comparing music and dance majors to visual art, theater, and writing majors found no significant differences between the groups on age ($t(78)<1$, $p>.3$ n.s.) or verbal IQ ($t(78)<1$, $p>.7$, n.s.). Simple ANOVAs therefore compared these groups' performance on each spatial and numerical task.

Finally, hierarchical, step-wise regression analyses tested for the effect of training duration and intensity in music, dance, visual arts, theater, writing and sports, after controlling for age, sex, and verbal IQ. Regressions proceeded by entering age, sex, and verbal IQ simultaneously as predictors in the first step of the model, followed by all training amounts in music, dance, visual arts, theater, writing and sports entered simultaneously as predictors in the second step.

Findings

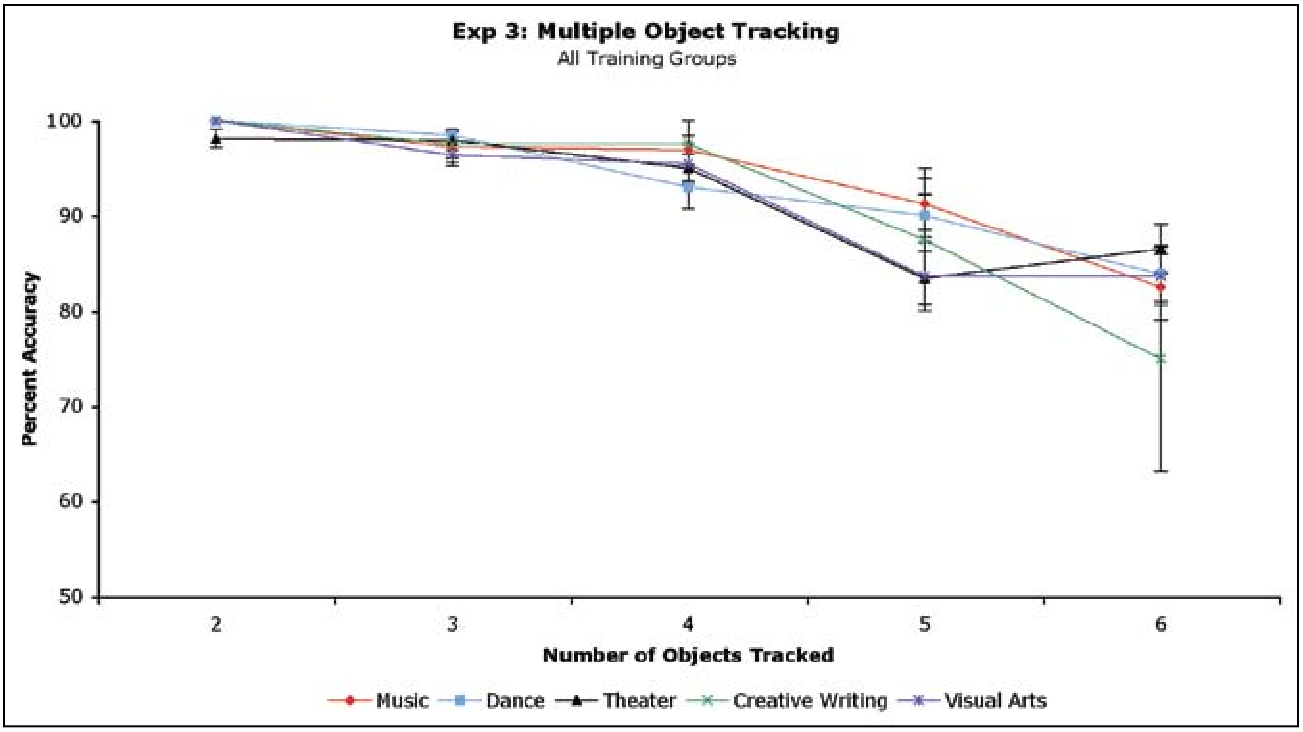
Small, exact number

Overall, MOT scores for these high school students were uniformly high (mean 93.48%, $t(79)>9{,}200$, $p<.001$), yielding a restricted range of variation (80-100%, s.d. 4.8). Because the distribution of scores was negatively skewed (z-skewness at each target number <-2), all analyses used the square root transform of the reflected percent correct on this task.

A two-way ANCOVA crossing arts major by number of items tracked and statistically controlling for age revealed a significant linear contrast on items tracked ($F(1,75)>120$, $p<.001$), no significant group difference ($F(4,74)<1$, $p>.7$), and no interaction between arts major and number of items tracked (using Greenhouse-Geisser correction for non-sphericity: $F(12.24,229.54)=1.18$, $p>.2$, n.s.; Fig. 4a). There was no significant effect of age ($F(1,74)=1.75$, $p>.1$). No pairwise post-hoc comparisons survived correction for multiple tests.

A second two-way ANOVA crossing arts major group (music and dance majors vs. visual arts, theater, and writing majors) by number of items tracked revealed no difference between the groups of arts majors ($F(1,78)=1.38$, $p>.2$, n.s.), the significant linear contrast ($F(1,78)>172$, $p<.001$), and no interaction (using Greenhouse-Geisser correction: $F(3.09,240.96)=2.42$, $p=.065$; Fig. 4a). No pairwise post-hoc comparisons survived Bonferroni correction. A subsequent one-way ANOVA comparing arts majors' performance on the hardest sub-set of trials (those with 5-6 targets) also revealed no effect of arts major, either in the comparison of the five groups ($F(4,75)<1$, $p>.6$ n.s.) or in the comparison of music and dance majors to the majors in theater, writing, and visual arts ($F(1,78)=1.75$, $p>.1$ n.s.).

Given that performance on the overall task was uniformly high with a restricted range of variation, in order to maximize the sensitivity of the measure, regression analyses focused on performance on the most difficult trials: those with 5 and 6 targets (mean 85.6%, $t(79)>4{,}300$, $p<.001$; range 60-100%, s.d. 10.2). Because the distribution of scores on this sub-set of trials is also skewed negatively (z-skewness=2.17), these analyses again used the square root transform of the reflected variable. This regression analysis revealed that dance training, visual art training, sex, and verbal IQ were all significant predictors of performance on MOT, such that children with greater dance or visual arts training, boys, and those with higher verbal IQ scores performed better on this task (standardized betas of: dance training=-.314, visual art training=-.301, sex=-.421, and verbal IQ score=-.343, all p's<=.01; R-square=.165, delta-R-square=.141, 1st step of model p=.003, 2nd step p=.038). Music training was not a significant predictor of performance.



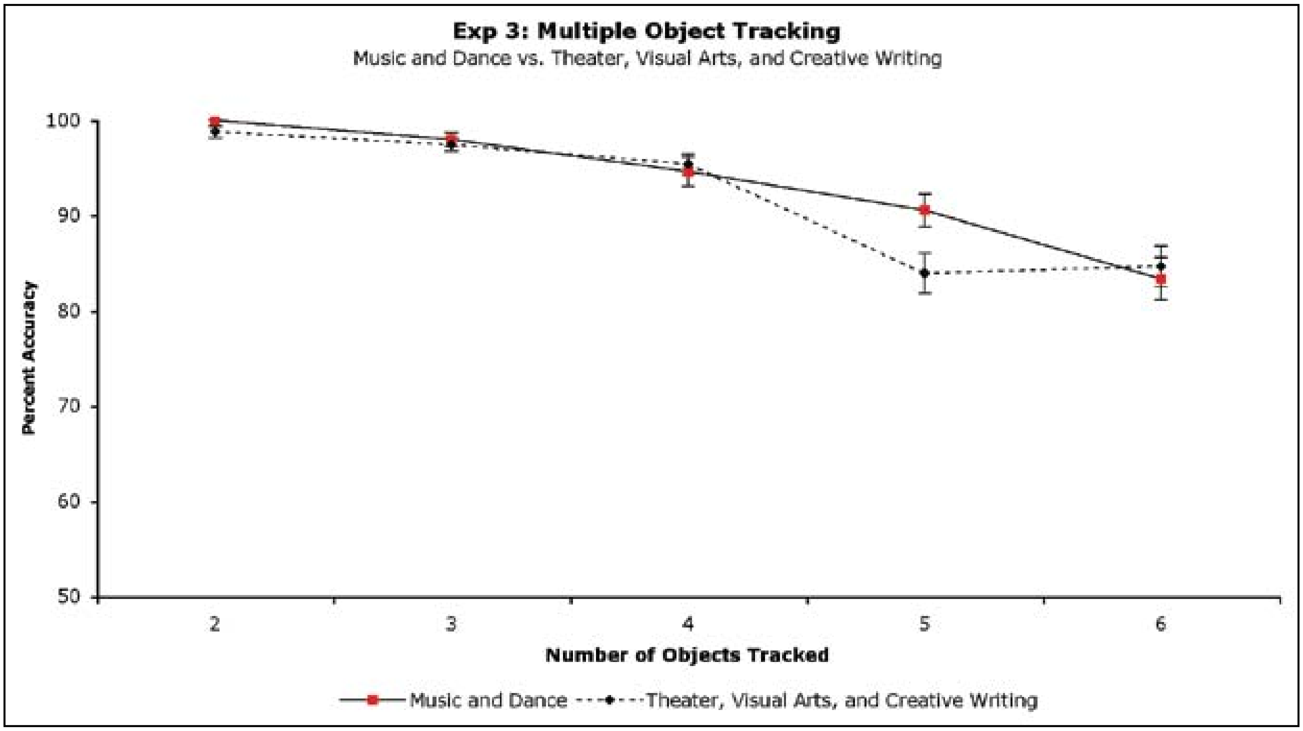


Figure 4a. Multiple object tracking by high school students in differing arts disciplines.

Large number comparison

Performance on the test of numerical comparison was well above chance and below ceiling, and it showed considerable variability across participants (mean 74.0%; $t(79)>6,000$, $p<.001$; range 56-90%; s.d. 7.2). Effects of arts training first were analyzed by a 5 (arts major) by 6 (Ratio) ANCOVA with age as the covariate. Although the effect of ratio showed a highly significant linear contrast, $F(1,75)>161$, $p<.001$, there was no effect of arts major ($F(4,74)<1$, $p>.7$ n.s.; Fig. 4b) and no effect of age ($p>.7$ n.s.). Follow-up analyses of performance at the hardest two ratios also found no significant effects of arts major. The ANOVA comparing music and dance majors to students in the other arts majors revealed the significant linear contrast on ratio ($F(1,78)>240$, $p<.001$), no effect of arts major ($F(1,78)<1$, $p>.5$ n.s.; Fig. 4b), and no interaction effect ($F(4.15,323.63)=1.87$, $p>.1$, after Greenhouse-Geisser correction for non-sphericity).

The regression analysis revealed that none of the training amounts or demographic variables was a significant predictor of performance on the numerical discrimination task (R-square=.012, delta-R-square=.105, 1st step of model $p>.8$, 2nd step of model $p>.4$, n.s.).

Geometrical invariants

Overall, performance on this task was well above chance and below ceiling (mean 83.43%; $t(79)>59$, $p<.001$; range 51-100%; s.d. 10.1). Because the distribution of scores was negatively skewed (z-skewness=-4.65) and kurtotic (z-kurtosis=2.68), all analyses used the square root transform of the reflected percent correct on this task. The 5 (arts field) by 7 (geometric property) ANCOVA controlling for age revealed a significant effect of arts major ($F(4,74)=9.39$, $p<.001$; Fig. 4c) and geometric property ($F(4.22,316.28)=27.27$, $p<.001$, after Greenhouse-Geisser correction for non-sphericity), and no interaction ($F(16.78, 316.28)=1.15$, $p=.09$). The effect of age was not significant ($p>.3$ n.s.).After Bonferroni correction for multiple comparisons, post hoc pairwise comparisons of arts majors revealed that music majors performed significantly better than theater majors ($p=.002$), dance majors outperformed both theater majors ($p<.001$) and writing majors ($p=.03$), and visual arts majors outperformed both theater majors ($p=.001$) and writing majors ($p=.026$).

A second planned two-way ANOVA crossing arts major grouping (music and dance majors v. visual arts, theater, and writing majors) with geometric property, found a significant effect of arts major grouping ($F(1,78)>14$, $p<.001$), such that music and dance majors performed better than the other group (Fig. 4c). It also showed the significant effect of geometric property ($F(4.28,333.82)>48$, $p<.001$, after Greenhouse-Geisser correction for non-sphericity) and no interaction ($F(4.28, 333.82)=2.15$, $p=.07$ n.s.).

Another set of planned ANOVAs compared the performance of music and dance majors to all other majors on each subset of the task. The ANOVA comparing music and dance majors to all other majors on the topology subset revealed no significant group difference ($F(1,78)=1.50$, $p>.4$ n.s.). However, the music and dance major group outperformed the other majors on the Euclidean geometry, geometric figures, symmetric figures, chiral figures, and metric properties subsets ($F(1,78)=7.57$, $p=.007$; $F(1,78)=11.12$, $p=.001$; $F(1,78)=4.73$, $p=.033$; $F(1,78)=8.88$, $p=.004$; $F(1,78)=6.99$, $p=.010$). There was no significant group difference on the geometric transformations subset ($F(1,78)<1$, $p>.5$ n.s.).

A follow-up set of ANOVAs tested the three-fold comparison of visual arts majors to the group of music and dance majors and the group of theater and writing majors on each of the task subsets. One-way ANOVAs tested for group differences on each of the demographic variables for this population, age and verbal IQ, and found

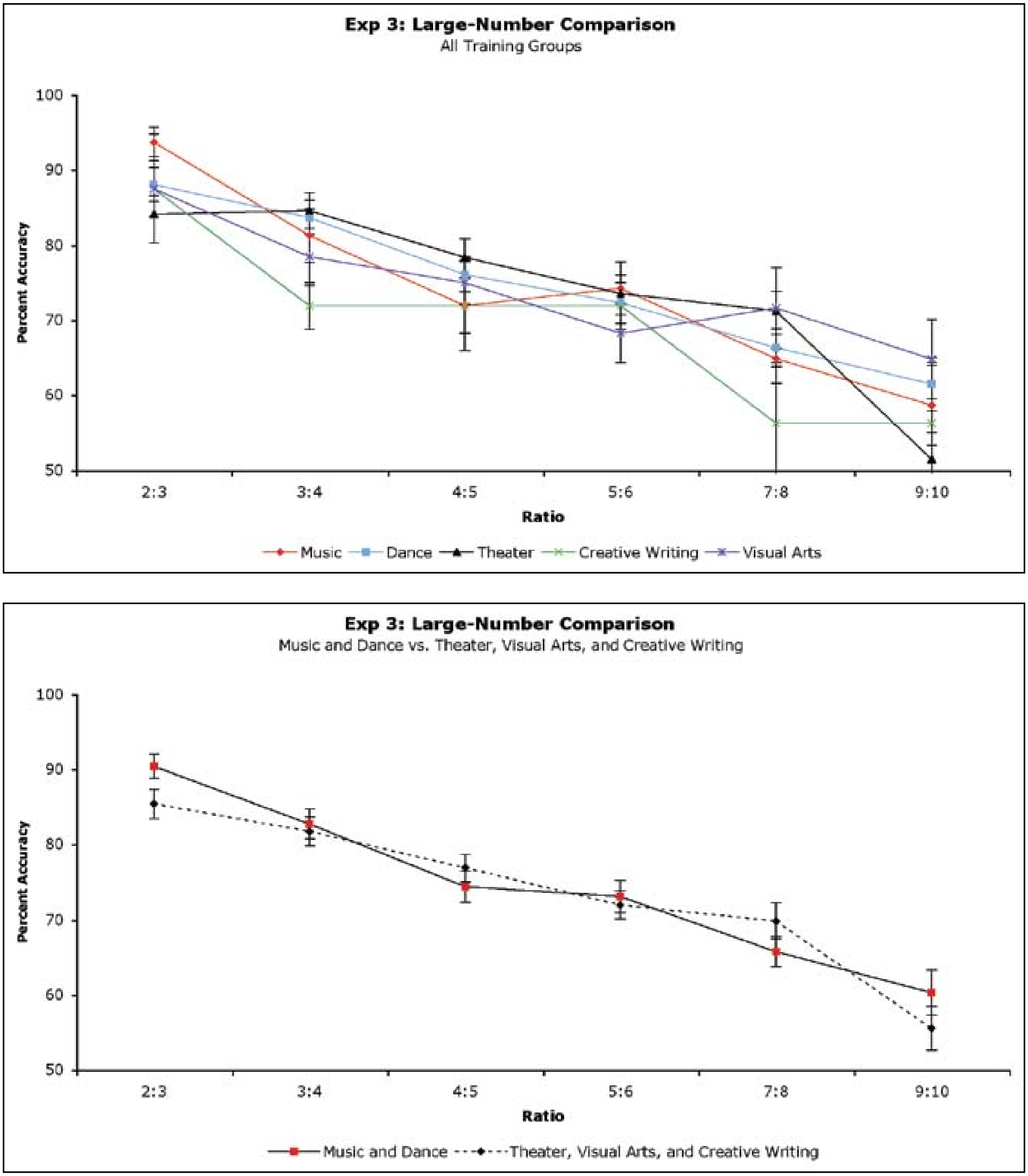
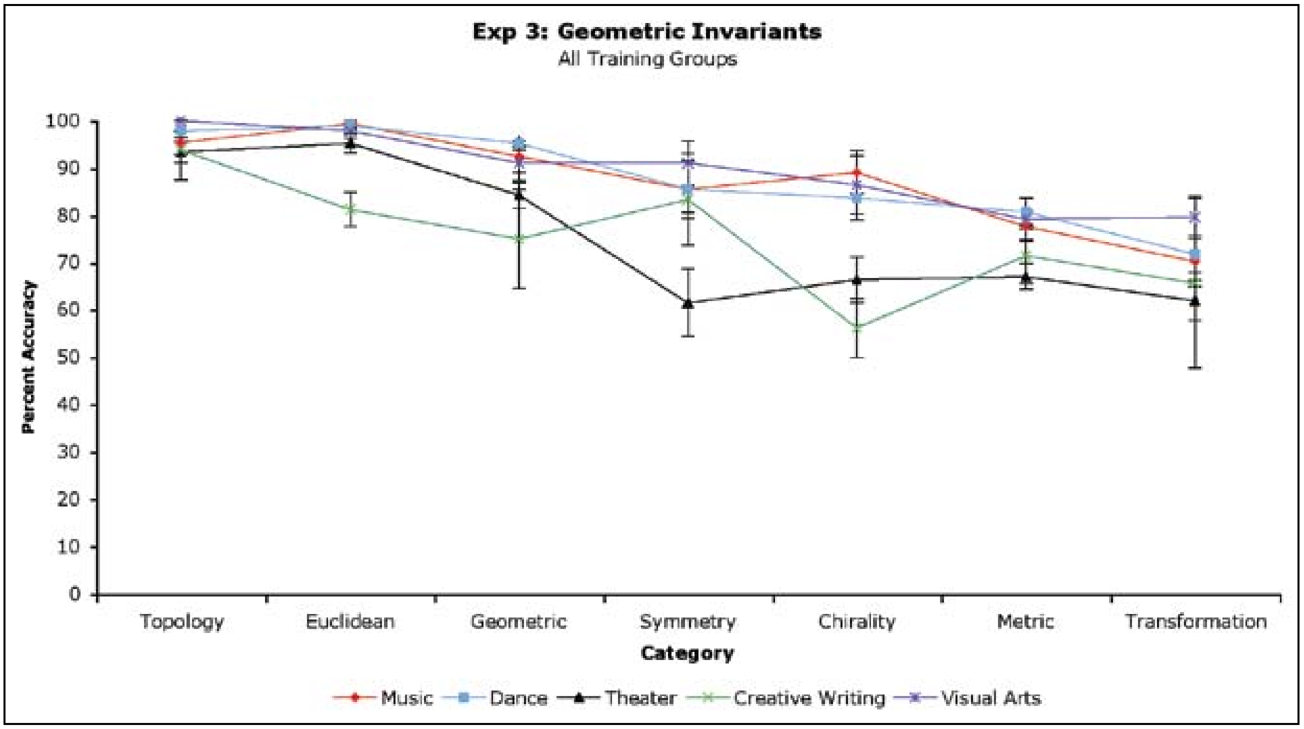


Figure 4b. Numerical comparison by high school students in differing arts disciplines.



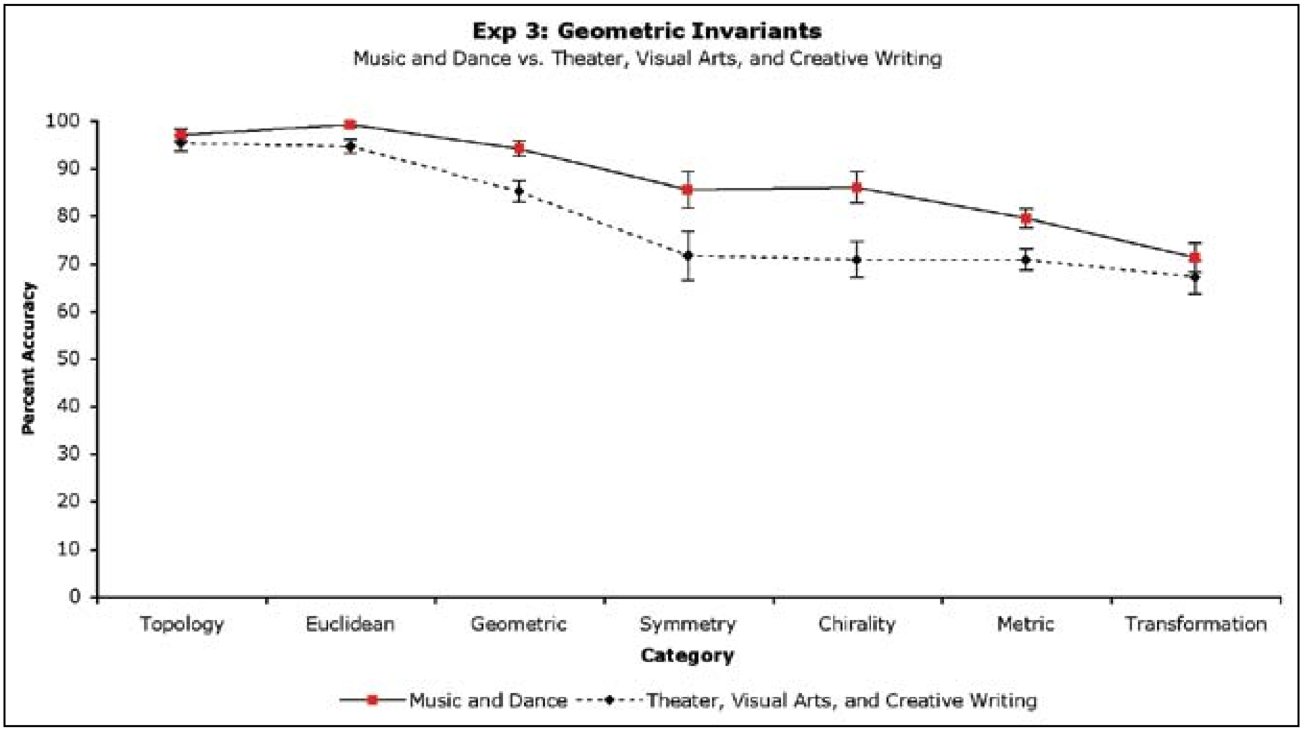


Figure 4c. Sensitivity to geometric invariants by high school students in differing arts disciplines.

no significant differences across these groups ($F(2,77)=2.31$, $p>.1$ n.s.; $F(2,77)=1.68$, $p>.1$ n.s.). Further ANOVAs revealed no effect of arts major grouping on the topology subset ($F(2,77)=2.49$, $p>.08$ n.s.) but significant effects on all the other measures. In particular, there was an effect of arts major grouping on the Euclidean geometry subset ($F(2,77)=5.04$, $p=.009$), and the geometric figures subset ($F(2,77)=7.65$, $p=.001$).

In both cases, post hoc pairwise comparisons corrected by the Hochberg's GT2 procedure revealed that music and dance majors significantly outperformed the theater and writing majors. There were also effects of arts major grouping on the chiral figures subset ($F(2,77)=8.53$, $p<.001$), the symmetric figure subset ($F(2,77)=5.83$, $p=.004$), and the metric properties subset ($F(2,77)=7.13$, $p=.001$). In all these cases, post hoc pairwise GT2-corrected comparisons showed that both music and dance majors and visual arts majors outperformed the theater and writing majors. Finally, there was an effect of arts major grouping on the geometric transformations subset ($F(2,77)=4.18$, $p=.019$, and post hoc pairwise GT2-corrected comparisons showed the visual artists outperformed theater and writing majors.

The regression analysis on overall task performance showed that amount of visual art training predicted performance on the geometry task (standardized beta=-.243, $p=.047$), such that students with more visual art training perform better on this task. Task performance was also predicted by amount of theater training—but in the opposite direction—such that children with more theater training perform worse on this task (standardized beta of theater training=.325, $p=.004$; R-square=.021, delta-R-square=.205, 1st step of model $p>.6$, 2nd step $p=.01$).

Estimation

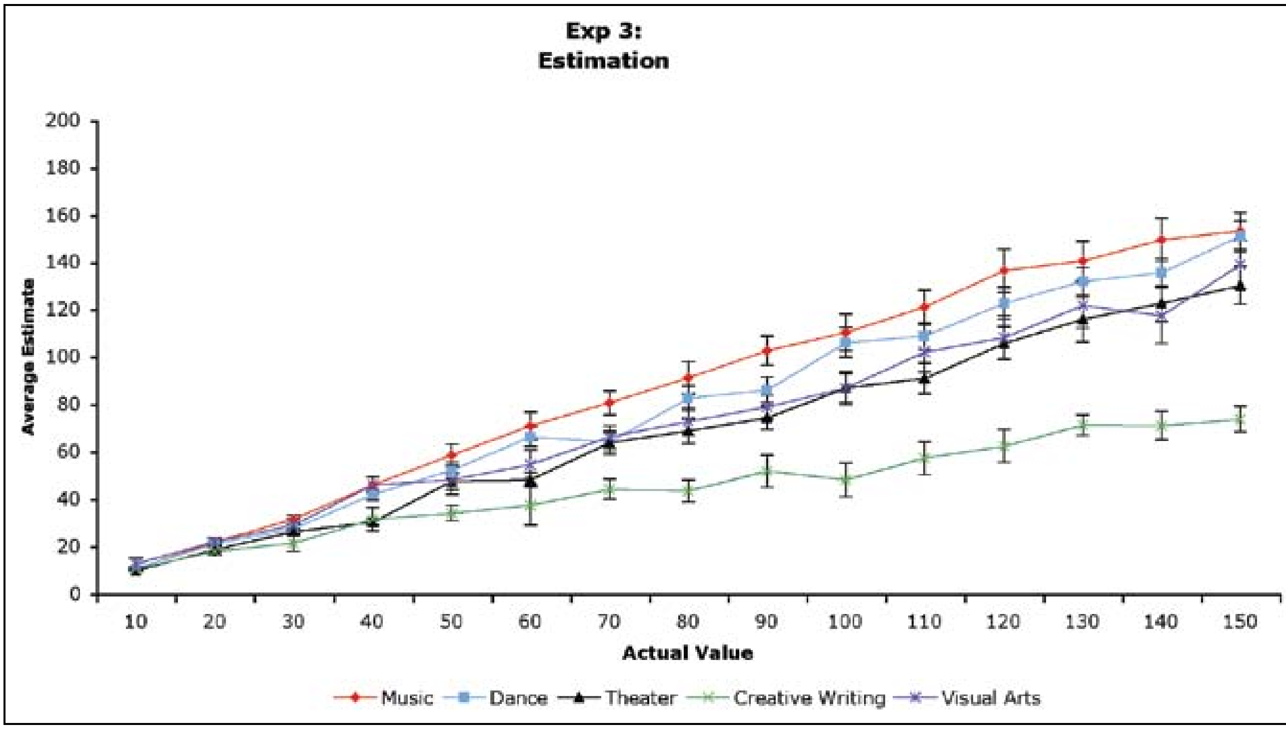
Performance on this task showed a significant linear contrast between number of dots presented visually and the verbal estimates given ($F(1,79)>813$, $p<.001$), indicating that subjects' estimates increased linearly and monotonically as the number of dots presented increased. As in the previous two experiments, the metric for performance on this task was amount of error as measured by the average distance of verbal estimates from the ideal line $y=x$. Because this distribution was positively skewed (z-skewness=3.41), correlational and regression analyses used the square root transform of the variable.

A one-way ANCOVA, comparing the 5 different arts majors and controlling for age, revealed a significant difference in performance between majors (omnibus ($F(4,74)=3.89$, $p=.006$). There was no effect of age ($p>.7$ n.s.). A second planned one-way ANOVA compared the performance of the music and dance majors to all other majors. It revealed that music and dance majors significantly outperformed the other majors ($F(1,78)=4.75$, $p=.032$; Fig. 4d).

Hierarchical regression analysis revealed that none of the training amounts or demographic variables was a significant predictor of performance on this task (R-square=.022, delta-R-square=.051, 1st step of model $p>.6$, 2nd step of model $p>.6$, n.s.).

Number line

Performance on the number line task showed reasonable accuracy, assessed by one-way repeated measures ANOVA on spatial estimates at each target number, with a significant linear contrast on the estimates given for each target number at the hundreds scale ($F(1,79)>7{,}000$, $p<.001$), the thousands scale ($F(1,79)>3{,}800$, $p<.001$), and the millions scale ($F(1,79)>3{,}400$, $p<.001$). Because the error distributions for the three scales were skewed and kurtotic (average z-skewness=10.63; average z-kurtosis=25.87), we performed a logarithmic transformation of the scores before performing our analyses.



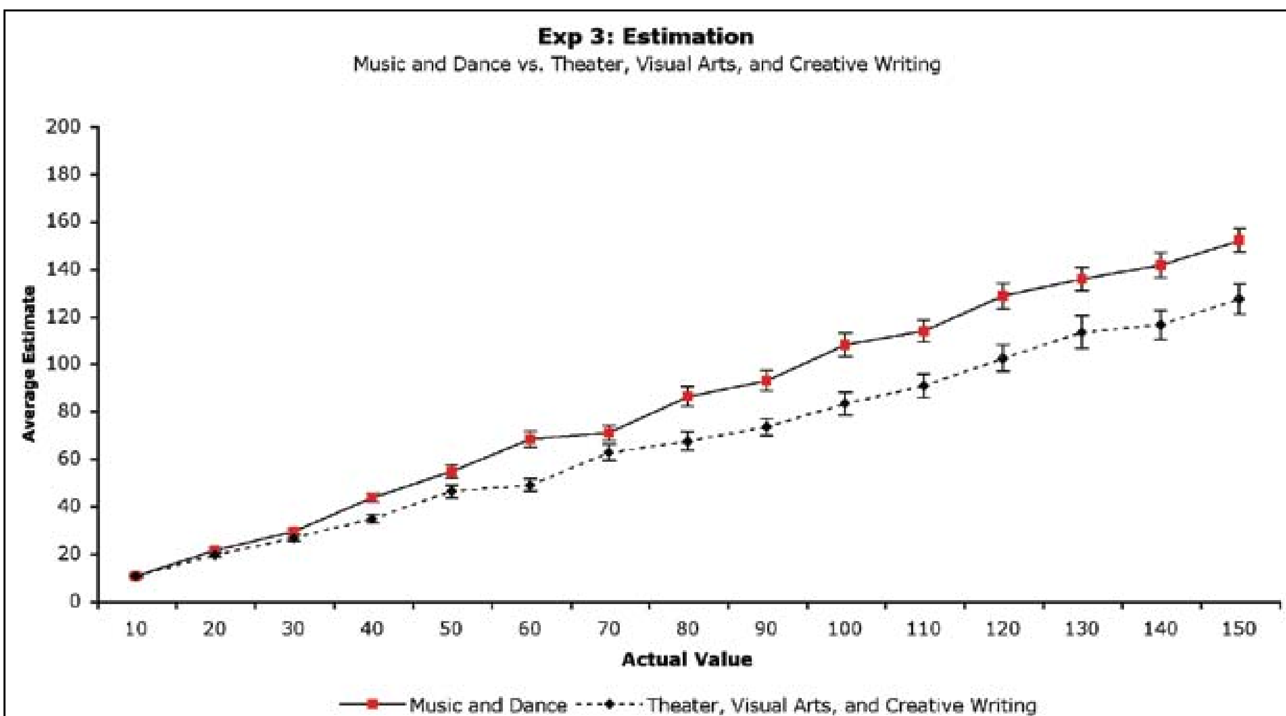


Figure 4d. Estimation by high school students in differing arts disciplines.

An ANCOVA crossing arts major and scale (3 levels) showed a significant linear contrast on scale (F(1,75)>11,000, p<.001), no effect of arts major (F(4,74)=1.31, p>.2 n.s.), and no interaction effect (F(8,150)=1.18, p>.3 n.s.). There was no effect of age (F(1,74)<1, p>.7 n.s.). A second planned ANOVA crossing arts major grouping (music and dance majors vs. all other majors) and scale showed that music and dance majors outperformed the other majors (F(1,78)=4.23, p=.043; Fig. 4e), as well as demonstrating the linear contrast on scale (F(1,78)>18,000, p<.001) and a lack of interaction effect (F(2,156)=2.44, p=.09 n.s.).

Regression analysis with age, sex and verbal IQ entered as the first step, followed by all the training variables in the second step, revealed only an effect of the amount of theater training predicted performance on this task, such that children with more theater training perform less well on this task (standardized beta of theater training=.345, p=.002; R-square=.073, delta-R-square=.156, 1st step of model p>.1, 2nd step of model p=.04).

Map

Overall performance on the map task was well above chance (mean 87.8%, t(79)>2,800, p<.001) with considerable variability (range 64-100%, s.d. 10.4). Because this distribution was negatively skewed (z-skewness=-2.22), all analyses used the square root transform of the reflected percent correct on this task.

Performance first was analyzed by a 5 (arts major) by 2 (trial type: landmark vs. no landmark) ANCOVA. This revealed no effect of arts major (F(4,74)=1.64, p>.1 n.s.), no effect of trial type (F(1,75)<1, p>.7 n.s.), and no interaction (F(4,75)<1, p>.8 n.s.). There was no effect of age (F(1,74)=1.01, p>.3 n.s.). No post-hoc pairwise comparisons were significant after correction for multiple comparisons. The second planned ANOVA crossing arts major group (music and dance majors vs. all others) and trial type found a significant difference in arts major groups such that music and dance majors outperformed the other majors (F(1,78)=4.77, p=.032), with no significant effect of trial type (F(1,78)<1, p>.4 n.s.) and no interaction (F(1,78)=1.22, p>.2 n.s.; Fig. 4f). Visual inspection of the graph reveals that visual artists and writers performed least well and that theater majors were intermediate.

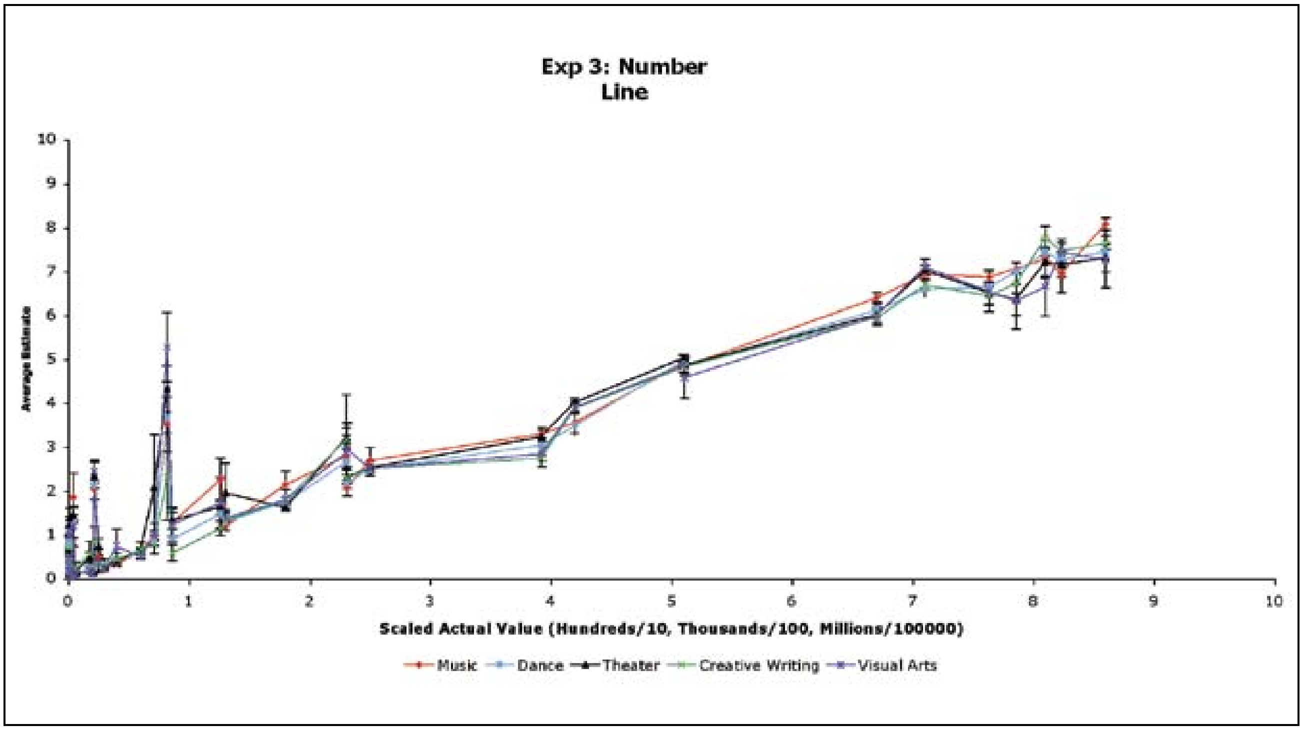
A one-way ANCOVA comparing the arts majors on trials in arrays with landmarks, and controlling for age, revealed no significant difference in the arts majors' performance (F(4,74)=1.87, p>.1 n.s.) and no significant effect of age (F(1,74)=3.05, p>.08, n.s.).

A one-way ANOVA comparing music and dance majors to all other majors on trials in arrays with landmarks revealed that music and dance majors outperformed all of the other majors (F(1,78)=5.41, p=.023). A one-way ANCOVA comparing the arts majors on trials in arrays without landmarks revealed no significant effects of either arts major (F(4,74)<1, p>.6 n.s.) or age (F(1,74)<1, p>.9 n.s.). A one-way ANOVA comparing music and dance majors to all other majors on trials in arrays without landmarks revealed no significant difference between the two groups (F(1,78)=1.43, p>.2 n.s.).

The hierarchical regression analyses of overall task performance showed that none of the training amounts or demographic variables was a significant predictor of performance on the map task (R-square=.03, delta-R-square=.085, 1st step of model p>.5, 2nd step of model p>.3). Similar negative findings come from regression analyses of performance on trials with a landmark (R-square=.079, delta-R-square=.159, 1st step of model p=.098, 2nd step p>.3) and trials without a landmark. (R-square=.027, delta-R-square=.074, 1st step of model p>.5, 2nd step of model p>.4).

Summary

This experiment confirms, strengthens, and clarifies the suggested findings of Experiment 2.



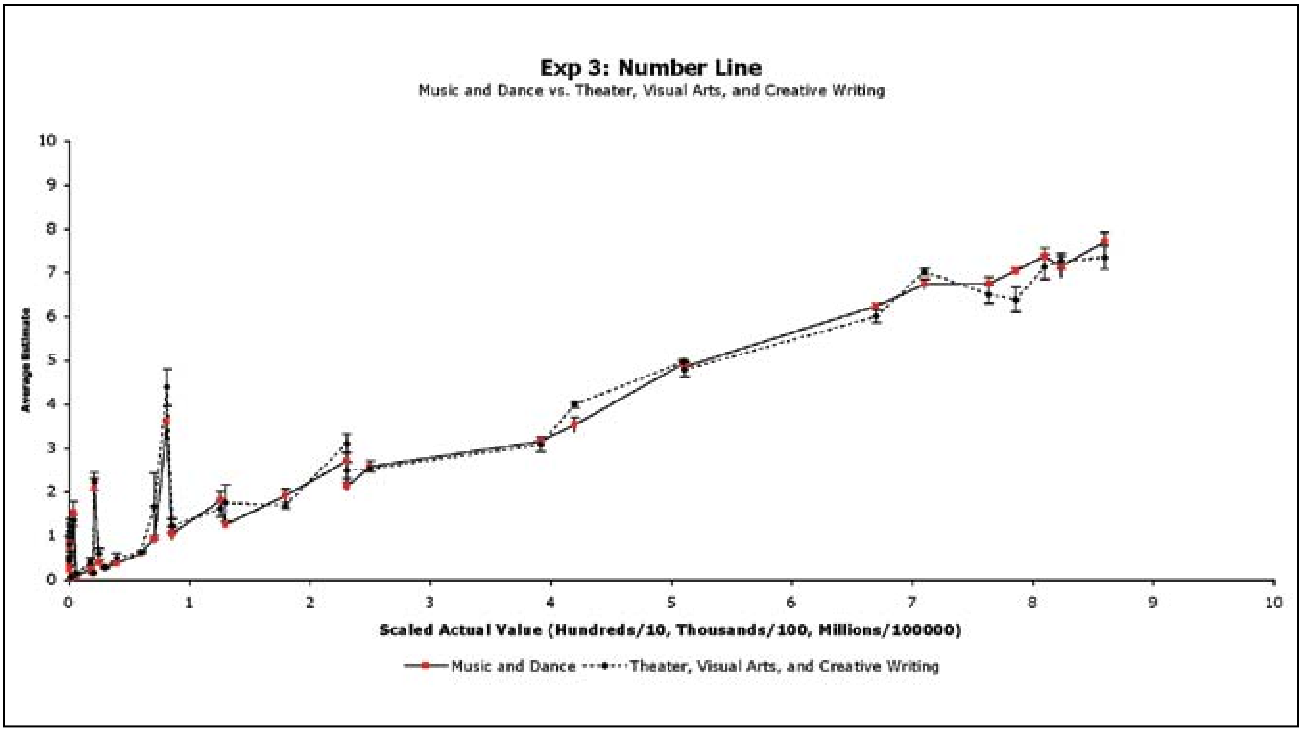


Figure 4e. Number Line performance by students in differing arts disciplines.

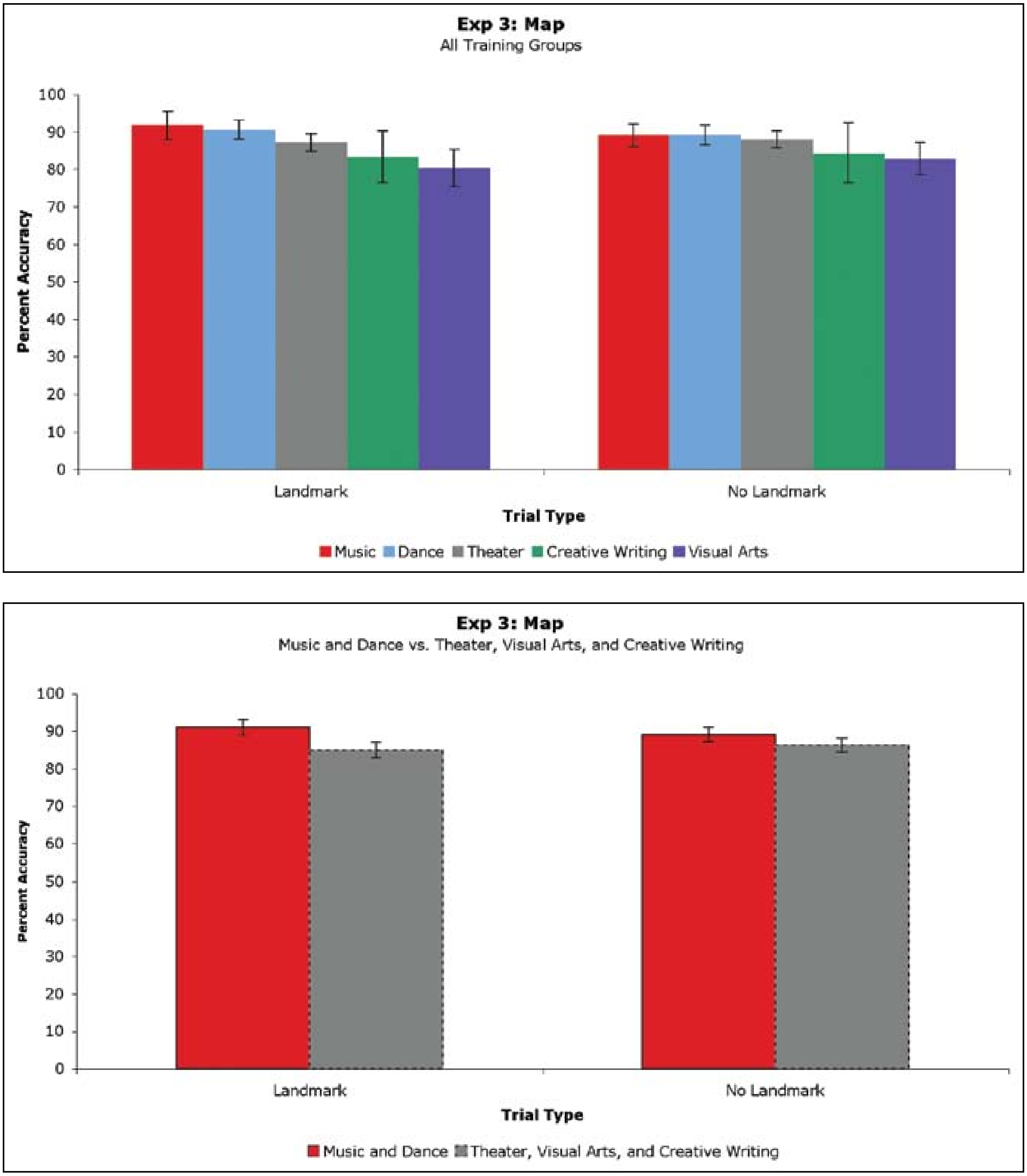


Figure 4f. Geometric map performance by high school students in differing arts disciplines.

Like Experiments 1 and 2, it provides no evidence for an association between training in music and representations of small exact numbers, large approximate numbers, or number words and verbal counting. Like Experiment 2, it provides evidence that music-trained students outperform students with no music training on tasks that involve geometric representations and reasoning. In the present study, this association was found on all three tasks involving geometrical reasoning. Music-trained students outperformed untrained students on a test of sensitivity to geometric invariants in visual forms, a test of mappings between space and number, and a test of understanding of geometric maps. The association also was found on a task that is believed to involve spatial representations indirectly: numerical estimation (see Dehaene, 1997).

The present findings … provide the first evidence that this relationship is specific to music training …

The present findings also clarify the relation between music training and geometry in two respects. First, they provide the first evidence that this relationship is specific to music training and not a more general effect of training in any form of the arts. Music-trained students excelled at spatial reasoning not only when compared to students lacking any special training in the arts (Experiment 2), but when compared to students who had pursued arts training at equal intensity but in other disciplines not involving music (especially theater and writing). Second, they provide evidence for an interesting role for training in the visual arts. Students with intense training in the visual arts excelled on the test of sensitivity to geometry in visual forms, but they performed less well on the other tests of sensitivity to geometry.

These findings suggest that … training in the arts can have diverse enhancing effects.

These findings suggest that geometrical cognition, like numerical cognition, has multiple sources, and that training in the arts can have diverse enhancing effects. This unexpected finding deserves to be replicated and extended.

Conclusions

Our experiments suggest that the well-documented association between music training and mathematical ability depends, in part, on a more specific relationship between music and the core system for representing abstract geometry. Music-trained students performed better than students with little or no music training on three tests of sensitivity to geometry: one focused on the geometric properties of visual forms, a second on the relation of Euclidean distance to numerical magnitude, and the third on the geometric relationship between forms on a map and objects in the larger spatial layout.

In our experiments, the relationship between musical training and geometric representation is specific in three respects. First, it is not a byproduct of individual differences in intelligence, academic achievement, or the social and economic factors that underpin these qualities, because all of the present analyses control for those important factors.

Second, it is not a byproduct of a more general relationship between music and all mathematical abilities, because no associations were found between music training and any of three tests of numerical reasoning. Third, it is not a byproduct of a more general relationship between geometric

representation and training in the arts, because students with extensive music training (either through study of music or study of dance) showed greater geometrical abilities than students with equally intense training in theater, writing, or (for two of the three measures) in the visual arts.

Our findings accord with those of recent studies linking impairments in music cognition to impairments in spatial cognition. Patients with amusia, a specific insensitivity to tonal relationships, were found to perform reliably worse than either music-trained or untrained adults on a test of mental rotation similar to the chirality subtest of our test of sensitivity to geometric invariants (Douglas & Bilkey, 2007).

… our experiments provide evidence for an association between music and geometry only when training in music is intensive and prolonged.

Moreover, patients with amusia showed less interference between spatial and tonal processing than the two comparison groups, producing a performance advantage on a tone-discrimination task with spatial interference (Douglas & Bilkey, 2007). These findings suggest that sequences of tones spontaneously activate representations of space in normal humans. Experiments in my lab are now beginning to probe the nature and development of this relationship in human infants and young children.

Finally, our experiments provide evidence for an association between music and geometry only when training in music is intensive and prolonged. No clear association was found in Experiment 1, which focused on a population of children whose training in music varied from light to moderate. Associations emerged in Experiment 2, which focused on children with more intense music training, but they were not uniformly strong.

Clear and strong relationships were obtained only in Experiment 3, which focused on older children whose primary interest and academic work centered on their music training. These findings provide no evidence that short-term, low-intensity training in music enhances abilities at the foundations of mathematics. It is possible, however, that this negative conclusion says more about the limits of our methods than about the true strength and generality of the association between music and mathematical achievement. Studies with larger samples may reveal more subtle enhancements in spatial abilities after music training of lower intensity.

More generally, our findings underscore both the importance and the feasibility of breaking down children's complex learning capacities into component systems at the foundations of human knowledge. With the present methods, developmental cognitive neuroscientists and educators can ask not only "is arts instruction good for children?" but "in what ways do arts instruction enhance children's academic ability: what brain/cognitive systems are enhanced by training in the arts?" These methods are simple, engaging to children across a wide age range, and revealing of the functioning of educationally relevant, core cognitive systems both in children and adults.

Because of its correlational approach, the present research does not reveal whether music training causes improvements in children's fundamental mathematical abilities. It does, however, provide tools that future experiments could use to answer that question.

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Training in the Arts, Reading, and Brain Imaging

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Summary

We undertook a series of studies to investigate how aesthetic ability and arts education correlate with improvements in children's reading abilities. As part of this research, we developed new analysis tools for diffusion tensor imaging (DTI), a method that identifies likely connections among brain regions involved in the development of reading skills. We also studied how exposure to the visual arts might relate to phonological awareness (the ability to manipulate speech sounds), which is correlated with reading ability. Further, based on an incidental finding in that research, we initiated a study to explore the relationship between exposure to the visual arts and children's math calculation abilities.

Our study included 49 children, aged 7 to 12, who were enrolled in an NIH-funded longitudinal study of the development of reading skills and the brain structures associated with this development. To this study, we added measures to determine the effects of arts training on the children's reading fluency and phonological awareness. We collected data, through parental questionnaires, on the extent of children's training in visual arts, music, dance, and drama/theater. We also collected parent-reported data on their children's temperament and openness to experience. We then correlated the arts training data with the children's test scores in reading fluency and phonological awareness over a three-year period.

The findings indicate that the amount of musical training the children underwent in the first year of our study correlated with the amount of improvements in the children's reading fluency over the three-year study period.

Additionally, we used DTI in each child to relate these behavioral measurements to individual differences in the anatomy of the corpus callosum- a structure that connects the brain's left and right hemispheres. We measured the tissue properties of specific

connections between brain regions (communication cables) to identify structural differences between strong and weak readers. We found that diffusion in the bundle of axons that connect the brain's temporal lobes is correlated with all our measures of reading ability; phonological awareness showed the strongest correlation. We also found a weak correlation between visual arts experience and phonological awareness. Finally, based on an incidental finding from this research, preliminary data suggest that exposure to visual arts may be correlated with improvements in children's math calculation abilities.

Introduction

Our team had two principal goals as part of the consortium. One was to develop and disseminate tools, to all Consortium grantees, for using diffusion tensor imaging (DTI) of the brain's white matter. White matter consists of axons (the brain cells' communication cables), which enable communication from one brain area to another. Our second goal was to investigate how aesthetic ability and arts education correlate with behavioral development of reading skills, and to investigate with DTI how these behavioral measurements correlate with the development of brain structures. To achieve these goals, we integrated this Consortium research into a National Institutes of Health (NIH)-funded longitudinal study of reading development in children ages 7 to 12, in which we assessed development of the children's reading skills over a three-year period. We have successfully advanced the two Consortium research goals over the past three years.

In the first section of this report, we describe the new behavioral measurements we created for assessing correlations between aesthetic ability and arts education, based on Deutsch's essential work on acquiring and analyzing arts questionnaires. In the second section, we briefly describe the new tools we developed for analyzing DTI, largely through Akers' creation of DTI software. In the third section, we describe preliminary results revealing a relationship between brain structure and behaviors that are essential for reading.

One of our major findings from these studies was that the amount of musical training measured in year 1 was significantly correlated with the amount of improvement in Reading Fluency demonstrated in children over the three-year period of our study.

Additionally, we discuss an incidental finding in section four: in our sample, we found a correlation between exposure to the visual arts and improvement in math calculation, as measured by children's calculation test scores. For this new research direction, we have initiated a collaboration with consortium investigators, Dehaene and Spelke from Harvard, and with our Stanford colleagues in the School of Education, Professor Richard Shavelson and Jessica Tsang.

Study Designs and Results

Section 1: Reading, Arts Education, and Aesthetics

In conjunction with the NIH-funded longitudinal study of reading development, we explored the relationship among training in the arts, children's temperament, and reading fluency. We developed an arts education questionnaire, and used a modified version of the Child Temperament and Personality Questionnaire (CTPQ) developed by Victor, Rothbart, and Baker (2003). The arts education questionnaire explores four areas of arts education: 1) Visual Arts 2) Music 3) Dance and 4) Drama/Theater, and includes in-school education, as well as formal training and independent practice, in each of these four areas.

Parents reported the number of hours per week their child received formal training outside of school, spent time in independent practice,

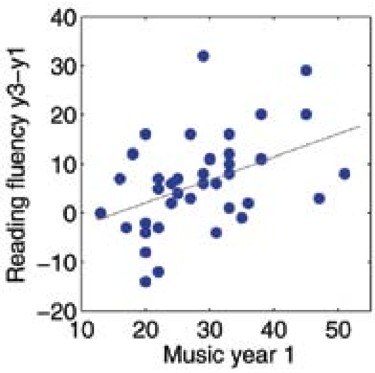

Figure 1.1. Music provided the strongest correlation between arts training and reading. Lifetime hours of music training as of year 1 is plotted against the difference (y3-y1) in reading fluency standardized scores (Woodcock-Johnson III). Pearson r = 0.43 (±0.13), p=0.006, N=40. One outlier was excluded based on an extreme music score. The gray line is fitted to the data points minimizing the mean least square error.

and received in-school instruction. Parents also rated their child's skill level. Aesthetic ability was measured by the Child Temperament and Personality Questionnaire. Between year 1 and year 2 of the reading study, we obtained questionnaire data on 49 children (ages 7 through 12). At year 3 of the reading study, we obtained questionnaire data on 41 of these children.

We examined the relationship among behavioral and imaging measures and the Openness to Experience Scale, which is comprised of four factors: 1) Ideas 2) Aesthetics 3) Intellect/Quick to Learn and 4) Perceptual Sensitivity. An exploratory principal components analysis (PCA) was conducted using SPSS (statistical software) to investigate the items from the Child Temperament and Personality Questionnaire in our sample of children (n=49). PCA analysis revealed five components, identified (in order of measured importance) as 1) Intelligence/Quick to Learn, 2) Aesthetics, 3) Perceptual Sensitivity, 4) Distractibility, and 5) Ideas. These explained, respectively, 22.5%, 18.1%, 10.1%, 7.3%, and 5.3% of the variance. The items generally weighted on the same components identified by the original Child Temperament and Personality Questionnaire. Parents' ratings of their children on the Intelligence/Quick to Learn factor was significantly correlated with several of the IQ and Reading Fluency measures. The correlations ranged from r=.42, (statistically significant at $p < .005$) to r=.57 (statistically significant at $p < .001$). Hence, parents' reports about their children were generally consistent with measurements using standardized tests of IQ and Reading.

The simplest and most compelling observation was this: The amount of musical training measured in year 1 was significantly correlated with the amount of improvement in Reading Fluency between years 1 and 3 (Figure 1.1). We hasten to add that this correlation does not imply that music training caused the reading improvement. It is possible that children who are intellectually capable of pursuing musical training are also ready for reading. The observed correlation should be followed-up with a controlled study to analyze the possibility of a causal connection.

A second, and more surprising, observation was a relationship between early visual arts experience and phonological awareness (attention to patterns

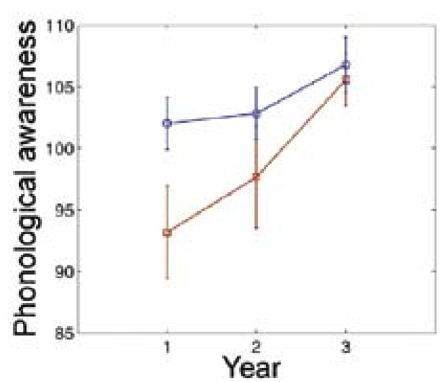

Figure 1.2. Subjects with any visual arts experience prior to age 4 (blue, N=37, 37, 34, for y1, y2, y3 respectively) score higher than those without such training (red; N=11, 9, 7) in the first year (t=2.01, p<0.05). The difference decreases in year 2 and disappears by year 3.

of speech sounds). Phonological awareness is an auditory skill that is reliably correlated with reading ability. In the first year of our study, children who had early training in the visual arts had a higher degree of phonological awareness than children with no such training. There was no significant age difference between these groups (mean ages were 10.2 and 10.9). The difference in phonological awareness scores between the two groups, shown in Figure 1.2, was quite large and highly significant (statistically) in the first year of our study. Two years later, however, when the group ages were roughly 12.5y, the difference in phonological awareness scores had disappeared. This phenomenon – an early correlation that dissipates with time – is commonly observed in the developmental literature. The explanation for the disappearance is thought to be that many factors contribute to skill learning. As children develop, they find many ways to master a skill. Hence, the impact of the factor revealed by the early association becomes less and less important with time.

We find this correlation between visual arts training and phonological awareness surprising. Perhaps an explanation can be found in the amount of attention to training provided by the parents, or by attendance to preschool, which provides training in both skills. The visual arts score may be an indicator of intense parental involvement and, with increasing years of schooling, the measured parental effect is reduced. Admittedly, the effect is based on a small sample and may disappear in repeated examination in a larger sample.

As part of our new collaboration with Professor Shavelson, we will extend our analysis of the reading data to item-specific analyses. We plan to complete the study of the full range of reading and general intelligence measures, as well as the correlations with arts experience.

Section 2: Diffusion Analysis and Visualization Tools

Methods for identifying the paths and properties of the large groups of white matter fibers (fascicles), the tracts of brain cell axons that facilitate cellular communication in the human brain, are an important component in understanding human brain organization and development. We have made substantial progress in developing computational algorithms to identify and measure these pathways.

Interpreting the pathways, estimated from diffusion tensor imaging (DTI) data, requires not only skilled scientists but also extensive visualization tools. David Akers developed a beautiful graphical interface for selecting, editing, and visualizing DTI white matter fiber tracts. He performed a systematic study of our work flow, and developed a software application that can assist all Consortium investigators who interact with DTI data. Figure 2.1 is from David's paper (published in the Computer-Human Interaction proceedings) and shows the interface to the software.

Existing algorithms for tracing white matter tract pathways were analyzed by Anthony Sherbondy, a student in the Electrical Engineering department, together with Robert Dougherty and Professor

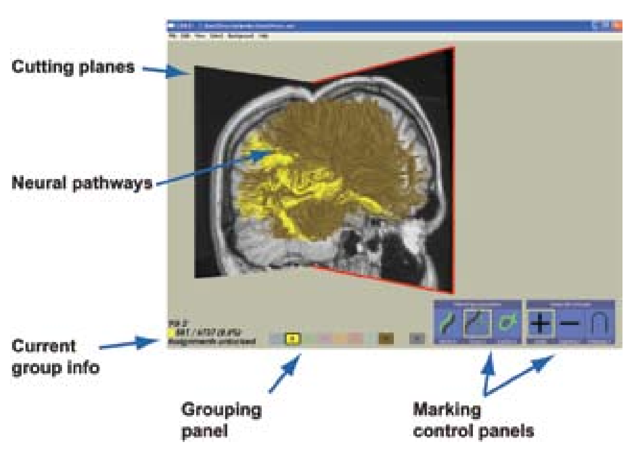

Figure 2.1. DTI visualization tool (Akers 2006).

Wandell. They identified several limitations in these algorithms that cause investigators to miss important fascicles (groups of axon fibers), limiting our ability to estimate the probability that two locations of "gray matter" (regions of nerve cell bodies) are connected, via their axons. Sherbondy, Wandell, and Dougherty developed new probabilistic tracking tools to better estimate these fascicles.

Robert Dougherty, who managed the software development efforts, integrated Aker's and Sherbondy's contributions with mrDiffusion, our general laboratory measurement tools for DIT analyses. This package is currently available for download (http://sirl.stanford.edu/software/). These improved tractography algorithms and analysis tools were integrated into our software for distribution to Consortium investigators as an update to our mrDiffusion package. For instance, Consortium investigators Posner and Neville plan to use our software tools in their research (through efforts by Akers and Dougherty, working with Yalchin Abdullaev, Jolinda Smith and Mark Dow at the University of Oregon Lewis Center for Neuroimaging.) These software development efforts also have been shared with the scientific community broadly. A paper describing the new white matter path-finding methods and algorithms that we developed is currently under review for publication. Further, Akers collaborated with NIH staff to incorporate the DTI visualization methods into the NIH neuroimaging tools, AFNI. This tool is used in hundreds of labs around the world.

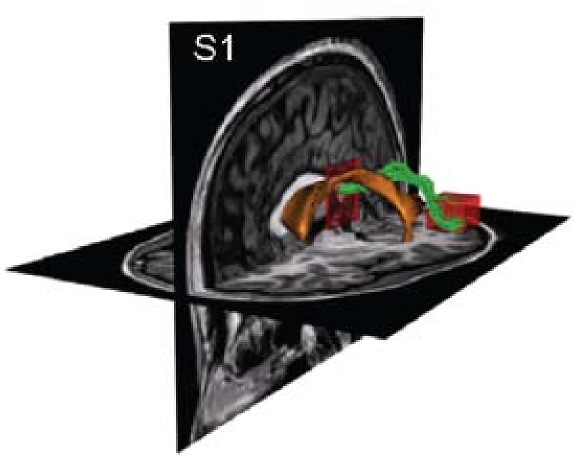

Figure 2.2. DTI tractography and tools (Sherbondy, Akers et al. 2005).

Section 3: White Matter Pathways, Reading, and Arts Training

The third component of our research is focused on making specific behavioral and neural measurements. Identifying the main axon fiber tracts in each brain is an important step in tracking brain development. Therefore, Arvel Hernandez developed a protocol for defining specific axonal fiber pathways in each child's brain and applied that protocol to all the brains.

The survey data from the 49 children who participated in our NIH-supported longitudinal study of reading development inform us about the parents' and children's experience with the arts. Described below are results of studies connecting the behavioral measurements with brain structure.

Our initial effort has been to identify the major pathways of axons that pass through the brain's corpus callosum (Figure 3.1), the structure that connects the brain's left and right hemispheres. This major commissure, connecting the human brain's two hemispheres, is comprised of more than 300 million axons. From anterior to posterior (front to back), the fibers in the corpus callosum systematically connect different regions of the brain's cortex. We have adapted and extended a callosal segmentation scheme proposed by (Huang, Zhang et al. (2005). This method allows us to segment individual corpus callosi and measure development that is localized to specific white matter (axonal) pathways.

A callosal segmentation in the brain of one child is shown in Figure 3.1. The different colors correspond to the zones where the various axon fiber bundles pass through the callosum. We expect that these zones develop at different rates, and that

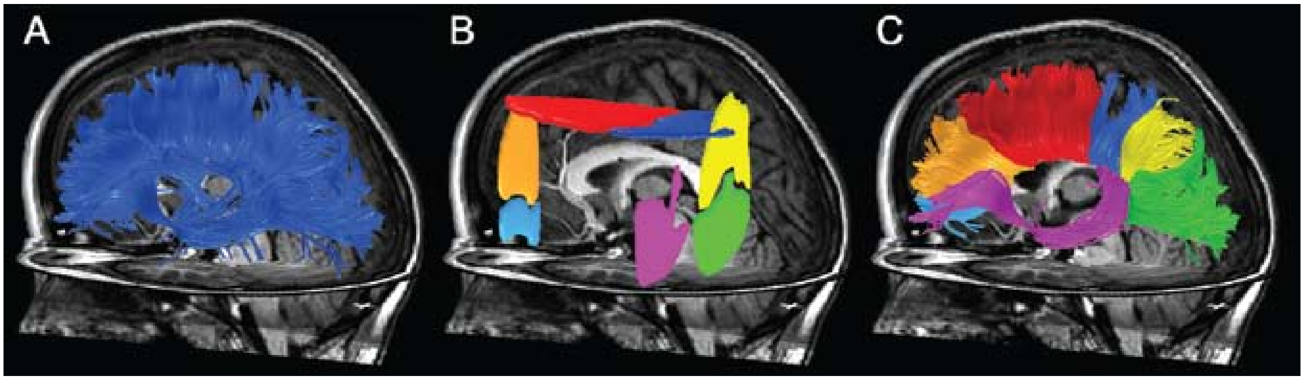

Figure 3.1. Segmenting a child's corpus callosum.

their diffusion properties will correlate with distinct aspects of cognitive development. For example, visual and auditory information must be integrated rapidly between the brain's two hemispheres in order to create a unified percept, while axon fibers that communicate between executive frontal lobe control-circuits may not need fast electrical conduction velocities.

… we expect the pathways connecting the brain's temporal lobes to be important for sound and music perception …

Thus, across all humans, the brain's sensory pathways should exhibit diffusion properties that are indicative of large, fast-conducting axons when compared to the diffusion properties of the executive control pathways. Further, different sets of callosal pathways are likely to be important for different cognitive and behavioral skills. For example, we expect the pathways connecting the brain's temporal lobes to be important for sound and music perception, and the pathways connecting visual cortices to be important for vision. Thus, individual variation in the diffusion properties in these pathways may vary according to the relevant behavioral measures.

The callosum itself is a dynamically changing brain region between the ages of seven through the early teens, exhibiting substantial changes in size and shape during this time (e.g., Thompson, Vidal et al. 2001). These morphological changes reflect changes at the cellular level (Aboitiz, Scheibel et al. 1992). We expect that many of these developmental changes are specific to particular pathways at different ages. For example, Thompson et al. suggest that temporal and parietal pathways in the posterior callosum are changing the most in children during their development from 6 to 12 years of age, possibly reflecting the development of complex linguistic and visuo-spatial reasoning ability.

These measurements, however, do not identify which specific axon fiber pathways are developing. Further, there is a distinct gap in the existing measurements. Studies in the brains of people who have died (post-mortem studies) provide excellent data at the cellular level, but behavioral or physiological measurements cannot, of course, be undertaken. Conversely, the gross anatomical studies (at the macroscopic, rather than microscopic, level) such as those of Thompson et al. provide compelling data on living subjects, but cannot go beyond gross morphology (form and structure). To fill this gap, we are using DTI to measure development of the brain's white matter. DTI shows networks of axons by analyzing the diffusion of water molecules in the brain, which tend to diffuse along the axons.

Because the diffusion of water in the brain acts as a probe for microscopic tissue structures, DTI provides a non-invasive window into the cellular changes in humans that occur during development.

Using these tools, we discovered that strong and weak readers differ at a particular location within the posterior segment of the corpus callosum. The diffusivity of water in the direction perpendicular to the callosal fibers is highly correlated with phonological awareness and reading skill (Ben-Shachar, Dougherty et al. 2007; Dougherty, Ben-Shachar et al. 2007).

We discovered that diffusion in the axon fiber bundles that connect the brain's temporal lobes is most strongly correlated with phonological awareness, an auditory skill that is reliably correlated with reading ability. Children with better phonological awareness skills have fewer and perhaps larger axons passing through the part of the callosum that connects the temporal lobes. While the arts training measures did not correlate with the first year callosal measurements, the behavioral correlation between music training and reading fluency improvement described in our studies above suggests that we may detect a relationship between music training and the development of the diffusion properties. We are currently in the process of making such measurements.

Section 4: Future directions- arts training and math abilities

Our group has acquired longitudinal imaging and behavioral measurements on a group of children with a wide range of reading skills. That study, funded in large part by the NIH, is now at its final year of data acquisition. In analyzing the Dana-supported study results of the arts questionnaires with our behavioral measures, we measured variables that were not part of the NIH study. As a result, we noticed an interesting relationship between visual arts experience and math skills (measured by the Woodcock–Johnson III Calculation test).

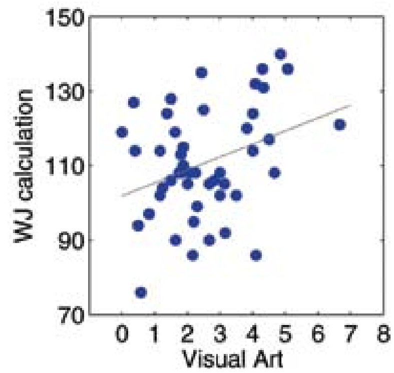

Figure 4.1. Visual art experience is correlated with math skills. The horizontal axis shows a weekly average of hours spent on visual art activities in school by y1. The vertical axis shows an age standardized score of calculation measured in year 1 (Woodcock-Johnson III). Pearson r = 0.34 (± 0.14), p=0.017, N=48. The gray line is fitted to the data points minimizing the mean least square error.

The correlation between visual art experience and Woodcock-Johnson result is shown in Figure 4.1.

We also identified a moderate correlation ($r=0.40$, $p<0.01$) between music experience outside of school and how well children could remember a series of numbers (CTOPP Memory for Digits test). That test is a reliable measure of working (short-term) memory, which is important for cognitive functions including calculations with larger numbers.

Our estimation of math skills was limited to one test, which was administered only in the first year of our study, given that our original focus had been on reading development. To further explore the relationship between arts experience, math skills, and brain structures, we are measuring performance on a variety of math skills. Ultimately, we will examine the relationship between these measures and the longitudinal DTI measurements and arts questionnaires.

The new mathematical skills measurements are based on two major findings on arithmetic in the adult brain. First, it has been shown that recalling answers from memory to arithmetic questions and

fully calculating answers are dissociable functions (Dehaene and Cohen, 1997). Second, adults use different brain areas to estimate arithmetic sums compared with calculating exact answers (Dehaene, Spelke et al., 1999). These findings suggest that three different types of arithmetic processing exist in the adult brain: recall, estimation, and exact calculation.

… problems recalled from memory take the shortest amount of time …

Based on these findings, we have piloted a task that may clarify how different arithmetic processes develop. In the task, participants see an arithmetic problem on a computer screen along with two answer options. They select the correct answer by pushing a button corresponding to the side of the screen on which the answer appears. We present three types of problems in blocks: simple multiplication and additions problems that can be answered by recalling memorized facts; two-digit addition problems in which the participant selects the exact answer; and two-digit addition problems in which the participant chooses the answer option that best approximates the right answer (estimation task). In addition to the computerized task, we have included a standard age-normed assessment of math ability, the WRAT-4 (Wide Range Achievement Test 4). This will be a measure of math achievement as it is traditionally tested.

Our pilot data from the computer task show that children spend different amounts of time answering the different types of problems, such that the problems recalled from memory take the shortest amount of time, the estimation problems the second shortest amount of time, and the exact calculation problems the longest.

As we continue to explore mathematical skills, we will be able to analyze whether these differences develop with age, how they relate to performance on other cognitive measures, and how they relate to white matter brain structures. The specific neuroanatomical hypothesis we are investigating concerns the anterior segment of the arcuate fasciculus (see Figure 4.2). This is a large pathway that connects cortical regions consistently activated in arithmetic tasks. This bilateral fiber tract may be important for working memory as well as for mathematical skills. We are in the processing of identifying this tract in the brains of all the children in our study.

Conclusions

Our Consortium research resulted in three advances. First, we developed and distributed advanced software tools for analyzing and visualizing DTI data. These tools can be used to study the neural basis for the development of cognitive skills. Second, our data on the relationship between arts training and cognitive development revealed a correlation between the amount of music training

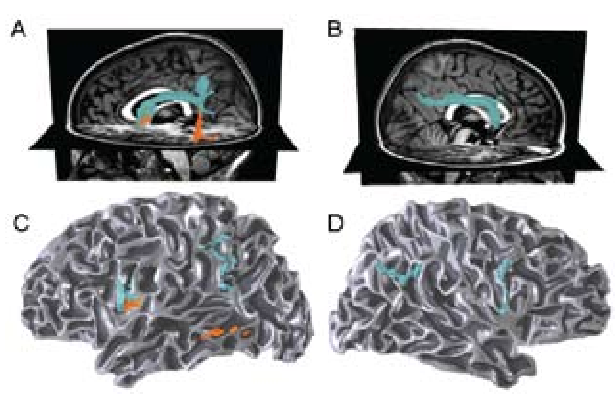

Fig. 4.2. Dorsal fibers of the arcuate fasciculus connecting the inferior frontal cortex with inferior parietal and posterior temporal cortex in a single child (7 year old female good reader). The anterior segment (cyan) is found bilaterally, while the long segment (orange) is found in the left hemisphere only.

and the amount of improvement in reading fluency in children. Third, we discovered a correlation between brain structure—the diffusion properties of a part of the corpus callosum—and reading ability as well as phonological awareness, an auditory skill that is closely related to reading ability.

Additionally, we have preliminary data on a relationship between mathematical skills and the arts. We have noticed a surprising correlation between visual arts training and math calculation skill, as measured by the Woodcock-Johnson III Calculation test. We have piloted a new set of experimental studies, based on the cognitive hypotheses from Dehaene and Spelke, and are undertaking studies to determine whether the anterior segment of the arcuate fasciculus might be a biological indicator of mathematical skill development, and whether this same segment may be encouraged to develop by training in the visual arts.

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Dance and the Brain

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Summary

The ubiquity of dance across cultures, ages, and history make it an "embedded" art form. Most of us already have significant dance experience by adulthood. This commonality of dance, therefore, shifted our research away from normative studies that attempt to show that dance is good for a person or their brain, that it makes one smarter, is worth learning, or that some types of dance make one smarter than others.

Instead, our studies concerned the mechanisms that allow us to learn to dance, and the concurrent learning-related changes in the brain. Prior behavioral research on observational learning suggests that physical and observational learning share many common features. Neuroimaging research on action observation has identified brain regions, including premotor, inferior parietal, and temporal regions, that are similarly active when performing actions and when watching others perform the same actions. The present study investigated the sensitivity of this "action observation network" (AON) to learning that is based on observation, compared to physical rehearsal.

Participants were trained for five consecutive days on dance sequences that were set to music videos in a popular video game context. They spent half of daily training physically rehearsing one set of sequences, and the other half passively watching a different set of sequences. Participants were scanned with fMRI (functional magnetic resonance imaging) prior to, and immediately following, the week of training.

Results indicate that premotor and parietal components of the AON responded more to trained, relative to untrained, dance sequences. These results suggest that activity in these brain regions represents the neural resonance between observed and embodied actions. Viewing dance sequences that were only watched (and not danced) also was associated with significant activity in the brain's premotor areas, inferior parietal lobule, and basal ganglia.

These imaging data, combined with behavioral data on a post-scanning dance test, demonstrate the emergence of action resonance processes in the human brain that are based on purely observational learning, and identify commonalities in the neural substrates for physical and observational learning.

A critical outcome of our research is that learning by observing leads to action resonance and prediction that is the same as occurs with physical learning. This strong link between learning by doing and learning by observing at the neural level might benefit from early exposure to dance, where the consistencies between training methods could be acquired.

… using functional neuroimaging, we characterized the neural underpinnings of observational learning …

Introduction

Many avenues exist for learning dance. For example, learning how to flamenco dance could be achieved in several different ways. One could learn the steps by following a verbal description of where, when, and how to move through space, by following step patterns traced on the floor, by trial and error, or by observing a dancer who knows the movements and performing the movements alongside this individual.

Behavioral research on action learning conducted during the past half-century suggests that the final option, learning from observing and simultaneously reproducing another individual's movements, results in the quickest and most accurate learning (e.g., (Sheffield, 1961; Schmidt, 1975; Bandura, 1977, 1986; Blandin et al., 1999; Blandin and Proteau, 2000; Badets et al., 2006).

This past research has demonstrated that not only is observation of a model helpful for learning (Blandin et al., 1999), but also that physical practice is more beneficial than mere observation of new movements (Badets et al., 2006). The current research was directed at exploring the separate and combined contributions that observing and practicing have on acquiring a novel movement sequence. Additionally, using functional neuroimaging, we characterized the neural underpinnings of observational learning, with or without the added benefit of physical practice.

Early behavioral investigations by Sheffield (1961) led to the proposal that observation of a model improved motor learning by means of providing a "perceptual blueprint," or a standard of reference for how the task to be learned should be performed. Carroll and Bandura elaborated upon these ideas by proposing that this "perceptual blueprint" improves learning by providing a means for detecting and correcting performance errors as well (Carroll and Bandura, 1987, 1990). Behavioral studies that compare observational and physical learning support this idea (Zelaznik and Spring, 1976; Doody et al., 1985; Carroll and Bandura, 1990; Lee et al., 1990; Blandin and Proteau, 2000) (for a review, see Hodges, 2007).

In one such study, Blandin and Proteau (2000) asked participants to perform a task that involved executing a speeded out-and-back movement pattern with the right arm while avoiding obstacles. Participants either physically rehearsed without observing a model perform the action, observed a novice performing the task before attempting to perform the task themselves, or observed an expert performing the task before attempting the task themselves. Observation of either type of model enabled participants to develop error detection and correction skills as effectively as physical practice.

Other work by Blandin and colleagues (1999) establishes that the quality of the model matters. Beneficial learning comes from observation of an

expert model and not a novice model during the acquisition of a novel motor task (Blandin, Lhuisset, & Proteau, 1999). Recent data from psychophysics and EMG (electromyography) data lend additional evidence in support of observational learning, as reported in a study by Mattar and Gribble (2005). They demonstrated that participants' learning performance of a novel, complex motor task was facilitated after they observed another individual learning to perform that same task, compared to watching another individual perform the task without learning, or learning to perform a different task (Mattar and Gribble, 2005).

... functional neuroimaging enables us to determine whether observational and physical learning modify the same, or different, neural substrates.

What follows from these and other studies (Barzouka et al., 2007; Bouquet et al., 2007) is the idea that observational and physical learning have similar outcomes on behavior, as evidenced by the outcome of training. However, as Blandin and colleagues note (1999), "this does not mean that all cognitive processes involved during physical practice are also taking place during observation or that observation does not engage participants in some unique processes not taking place during physical practice" (p. 977).

The work presented above provides a behavioral foundation for exploring areas of overlap and divergence between observational and physical learning. However, it is difficult to determine with only behavioral procedures the degree of correspondence of cognitive processes subserving these two types of learning. Behavioral and EMG (electromyography) studies (study of electrical activity of both muscle and nerve) alone cannot satisfactorily address the underlying neural mechanisms, whereas the addition of functional neuroimaging enables us to determine whether observational and physical learning modify the same, or different, neural substrates.

Research Design

In the current research, we investigated this hypothesized overlap of cognitive mechanisms for observational and physical learning through concurrent use of behavioral and neuroimaging procedures. If we found that both types of learning engage the same areas of the brain, then we can infer that both observational and physical learning engage comparable cognitive processes. Conversely, the emergence of different areas of neural activity based on learning would imply that distinct cognitive processes underlie each of these two types of learning.

We investigated observational learning by training novice dancers to perform complex dance movement sequences while manipulating training elements. Specifically, we determined whether observational and physical learning resulted in quantitatively similar or different behavioral performance and patterns of neural activity, and examined how adding an expert model to the training procedure influenced behavior and neural activity. Due to the complexity and unfeasibility of having participants actually perform dance sequences in the scanner (but see Brown et al., 2006), we instead chose to train participants to perform the movement sequences with videos outside the scanner, and then asked them to observe the training videos during the scanning sessions, as shown in Figure 1.

A growing body of evidence indicates that action observation during imaging can be used as a surrogate marker for studying the neural systems

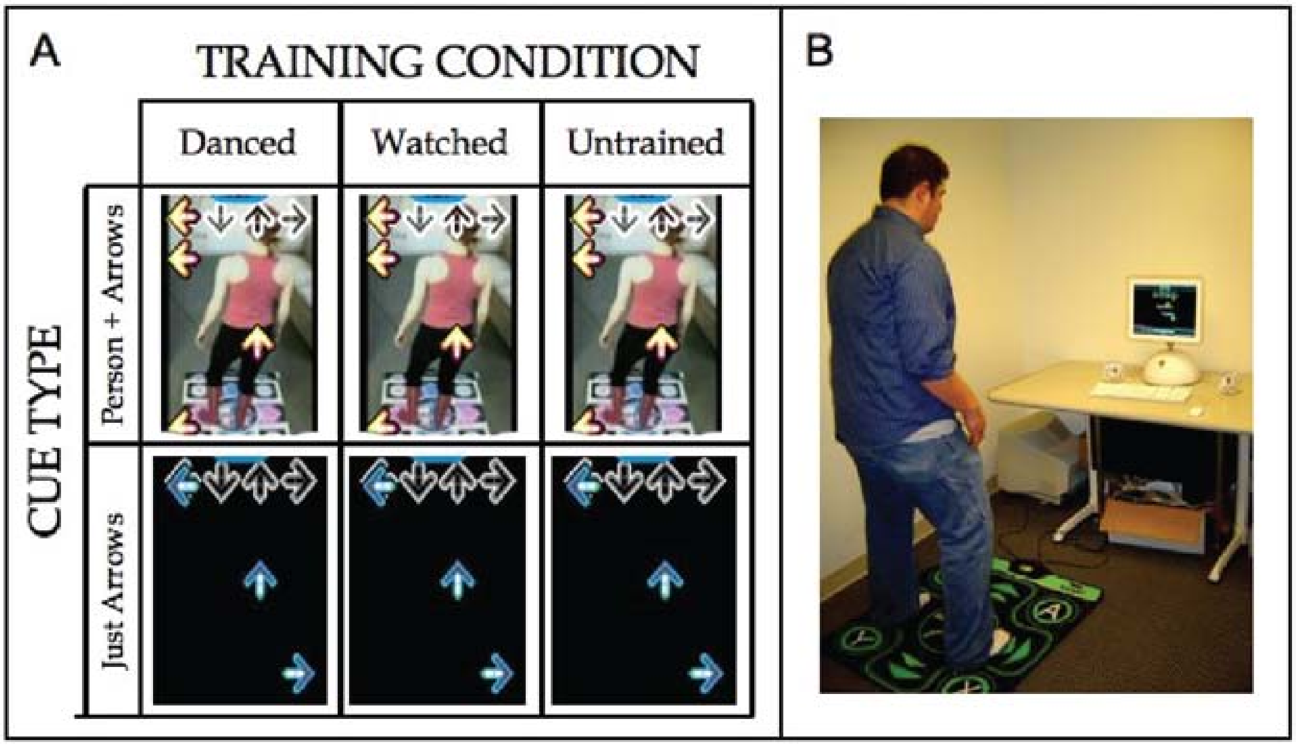

Figure 1. Part A: Schematic representation of the study design. The findings from this report focus on overlaps between the danced and watched training conditions, whether a small figure is present in the instruction or not. Part B: Training apparatus. On a dance pad connected to a computer, participants step on arrows arranged in the four cardinal directions (front, back, right, and left) in time with arrow cues on the screen. Each dance sequence is linked with a particular song.

involved in physical skill. Numerous studies have demonstrated that action observation models can be used to characterize the neural substrates for action understanding and action learning (e.g., Decety and Grezes, 1999; Brass et al., 2000; Buccino et al., 2001; Grezes and Decety, 2001; Rizzolatti and Craighero, 2004). These experiments identify a distinct set of brain regions that are active both when observing and when performing actions, referred to as the "mirror neuron system" or, more broadly, the "action observation network"(AON).

For the purposes of this research, we use the term "action observation network" over "mirror neuron system," since this latter term is more general and encompasses all of the brain regions involved in action observation processes, not simply the two main mirror neuron regions (inferior parietal and premotor cortices). The brain regions that are generally included in the AON include the supplementary motor area (SMA), the ventral premotor cortex (PMv), the inferior parietal lobule (IPL), and posterior superior temporal sulcus/middle temporal gyrus (pSTS/pMTG) (Stephan et al., 1995; Decety, 1996; Grafton et al., 1996; Rizzolatti et al., 1996; Binkofski et al., 2000).

In line with the present experiment, several past studies have demonstrated the feasibility of using dance learning and observation as a paradigm for investigating the properties of the AON (Calvo-Merino et al., 2005; Calvo-Merino et al., 2006; Cross et al., 2006). The first such study was conducted by Calvo-Merino and colleagues. They investigated the specificity of the AON to observing one's own movement repertory, compared to an unfamiliar

and untrained movement repertory (Calvo-Merino et al., 2005). In this study, expert ballet dancers, capoeira dancers, and non-dancer control participants passively viewed ballet and capoeira dance clips while undergoing fMRI scanning.

The authors reported significantly greater activity within the AON, including bilateral PMv and IPL activity, right superior parietal lobe, and left STS, when dancers observed the movement style of which they were expert. From this, Calvo-Merino and colleagues concluded that the AON is able to integrate one's own movement repertoire with observed actions of others, thus facilitating action understanding.

A related study from our laboratory investigated the possibility of creating an action simulation de novo in a group of expert modern dancers and exploring how this new learning might be reflected within AON activity (Cross et al., 2006). For this study, we measured patterns of neural activity within 10 dancers as they learned a complex new modern dance work over a six-week period. While being scanned, the dancers observed short clips of the new dance work they were learning, and of non-rehearsed, kinematically similar control dance sequences. After each clip concluded, participants rated their ability to perform each movement sequence. The critical contribution of this study was that, as the dancers' expertise with the rehearsed dance sequences increased, activity within the brain's PMv and IPL tracked parametrically with their perceived expertise.

A second study by Calvo-Merino and colleagues (Calvo-Merino et al., 2006) examined the influence of visual, compared to motor, experience on AON activity during action observation. In order to parse visual familiarity from physical experience, expert men and women ballet dancers observed videos of movements learned only by their sex, only by the opposite sex, or moves that are performed by all dancers. The motivation behind this procedure was to determine whether equally robust action resonance processes may be elicited by observation of movements that are equally visually familiar, because men and women dancers train together, but unequal in terms of physical experience.

The authors reported that when effects of visual familiarity are controlled for (i.e., when dancers watched moves from their own movement repertoire, compared to moves that they frequently saw, but never physically performed), evidence for action resonance based on pure motor experience was found in inferior parietal, premotor, and cerebellar brain cortices. The authors conclude that actual physical experience is a necessary prerequisite for robust activation in these areas of the AON. This study provides an excellent point of departure for the present study, as we also are interested in measuring how purely observational experience is represented in the AON.

Taken together, these prior dance studies provide robust evidence for changes within the AON with the presence (or emergence) of execution competency. The current study built upon this foundation by addressing open questions about the sensitivity of this network to real and observational learning.

To that end, the objectives of this study were to determine how movement training influences activity within the AON, and how observational learning (such as when one simply watches the dance instructor without imitating the movements) is represented within the AON. By addressing these questions through the use of both behavioral and neuroimaging measures, we aim to better characterize the processes that underlie the various ways that people acquire new movements.

Results

Behavioral Training

Participants' performance on the rehearsed dance sequences improved across days, $F(2.15, 29.97) = 45.1$, $p < 0.0001$. In terms of behavioral performance for training with videos that included an expert human model, participants performed better when a model was present, $F(1, 15) = 10.16$, $p < 0.003$.

Behavioral Retest

Results from the post-scanning dance retest—where participants performed three songs they had trained on during the week, three that they had passively watched, three untrained songs, and three entirely novel songs—demonstrated a main effect of training experience, $F(3, 39) = 4.6$, $p = 0.008$. Pairwise comparisons revealed statistically significant differences between trained and untrained sequences ($p = 0.001$) and between trained and novel sequences ($p = 0.002$). Because performance was so similar between the untrained and novel sequences, our discussion for the post-scan dancing data focus only on differences between stimuli that were danced, watched, and untrained. Between these stimuli types, there was a linear trend of experience, with participants performing the best on sequences they danced, an intermediate level on those they passively observed, and the poorest on untrained sequences, $F(1, 13) = 29.85$, $p < 0.0001$.

Imaging Effects of Dance Training

The first set of imaging data analyses focused on locating brain regions within the action observation network that demonstrated a significant main effect of training during the post-training scan session. In order to assess the response of the AON to actions that have been rehearsed, whole-brain analyses were performed comparing the relative BOLD fMRI imaging responses while participants watched and listened to the set of videos that they had danced for five days ("danced"), and another set of videos for which they had received no training ("untrained").

A t-test revealed a main effect of training, regardless of cue type, in several areas of the action observation network, including bilateral ventral premotor cortex, left inferior parietal lobule, supplementary motor area/pre-SMA, and mid STS. These results indicate that premotor and parietal components of the AON responded more to trained, relative to untrained dance sequences, suggesting that activity in these regions represents the neural resonance between observed and embodied actions.

Imaging Effects of Observational Learning

A separate set of imaging analyses focused on locating brain regions within the action observation network that demonstrated dissociable responses with respect to training type (whether the sequences were physically rehearsed, passively observed, or untrained). Viewing dance sequences that were only watched (and not danced) also was associated with significant activity in premotor areas, inferior parietal lobule, and basal ganglia, as shown in Figure 2.

Concluding Comments

Overall, our results indicate that at the neural level, learning by observing and physical learning lead to the same action resonance and prediction. This strong link between learning by doing and by observing suggests that early exposure to dance might enhance this link, through consistencies between the training methods.

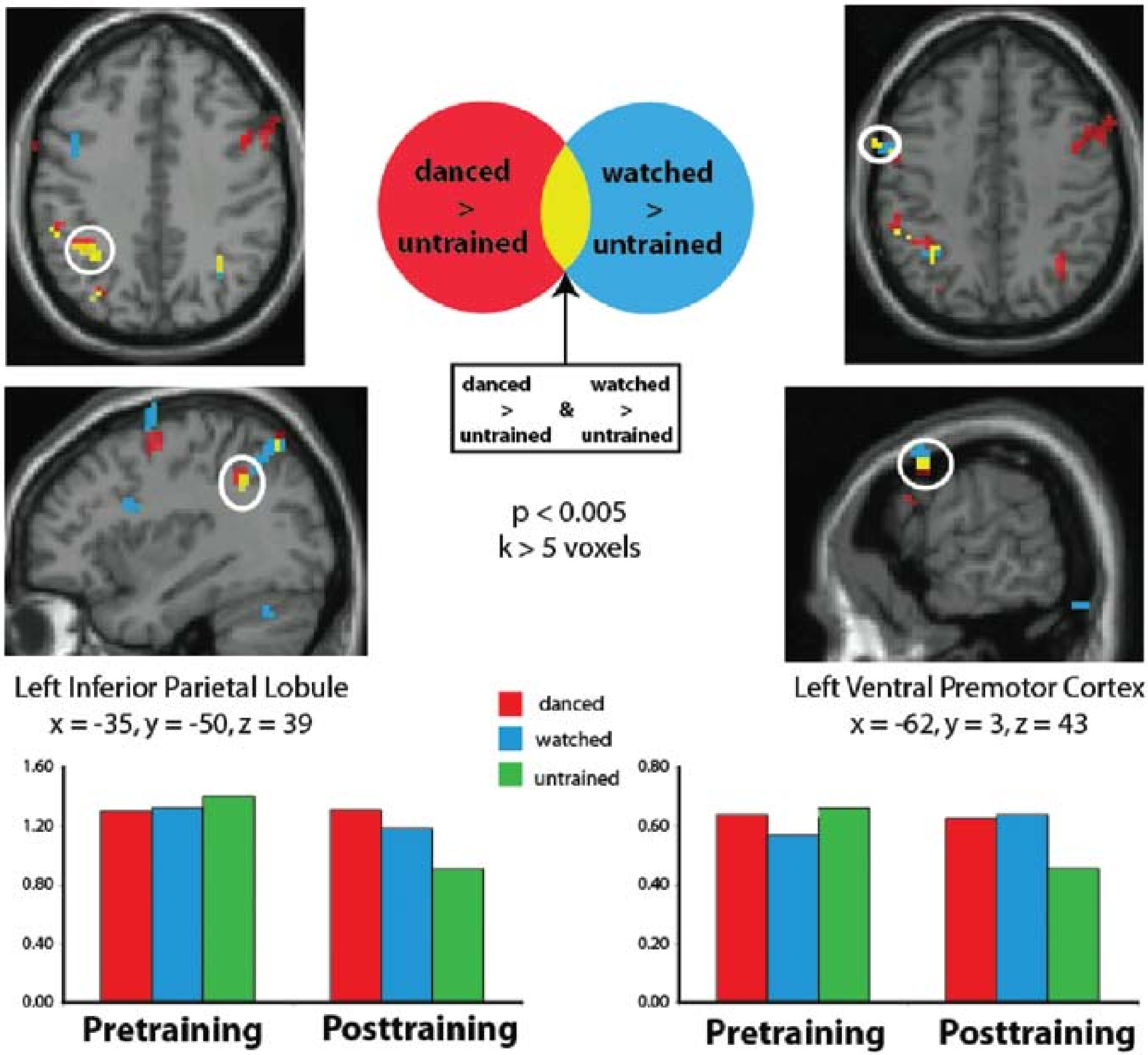

Figure 2. Overlapping areas that are engaged for action understanding after training by doing (danced) or training by watching.

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Developing and Implementing Neuroimaging Tools to Determine if Training in the Arts Impacts the Brain

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Summary

Over the last three years we have developed and used advanced functional magnetic resonance imaging (fMRI) tools that can address the question of whether arts training impacts the brain. We: 1) developed multivariate statistical analyses for fMRI data; 2) developed fMRI biomarkers of cognitive processes; 3) employed new fMRI imaging tools to investigate neural processes underlying music practice; and 4) undertook fMRI imaging in pianists and non-pianists to investigate the neural processes underlying long-term expertise gained through "slow learning" compared to "fast learning." Slow learning is characterized by gradual performance improvements that produce structural and functional changes in the brain. Fast learning involves rapid improvements in performance that lead to habituation-like brain changes, perhaps due to changes in synaptic strength.

Since we contend that current fMRI data analytic methods have been inadequate for fully assessing the types of changes that may occur in the brain with learning, we developed numerous new methods. These methods combine univariate and multivariate approaches for analyzing fMRI data, to assess the impact of formal arts training on the brain. We have used these tools and made them available to consortium members for their use in analyzing their own fMRI datasets.

We gathered data to test the Consortium's hypothesis that cognitive processes that are facilitated by training in the arts are transferred successfully to other cognitive domains. We explored whether fMRI measurements can effectively serve as a biomarker—an indicator—signaling an event or condition that gives a measure of exposure, effect, or susceptibility. With a reliable biomarker, we can quantify the effect of arts training on the developing brain of a young person. Our research focused on the system of "cognitive control," thought to be a critical function of the prefrontal cortex. This system allows us

to flexibly guide our behavior, and is critical for all types of learning.

We derived several fMRI biomarkers by using a task that directly assesses the neural mechanisms underlying top-down (cognitive control) changes. We investigated the cognitive control processes involved when 60 study participants were imaged as they performed two memory tasks. The tasks required that they enhance relevant, and suppress irrelevant, information. The fMRI measurements are derived from both univariate as well as multivariate data analyses. We also asked the participants to fill out musical training questionnaires. Based on data from 40 of the 60 participants analyzed to date, we categorized participants by whether or not they could read music, and by whether or not they had received formal music training. We assessed differences between these groups on our fMRI biomarkers.

We found that participants with formal musical training showed significantly stronger neural enhancement and suppression effects, indicating better cognitive control. Moreover, since the memory tasks had no specific linkage to reading music, these results suggest that formal musical training may generalize, by having an impact on other brain systems that are different than those affected by music training.

Our empirical studies of task practice and motor learning in pianists have laid a foundation for understanding the neural mechanisms by which formal arts training may impact the brain. The next step will be to develop interventions that can provide evidence that formal arts training **caused** the observed changes in cognition and brain function that have been demonstrated in **correlative** studies. Reliable, quantifiable fMRI biomarkers will be necessary to assess such causal effects on the brain.

Introduction

Theories of brain organization focus on two distinct, but complementary principles: modularity, the existence of neuronal assemblies with intrinsic functional specialization; and network connectivity, the integration of information from distributed brain regions resulting in organized behavior. While the modular model may be reasonable to describe fundamental features of the function of primary cortices (e.g., primary motor or visual cortex), it is insufficient to explain complex cognitive processes that cannot be localized to isolated brain regions. Rather, cognitive abilities emerge from contextual relations that are subserved by widespread cortical connections.

Functional MRI (fMRI) in humans is ideally and uniquely suited to explore neural networks, since it simultaneously records correlates of neural activity throughout the entire functioning brain with high spatial resolution. However, most fMRI studies utilize univariate analyses, permitting only the independent assessment of activity within each brain region in isolation of all others. With Dana Foundation funding, we have developed several multivariate approaches to analyze neuroimaging data in a manner that more directly addresses the network model of cognition. Also, if any fMRI measurement is expected to assess the effects of an intervention, such as training in the arts, that measure must be quantifiable and reliable. A second approach we have taken is to test whether fMRI data can provide a biomarker for changes in brain function.

In addition to developing novel functional neuroimaging tools, we are using these tools to investigate fundamental neural mechanisms that may mediate how formal arts training can impact brain development and function. We have focused on the neural mechanisms underlying our ability to adapt flexibly to new experiences with practice, as well as on mechanisms underlying fast learning (i.e.,

rapid improvements in performance that lead to automatization and habituation-like brain changes, perhaps due to changes in synaptic strength) versus slow learning (i.e., gradual performance improvements that cause functional reorganization and morphological changes to the brain).

Specific Research Approaches:

1. Development of multivariate statistical analyses for functional MRI data.
2. Development of fMRI biomarkers of cognitive processes.
3. Using neuroimaging, investigation of the neural mechanisms underlying paractice (e.g., systematic training by multiple repetitions).
4. Using neuroimaging, investigation of the neural mechanisms underlying long-term expertise (slow learning) versus fast learning, by studying pianists and nonpianists.

Specific Approach #1: Functional MRI multivariate analyses

Multivariate analyses of imaging data allow the generation of functional and effective connectivity maps of brain regions that interact within the framework of a distributed system to underlie emergent cognitive processes. These methods do not trivialize the functional specialization of brain regions, but rather emphasize the role of brain regions within the context of other covarying, anatomically connected, active brain regions, as well as the specific cognitive process that is being engaged. Over the past three years of funding, we have tested and validated four methods for use with fMRI data:

Coherence

Coherence is a spectral measure that has been used in electroencephalography (EEG) and other imaging modalities to study functional relationships between different brain areas. Just prior to Dana funding, my lab demonstrated that coherence could also be used to investigate functional connectivity in fMRI data (Sun et al., 2004). Because coherence is invariant to inter-regional hemodynamic response differences, coherence may provide a more appropriate method for measuring functional connectivity than correlation or covariance measures.

… different cortical areas maintain relatively different types of information …

With Dana Foundation funding, we extended this method to include temporal measurements. That is, using coherence analyses, we can measure relative latencies between functionally connected brain regions using the phase-delay of fMRI data. Subsequently, using this method, we published two empirical studies (Curtis et al., 2005; Miller et al., 2005), demonstrating that this method can be applied to address the types of questions proposed and implemented by researchers in the consortium. For example, we previously demonstrated that different cortical areas maintain relatively different types of information when individuals are remembering that information across short periods of time (Curtis et al., 2004). Despite these differences in regional brain activity, we could only assume but not address the functional interactions between the identified nodes of the putative brain network. Thus, we used coherence to formally characterize functional interactions between these brain areas.

We found that the type of representational codes that are being maintained in working memory

bias frontal-parietal interactions. For example, coherence between frontal eye fields (FEF) and other oculomotor areas were greater when a motor representation was an efficient strategy for remembering information across a delay period. However, coherence between the FEF and higher-order multimodal brain regions, e.g., prefrontal cortex, was greater when a sensory representation (e.g., the location of an object in space) must be maintained in working memory. We were also able to demonstrate that the timing of the events mediated by these brain regions differed during different stages of processing, such as the encoding and retrieval of memories. This type of temporal information, derived from these coherence analyses, cannot be obtained in traditional univariate analyses. Thus, it can provide valuable information about the sequence of cognitive processes within a brain network.

Granger Causality

We have also tested and validated a *second* multivariate method, called Granger causality, to analyze fMRI data (Kayser & D'Esposito, in revision). Granger causality is an exploratory multivariate method that allows one to make quantitative statements about the ability of one time series to predict another. In practice, this ability to make predictions (hence the term Granger "causality") lies in the way in which time series are modeled. Imagine two time series, taken from two different voxels in the brain. Initially, the first of those time series is fit by a simple model that attempts to predict subsequent time points in the time series, based on previous time points. Because the fit of the model will not be perfect, there remains a residual, with a variance "Var1," representing the portion of the time series for which the model does not account. If previous time points from the second time series are then also incorporated into the simple model of time series 1, the new fit results in a new residual, with variance "Var2." If Var2 is less than Var1, then time series 2 is said to be "Granger causal" for time series 1, because it explains additional variance.

This technique has recently been adapted to fMRI data by Goebel and colleagues, and we extended its use by relying on its use in the econometrics literature (e.g., the so-called "conditional" Granger causality). Importantly, we compared it directly to coherence, in order to provide more information about multivariate methods in general, but also to determine how much it complemented, versus replicated, this method. Like coherence, Granger causality analyses further informed our understanding of this interregional connectivity. Importantly, in specific instances, Granger causality provided new information that coherence did not. Thus, Granger causality can also serve as a principled and integrated method of data analysis within the increasing array of multivariate techniques.

Information Theory

A *third* approach for analysis of event related fMRI data that can also assess functional connectivity is based on measures from information theory and is used both for spatial localization of task-related activity, as well as for extracting temporal information regarding the task dependent propagation of activation across different brain regions (Fuhrman et al., 2007). This approach enables whole brain visualization of areas most involved in coding of a specific task condition, the time at which they are most informative about the condition, as well as their average amplitude at that preferred time. An advantage of this approach is that it does not require prior assumptions about the shape of the hemodynamic response function, nor about linear relations between the fMRI BOLD signal and presented stimuli (or task conditions). We have demonstrated that relative delays between different brain regions could also be computed without prior knowledge of the experimental design, suggesting a general method that could be applied for analysis of differential time delays that occur during natural,

uncontrolled conditions.

To validate this method, we analyzed fMRI data during performance of a motor learning task. We showed that during motor learning, the unimodal motor cortical activity preceded the response in higher-order multimodal association areas, including posterior parietal cortex. Brain areas found to be associated with reduced activity during motor learning, predominantly in prefrontal brain regions, were informative about the task typically at significantly later times. Importantly, these findings replicated our results using coherence and Granger causality (Kayser & D'Esposito, in revision).

Beta-correlations

Finally, just prior to Dana funding, we had developed a *fourth* approach for characterizing inter-regional interactions using event-related fMRI data (Rissman et al., 2004). This method's principle advantage over existing analytical techniques is its ability to model the functional connectivity between brain regions during distinct stages of a cognitive task. The method is implemented by using separate covariates to model the activity evoked during each stage of each individual trial in the context of the general linear model (GLM). The resulting parameter estimates (*beta values*) are sorted according to the stage from which they were derived, to form a set of stage-specific *beta series.* Regions with beta series that are correlated during a given stage are inferred to be functionally interacting during that stage.

We published an empirical paper demonstrating the utility of this method during the performance of cognitive tasks (Gazzaley et al., 2005). In a working memory task, a beta-correlation analysis revealed a network of brain regions exhibiting significant correlations with the prefrontal cortex during the working memory delay period, even though there was minimal activity in this network of brain regions when each region was analyzed independently using univariate analyses. Again, these findings support the notion that the coordinated functional interaction between nodes of a widely distributed brain network underlies cognitive processing that cannot be revealed in traditional analyses.

Application of our fMRI Methodology to the Questions Funded by the Dana Grant

Over the past three years, we have collected our own empirical fMRI data during the performance of several cognitive paradigms that not only will be useful for continuing to validate our multivariate analytic methods, but also will provide data that can directly address the hypotheses set forth by the Dana Foundation consortium (see below under Specific Approach #3 and #4). Also, we have made our fMRI data analytic tools available to all of the researchers in the Dana Foundation consortium. Sharing such analytical tools is quite labor intensive, since each functional imaging laboratory collects data from different MRI scanners, and uses different computer workstations, platforms and software to analyze the fMRI data it collects.

Also each of our fMRI data methods is computationally intensive and requires sophisticated algorithms to implement. We have written software for these tools in Matlab, which is widely available to most imaging laboratories, although we must write extensive documentation for these programs in order for them to be implemented by students, post-doctoral fellows, and faculty in other labs. This software, and set-up on-site training, is available to all consortium investigators who have collected fMRI data, so that they can extract additional information from their data by adding multivariate approaches to the univariate approach they have already undertaken.

Such new directions in fMRI data analysis should provide further insight and a more complete understanding of the neural mechanisms underlying the influence of formal arts training on the developing brain. These tools also have been provided to non-consortium laboratories

from around the world, already resulting in several published papers.

Specific Approach #2: Functional MRI biomarkers

Any study of the "impact of the arts on the brain," in my opinion, must have a reliable marker of "brain" function that can be measured and quantified. "Patterns of brain activity" which is the most commonly reported fMRI measurement cannot be easily quantified and tested for its reliability. Thus, how can we use fMRI to measure whether formal arts' training has had an impact on the brain without the current existence of such markers? Functional MRI definitely has the potential to provide the types of measurements we need to test our hypotheses.

… cognitive control is a system that is critical for all types of learning.

However, the most commonly used methods for analyzing fMRI data thus far have not tapped into the full potential of this data. For example, most fMRI studies of individuals who have had formal arts training (e.g., musician, dancers), typically report only patterns of brain activity (or brain maps) that differentiate them from groups of individuals that have not had such training. These analyses do not produce reliable, quantifiable measurements that reflect the underlying neural systems that are being studied. And, in most instances, such fMRI findings only identify "where" changes due to training are occurring in the brain, without providing any insight into the neural mechanisms mediating those changes.

A biomarker is an indicator, signaling an event or condition in a biological system or sample, and giving a measure of exposure, effect, or susceptibility. Can fMRI measurements serve as biomarkers? For several years, with support from the Dana Foundation, my lab has been trying to answer this question. The premise that we are working on is that if we have a reliable biomarker of the neural system we wish to study, we can reliably quantify how such a neural system is affected by almost any input. The input may be the effects of a drug, the effects of cognitive therapy, it may be the effects of a disease process, or it may be the effects of formal arts training on the developing brain of a young individual.

The neural system that my lab investigates is the one that underlies cognitive control. Cognitive control allows us to flexibly guide our behavior. Goal–directed behavior is clearly guided by an interaction of top-down and bottom-up processes. By bottom-up, I mean those processes that guide automatic behavior and are determined by the nature of sensory input. By top-down, I mean those processes that guide behavior that is determined by internal states such as knowledge from previous experience, expectations, and goals. Without cognitive control we would be unable to overcome reflexively triggered instinctive behaviors that are impervious to the context of the situation. Thus, cognitive control is a system that is critical for all types of learning. It is likely that the neural system mediating cognitive control is influenced by formal arts training. In addition, the integrity of this system may be a critical determining factor regarding how formal arts training impacts brain function.

We have derived several fMRI biomarkers by using a task that directly assesses the neural mechanisms underlying top-down modulation by investigating the processes involved when study participants are required to enhance relevant, and suppress irrelevant, information. During each trial of the task, participants observe sequences of

two faces and two natural scenes presented in a randomized order.

The tasks differed in the instructions informing the participants on how to process the stimuli: 1) *Remember Faces and Ignore Scenes*, 2) *Remember Scenes and Ignore Faces*, or 3) *Passively View* faces and scenes without attempting to remember them. In each task, the period in which the cue stimuli were presented was balanced for bottom-up visual information, thus allowing us to probe the influence of goal-directed behavior on neural activity (top-down modulation). In the two memory tasks, the encoding of the task-relevant stimuli requires selective attention and thus permits the dissociation of physiological measures that index the enhancement of relevant information, versus the suppression of irrelevant information. These measurements are derived from both univariate as well as multivariate analyses.

A causative study is the next logical direction …

We gave musical training questionnaires to all participants who have performed this cognitive control task during fMRI scanning. We currently have data from about 60 participants, although we have analyzed data from about 40 of these. In our first analysis of this data, we simply categorized subjects as those who could read music or not, and those who had formal music training or not. We have assessed differences between these groups of participants on our fMRI biomarkers. We found that participants who had formal musical training showed show significantly stronger neural enhancement and suppression effects (as measured by fMRI), indicating better cognitive control. And, these participants performed better on this cognitive control task. Importantly, unlike other studies that typically test participants with fMRI on tasks that are similar to types of expertise they have, this task has no specific linkage to reading music. These results suggest that formal musical training may generalize by having an impact on other brain systems that are different than those affected by training.

Alternatively, our participants with formal musical training may have had a "better" cognitive control system prior to formal musical training. These two possible explanations for our fMRI highlight the difference between a "correlative study," which this was, and a "causative" study, which can distinguish between these alternative explanations. A causative study is the next logical direction for this line of investigation. However, this fMRI study does highlight an approach in which one can study the impact of formal arts training on neural systems that differ from those neural systems that were trained. In this particular study, there are numerous additional analyses that can be performed on this rich dataset, which will be performed in our laboratory in the future.

Specific Approach #3: Neural mechanisms underlying practice

Previous functional neuroimaging studies have shown that neural activity changes with task practice. The types of changes reported have been inconsistent, however, and the neural mechanisms involved remain unclear. In an fMRI study (Landau et al., 2004), we investigated the influence of practice on different component processes of working memory (WM), on a similar paradigm as described above. Event-related fMRI allowed us to examine signal changes from early to late in the scanning session (lasting approximately 1 hour) within different task stages (i.e., encoding, delay, retrieval). Event-related fMRI also enabled us to determine the influence of different levels of WM load on neural activity. We found practice-related decreases in fMRI signal and effects of memory

load occurring primarily during memory encoding. This suggests that practice improves the efficiency of memory encoding, especially at higher memory loads, through a mechanism of neural efficiency.

The fMRI signal decreases we observed were not accompanied by improved behavioral performance, indicating that practice-related changes in activation may occur during a scanning session without behavioral evidence of learning. Our results challenge the idea that dynamic changes in activation are linked to faster or more accurate performance, as has been commonly reported in experiments on cognitive and motor skill learning. Instead, the neural activity we observed changes over time, but it is independent of task improvement, suggesting that there are important neural changes associated with learning that are not captured in the behavioral data.

In a follow-up fMRI study (Landau et al., in press), we extended this work to investigate how practice on cognitive tasks affects different types of cortical regions (e.g., highly specialized primary sensory cortex compared to unimodal, compared to multimodal associative cortex). Little is known about whether task practice influences these types of regions differently. We used event-related fMRI to examine practice-related activation changes in different region types over the course of a scanning session while participants performed a WM task. We observed significant decreases, and not increases, in fMRI signal that occurred primarily during WM encoding in multimodal and unimodal regions, but not in primary sensory regions.

Furthermore, multimodal lateral frontal regions decreased by 39.4% during the cue, which was disproportionately greater than the 8.1% decrease for primary regions. These findings indicate that task practice does not have a uniform effect on stages of cognitive processing *or* on different brain regions. Instead, regions engaged during specific stages of processing (such as encoding or retrieval), may have greater capacity for functional plasticity than other processing stages. Additionally, the degree of specialization within brain regions may determine their processing efficiency. Multimodal and unimodal regions may be specialized for flexible experience-related change, while those supporting primary sensory processing may operate at optimal efficiency and are less susceptible to practice.

Together, these two fMRI studies have provided valuable insight into the neural mechanisms underlying task practice. Such mechanisms are likely fundamental to all types of learning, and suggest that different cognitive processes and cortical regions are affected by practice in different ways. The next logical step is to examine these practice-related changes during more extended practice, such as that experienced during formal arts training, as well as to compare these changes in individuals who have already undergone formal training compared to those who have not.

Fast learning refers to rapid improvements in performance, leading to automatization and habituation-like brain changes …

Specific Approach #4: Neural mechanisms underlying slow and fast learning

Previous studies of motor learning have proposed a distinction between “fast” and “slow” learning. *Fast learning* refers to rapid improvements in performance, leading to automatization and habituation-like brain changes, perhaps due to changes in synaptic strength. *Slow learning* refers to gradual performance improvements causing functional reorganization and morphological

changes to the brain. These mechanisms have rarely been examined simultaneously, which was the focus of another fMRI study we performed (Landau et al., 2006).

Overall, the results of this experiment support the hypothesis … "training in the arts changes the brain."

We examined the influence of long-term motor expertise ("slow" learning) while pianists and non-pianists performed alternating epochs of sequenced and random stimuli ("fast" learning) during functional MRI scanning. All study participants demonstrated learning of the sequence, as demonstrated by decreasing reaction times (RTs) on sequence trials relative to random trials, throughout the session. Pianists also demonstrated faster RTs and superior sequence acquisition compared with non-pianists. Within-session decreases in primary sensorimotor cortex and multimodal parietal cortex was observed in both groups.

Additionally, there was more extensive activation throughout the session for pianists compared with non-pianists across a distributed prefrontal-parietal network. These findings provide evidence that different neural systems subserve "slow" versus "fast" phases of learning. Importantly, pianists, who have undergone long-term motor training, recruited an enlarged brain network that included both motor and nonmotor regions. This suggests that slow learning mechanisms selectively modify the efficiency of regions specific to the domain of expertise, as well as that of higher-level associative regions.

Our next set of analyses with this data is to apply our different multivariate methods to investigate changes in functional connectivity between pianists and non-pianists to gain further insight into the neural mechanisms underlying fast vs. slow learning. Overall, the results of this experiment support the first general hypothesis of the Dana Foundation grant, that is, "training in the arts changes the brain."

Concluding Comments

Our three years of research have led to the development of numerous novel, advanced methods for analyzing fMRI data to assess brain function. It is our opinion that both univariate, and multivariate approaches towards fMRI data must be utilized to fully understand the neural mechanisms underlying the impact of formal arts training on the brain. In our research related to the hypotheses of the Dana Foundation grant, we have utilized these tools. Moreover, we have made these tools available to Dana Foundation consortium members in order to analyze their own fMRI datasets. Finally, our empirical studies of task practice, as well as motor learning in pianists, have laid a foundation for understanding the neural mechanisms by which formal arts training may impact the brain.

In my opinion, the next step will be to develop interventions that can provide evidence that formal arts training **caused** the observed changes in cognition and brain function that have been demonstrated in **correlative** studies. Reliable, quantifiable fMRI biomarkers will be necessary to assess such causal effects on the brain. Unfortunately, little effort has been put forth by the users of neuroimaging to develop such biomarkers. Thus, it should be a continued priority of funding agencies to provide a balance of support between both empirical and methodological research.

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Arts Education, the Brain, and Language

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Summary: Overall Approach

The goal of our research was to determine whether there are cognitive differences between performing arts and non-performing arts students, and to discover what the brain-based differences are that underlie the cognitive differences. We compared performing arts students in theater and music to students who are not involved in the performing arts. We investigated performance on a variety of reasoning tasks and investigated whether there were differences in patterns of brain activity of the students. We used functional Magnetic Resonance Imaging (fMRI) to investigate this question.

fMRI makes it possible to monitor the activity of the brain. The basic idea of fMRI is that regions of the brain that are being used in a specific mental activity will use more oxygen than regions of the brain that are not used in the task, and fMRI is sensitive to changes in oxygen uptake in the brain. Thus, fMRI is an index of how active specific regions of the brain are in particular tasks.

The hypothesis being tested in our Dana-funded research is that if performing arts students are using their brains in a different way from the non-performing arts students, then we should see differences in brain activation patterns between these different groups. It may be the case that specific regions will show increased activation in the performing arts students and that other regions may show decreased activation. Of course it may be that we see no differences between the performing arts students and non-performing arts students in the tasks that we used. The goal of the research was to obtain first ever information on this important issue and we began the research with open expectations as to what we might discover.

The focus of our research was twofold. The first was to determine the types of brain-based changes that occur as a function of being exposed to a performing arts education.

The second was to postulate the brain-based mechanisms that might lead to these improvements. This second aim is particularly important since previous attempts to investigate whether the arts have important effects on the brain have not posited specific neural mechanisms that might be involved. Thus, the goal of the research was to go beyond vague and general claims about the effects of a performing arts education to testing specific hypotheses.

One common claim about the effects of training in the performing arts is that it fosters creativity.

In particular, the research conducted in the Dunbar laboratory was to study the effects of the performing arts on key cognitive processes involved in reasoning, such as generating novel and creative concepts, and being able to map information from one context to another, very different, context. This is known as transfer. The overarching question here is whether abilities that are acquired in the performing arts will transfer to other domains. Our goal was to investigate whether education in the performing arts influences abstract reasoning ability.

We investigated whether students in theater and music reasoned differently from non-arts students and what the brain-based changes that underlie these differences might be. Another question that we investigated is whether arts students are intrinsically different from non-arts students. We investigated this question by comparing performing-arts students' genetic makeup to non-performing arts students genetic makeup. This allowed us to investigate the possibility that differences between performing arts students and non-performing arts students' might be due to underlying genetic differences that predispose students to prefer and choose the performing arts rather than other areas of education.

Year 1 Research Summary

In the first research year, we conducted an fMRI (functional magnetic resonance imaging) investigation, comparing brain activity of theater students with non-theater students as they worked on a new variant of a widely used task of creative thinking. One common claim about the effects of training in the performing arts is that it fosters creativity. This task—*The Uses of Objects* task-provides a measure of divergent thinking. This task is deceptively simple: particpants are given the name of an object, such as a brick, and are asked to generate as many uses for the object as they can think of. Previous researchers have found that this task is a useful measure of creative thinking (e.g., Carlsson, Wendt, & Risberg, 2000). Furthermore, researchers have found that arts students perform differently from non-arts students; they produce more varied and creative uses than students not in the arts (see Guilford, 1967 and Hudson, 1967 for the classic study on creativity and the arts). Postdoctoral student Dr. Jinathan Fugelsang, graduate student Adam Green, and undergraduate student Raphael Lizcano were actively involved in this research.

… we investigated changes in creativity using a standardized test that measures the ability to reason creatively …

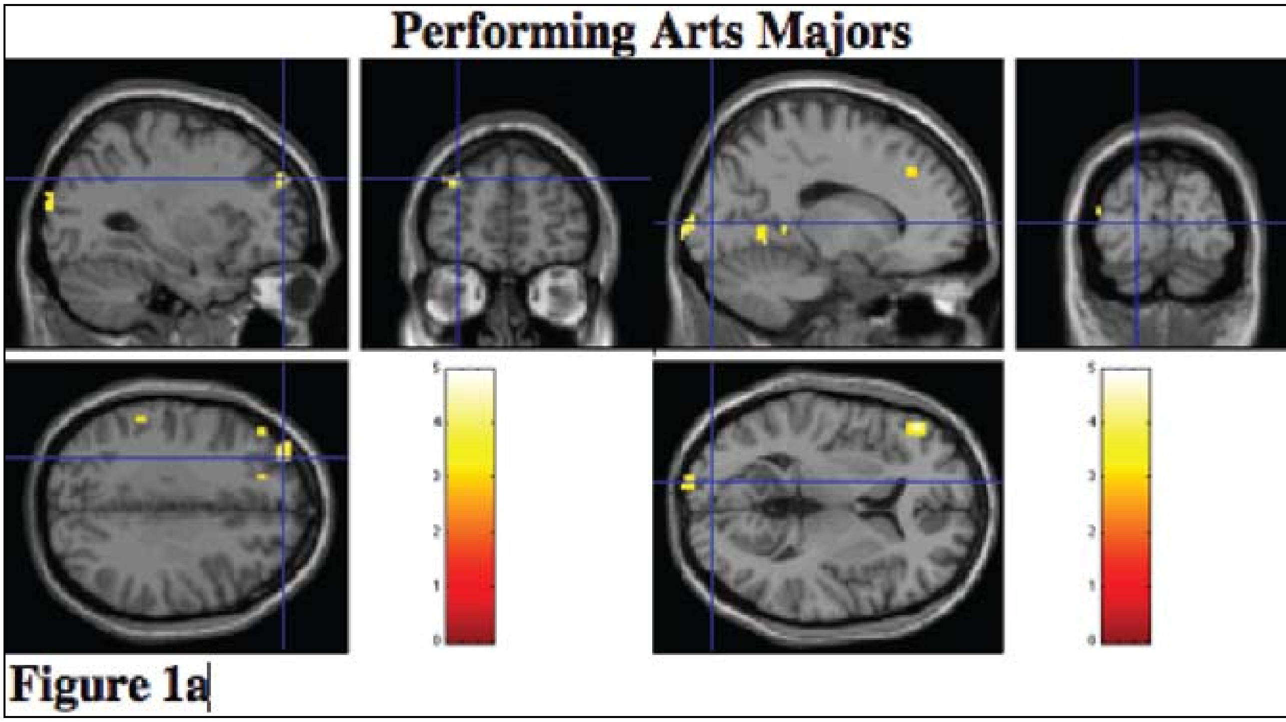
In our research, we investigated changes in creativity using a standardized test that measures the ability to reason creatively: or the Uses of Objects task. We hypothesized that training in

the performing arts should lead to increased performance on the Uses of Objects task. We investigated the Uses of Objects task in arts and non-arts students. In year 1, we focused on using Guilford's Uses of Objects test (Guilford, 1967), which we adapted for use in fMRI. In the original version of this task, participants must generate as many uses for an object as they can. Participants who generate unusual items are called divergers and those who generate standard uses are called convergers. We modified this task for the fMRI experiment that compared performing arts students with non-performing arts students. We used photographs of objects to present stimuli to the participants and we devised a button-pressing technique for responses that eliminated the need for writing a response. Of course we compared our new task to the more standard task and found good correlations between performance on the two different versions of the task. Our hypothesis was that performing arts students would generate more divergent answers than non-performing arts students and that the different groups would display different patterns of brain activation. This is a sensitive task that has been used in assessing creativity in many domains and occupations.

The finding that performing arts students have increased activation in this area suggests that they are taking a more linguistic approach to the task ...

This first-year research provides the first fMRI comparison ever undertaken of performing arts students with non-performing arts students. We analyzed the task-related BOLD (blood oxygenation level dependent) fMRI imaging response for conditions in which participants were judging the Uses of Objects minus the materials judgments. As can be seen from Figures 1a and 1b, we found differences in activation levels between the performing arts and non-performing arts groups. Regions in the medial fusiform gyri were selectively activated for the Uses of Objects task for the non-performing arts majors and not for the performing arts majors. Performing arts majors showed increased activation in two frontal areas: the left inferior frontal gyrus and in the left superior frontal gyrus. Prior work on word generation tasks has demonstrated that the left inferior frontal gyrus is involved in generating names in language processing tasks. The finding that performing arts students have increased activation in this area suggests that they are taking a more linguistic approach to the task, whereas the non-performing arts students are taking a more perceptual approach to the task. This result is important, as our other research on scientific thinking and expertise indicates that expertise can lead to increased activation in linguistic areas that are associated with conceptual thinking (Dunbar and Nelson, in preparation).

Our work on relational reasoning indicated that a region of the prefrontal cortex, frontal polar cortex, should show increased activation in the Uses of Objects task, and we therefore conducted a region of interest analysis of the frontal poles for the Uses of Objects task. We indeed found increased activation in the frontal poles (See also, Green, Fugelsang, Kraemer, Lizcano, & Dunbar, in preparation). However, there were no significant differences between the performing arts students and our controls in activation levels. Thus, while we have found differences between performing arts and controls, these differences appear to be in areas of the brain associated with linguistic symbolic retrieval from memory, rather than mapping from one semantic domain to another. This finding is important as it indicates a more precise locus for the effects of performing arts expertise than has been previously offered.


Performing Arts Majors
Figure 1a

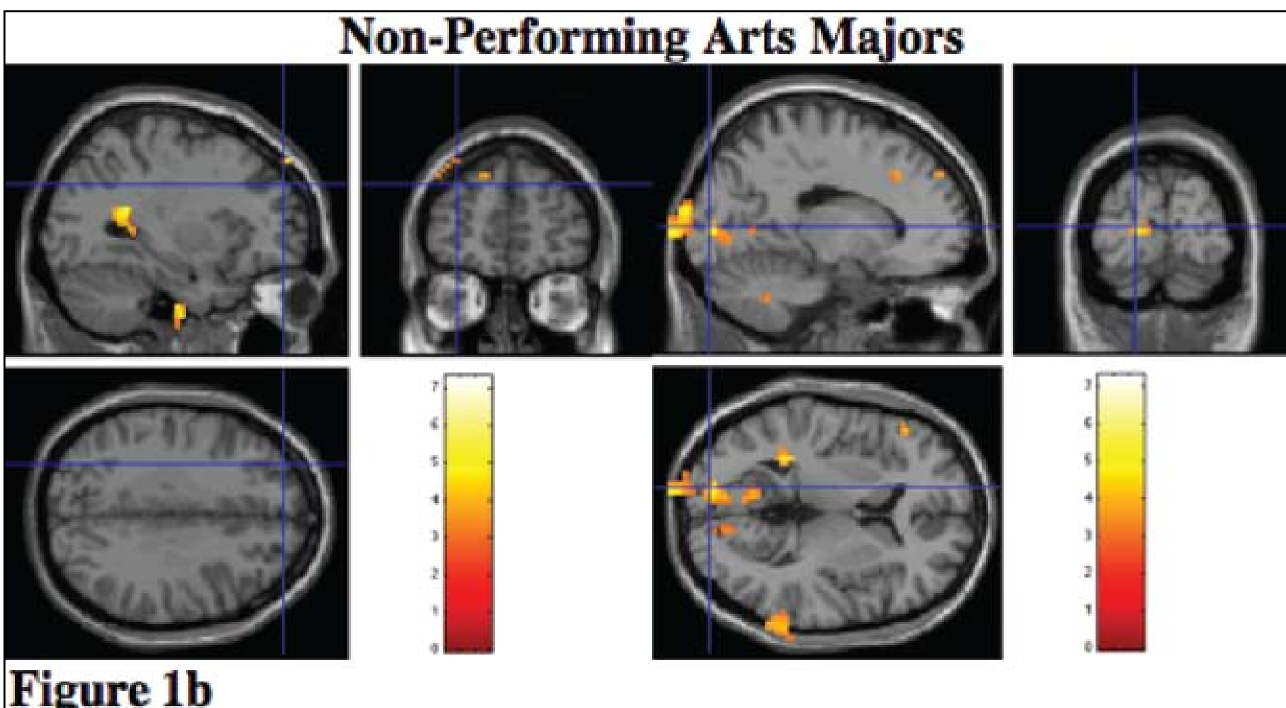

Non-Performing Arts Majors
Figure 1b

Figure 1

Year 2 Research Summary

Research in Year 2 concentrated on three main levels, prompted by the meeting of the consortium investigators in fall 2005. A goal of the research was to use many of the same tasks that other laboratories were using. Thus, we developed a battery of tasks that measure performance on attention, working memory, and reasoning that could be administered within a 1-hour period. Postdoctoral fellow James Nelson, graduate student Adam Green, and undergraduates Raphael Lizcano and Oya Nuzumlali were involved in the development of these tasks.

… a third possible hypothesis is that an interaction between environmental and genetic mechanisms may be at the root of differences …

In a second level, a key point that arose at the consortium meeting was the need to tease apart, at multiple levels, the effects of a performing arts education on the brain. The multiple levels approach is particularly important when adults are being studied, since our adult performing arts participants may have self-selected into performing arts; differences between performing arts students and non-performing arts students may be due, therefore, to underlying trait differences rather than to the effects of a performing arts education per se. This is a centuries old question for this type of research. The problem is that if a researcher finds differences between students in the performing arts and non-performing arts students it may be due to the training in the performing arts, or to inherent genetic differences. Teasing apart these two types of reasons is notoriously difficult. One way of addressing this centuries-old conundrum is to have a measure of student's underlying genetic traits. Dr. Posner has espoused this view at the Dana meetings, and this is an important way of determining whether any differences between performing arts students and non-performing arts students is due to underlying genetic differences or to the effects of a performing arts education. With this goal in mind, my graduate student Adam Green spent the winter term of 2006 at the Sackler Institute in New York learning to conduct DNA genotyping using buccal swabs (i.e., saliva). This is a relatively inexpensive and easy to obtain technique that we used in our 2006-2007 research. Rather than postulating a genetic or an environmental approach, a third possible hypothesis is that an interaction between environmental and genetic mechanisms may be at the root of differences or between performing arts and non-performing arts students. We are currently developing a DNA-microarray technology to address this question. Using this technique we are able to determine how training in a domain influences the expression of a wide variety of genes in the human genome. Dunbar & Petitto, (in preparation).

The third component of our Year 2 research was to develop tasks that we could use to assess differences, through imaging, in brain activities of performing arts and non-performing arts students. We refined our analogical reasoning tasks and focused on the frontopolar cortex as a key area for region of interest analyses. We also refined and developed the Uses of Objects task that we have been using to assess differences between performing arts students and non-performing arts students. The new Uses of Objects task was a categorization task, in which participants assess how good each of various uses is, for a particular object. This new modified Uses of Objects task provides more data and decreased error variance in the data, resulting in a more stable measure of divergent thinking. Dartmouth acquired a new 3.0 Tesla fMRI scanner during our second research year, and in the interim before the scanner became operational, we

developed our DNA genotyping skills, the cognitive test battery, and the fMRI tasks to be used in our third research year.

… we predicted that we would observe differences between our groups of participants at both the behavioral and neural levels …

Year 3 Research Summary

The goal of the third year research was to investigate differences between students studying theater compared to music, and between performing arts students and non-performing arts students. We identified a group of students in each of these categories. Based upon our prior years' research, we developed a verbal version of the Uses of Objects task that could be administered in an fMRI experiment, and developed a fine-grained version of our analogy generation task that could be conducted in a neuroimaging context. Based on our first two years of research, we predicted that we would observe differences between our groups of participants at both the behavioral and neural levels and could also determine whether differences between the groups were due to inherent genetic differences, or experience with a particular performing arts field. Postdoctoral fellow James Nelson, and graduate student Adam Green, were actively involved in this research. The third year research was conducted at three main levels:

1. Administering a cognitive test battery to the performing arts and non-performing arts students. The battery consisted of working memory tasks (backwards and forwards), analogy task, Uses of Objects task, language proficiency task, and a general background expertise questionnaire (based in Ericsson's work and also similar to those used by Petitto and Jonides). We tested more than 60 students (3 groups of 20 students; performing arts theater, performing arts music, and non-performing arts students).
2. Obtaining buccal swabs (i.e., saliva) from this set of 60 students for DNA genotyping. The DNA genotyping focused on a small number of polymorphisms (small changes in sequence) of key genes that are markers of cognitive differences (DRD4, DRD5, MAOA, COMT, 5-HTTLPR, SNAP-25, 5HT1B). The goal of this part of the research was to determine if the performing arts students differ in terms of genes known to be related to the types of psychological traits—such as attentional control and temperament—that are hypothesized to be important in performing arts students.
3. Conducting an fMRI study of students that we have both genotyped and tested behaviorally on our test battery. We imaged 30 students (10 in each of our 3 groups). The two tasks that we used in the 2006-2007 year were our modified Uses of Objects task and our analogical reasoning task. We hypothesized that we will see differences in activation in key brain areas, such as the frontopolar cortex, and anterior cingulate cortex.

Participants

A total of 60 participants completed the behavioral session and had buccal swabs taken for genetic analysis. Twenty participants (10 male, 10 female) were in each of three subgroups—those with theater training (average age 20.9, range 18-25), those with music training (20.1, 18-22), and those

with no or minimal performing arts training (20.6, 19-22). Performing arts students were all receiving professional training, and had at least 4 years of such training and 10 total years of experience; non-performing arts student were not currently receiving training or practicing and had not had professional training, at least from age 14 to the time of the study.

Behavioral Session

In a behavioral testing session, all participants completed the following tasks: Shipley Vocabulary (Shipley, 1940), WAIS-III Digit Span Forward and Digit Span Backward sub-tests (Wechsler 1997), an in-lab multiple choice Analogy Completion task, the Group Embedded Figures Task (O'Leary, et al. 1980), a 4-item written version of the Uses of Objects task (Hudson, 1967), and a questionnaire verifying and detailing their educational background. These tests were given in rotating order; the questionnaire was always given last. At the end of the session, participants gave a buccal swab sample for genetic analysis, described later.

Two planned t-tests were done for each test score: a comparison of performing arts (PA) students vs. non-PA students, and a comparison of music vs. theater PA students. While there were no significant differences between PA and non-PA students, music students had significantly better performance on the Backward Digit Span task than theater students, and theater students had a strong statistical trend towards higher divergence scores on the Uses of Objects task (number of non-standard uses listed for all objects). See Table 1. Participants with music training showed greater ability to manipulate items in working memory, while those with theater training showed a tendency towards more divergent thinking.

DNA Genotyping Research

Buccal samples are being analyzed for genetic polymorphisms on a sample of genes thought to be associated with attention and cognition (e.g. Fosella, et al. 2002; Fan, et al. 2003) or to influence participation in a performing art (Bachner-Melman, et al., 2005). While analysis is still incomplete

Digit Span: Backward	N	Score	(se)	P.A. vs. Non P.A.	Music vs. Theater
Theater	20	7.95	.484		
Music	20	9.85	.568	n.s.	M>T p=.015
Non P.A.	20	8.2	.574		

Divergence Score	N	Score	(se)	P.A. vs. Non P.A.	Music vs. Theater
Theater	20	26.8	2.598		
Music	20	19.05	2.925	n.s.	T>M, n.s., p=.055
Non.P.A.	20	24.5	2.220		

Table 1: Structure of the Aesthetics Questionnaire

(23 participants have not been analyzed), initial results show interesting trends. First, for COMT position 158, the homozygous val/val genotype is prominent in our non-performing arts students (7/12), but relatively rare in performing arts students (3/25). COMT also may be related to scores of divergent thinking from the Uses of Objects task, as study participants who are heterozygous val/met show the lowest mean divergence score (n.s., $p<.10$). MAOA also shows trends ($p<.10$) for predicting performance on the Backwards Digit Span task for both Exon 14 and for promoter region polymorphisms.

fMRI Studies: Divergent and Analogical Thinking

Nine non-PA students, eight music students, and 11 theater students underwent an fMRI session, which alternated two blocks each of an analogy verification task and a simplified Uses of Objects task. Seven participants from each group were entered into the final analysis of the Uses of Objects task (others were eliminated due to excessive movement, or due to artifacts in the MRI data). In this version of the Uses of Objects task, students were given a pair of words, and evaluated whether the first-named object could be used as the second-named object (e.g., Hose, Rope), and rated the object on a 1 to 3 scale (1= "Good use", 2 = "Fair Use", 3 = "Poor Use"). Pairs of words were chosen, based on pilot data, to provide a range of "good" to "poor" uses. Sixty pairs of objects were evaluated, with 4 seconds allotted for each judgment. Thirty fixation trials of 4 seconds length were randomly inserted (with no more than three fixation trials in a row).

For the analogy verification task, participants completed 60 trials, split evenly between valid and invalid analogies, and cross-domain versus within-domain analogies. Six seconds were allotted for the participant to rate each four-item analogy For this analogy task, at the time of writing, only six individuals had been fully analyzed, an insufficient number for meaningful comparison based on group membership or performance.

However, the analyses for the Uses of Objects task are complete. The results comparing the Uses task to fixation trials across all participants are shown in figure 2. Red regions are significant at a False Detection Rate of $p<.05$ and include bilateral PFC, left parietal, left inferior temporal brain regions, and cerebellar activations. The yellow areas were significant at the much more stringent threshold of Family-wise Error $p<.05$. Prominent is a peak activation in left dorsolateral prefrontal

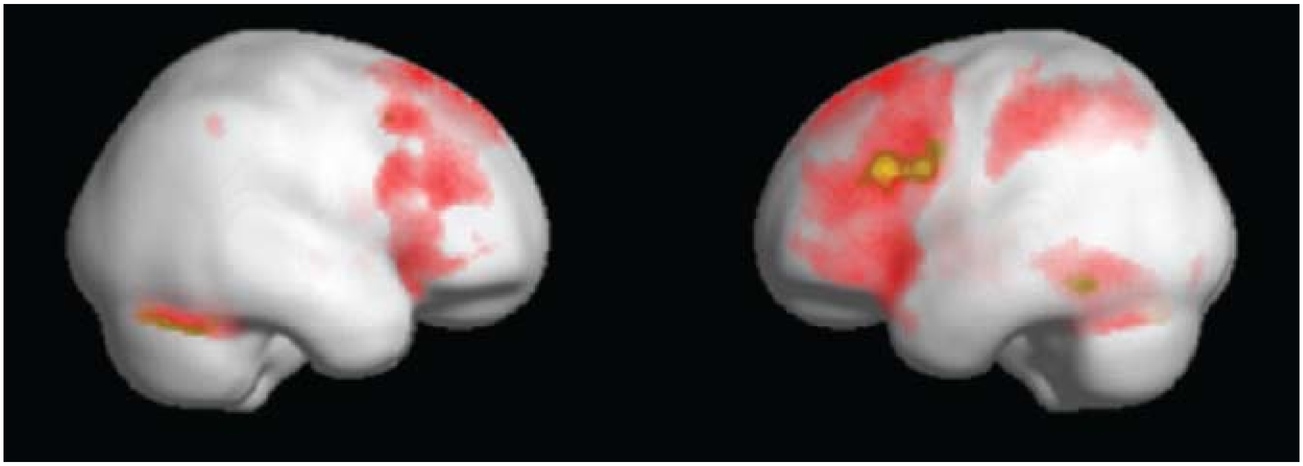


Figure 2

cortex in Brodmann's Areas 9 and 46 (peak voxel at MNI coordinates x=-56, Y=12, Z=28, 2.36 cubic centimeters volume).

Whole brain contrasts reveal no differences among differing performing arts backgrounds, but a median split of high vs. low divergence scores shows bilateral activation (uncorrected $p<.001$, >5 contiguous voxels), with right hemisphere activation dominated by an activation in inferior parietal cortex near the right temporal-parietal junction in Brodmann's areas 40 and 43 (peak voxel at MNI 50 -24 16, 1.54 cubic cm volume), and left hemisphere activation scattered among several smaller activations surrounding the left temporal parietal junction.

Further ROI (region of interest) analyses were done on the left DLPFC area identified in the whole brain Task vs. Fixation contrast, and also an area of anterior frontal cortex identified by Green, et al., (2006) that is active during abstract analogical reasoning (MNI:-8, 60, 31; 10mm radius sphere). However, no significant group differences were found in these frontal ROIs, nor were differences found between high and low divergent subjects (figure 3). This difference in results may be due to the fact that we switched from a version of the task where students were asked to generate Uses of Objects to a version of the task where they assessed how well a particular use fits an object.

Year 3 Research Summary and Discussion of Results

The results of our behavioral tasks indicate significant working memory differences between the music students and our other two groups of students (theater and controls). In addition, our DNA genotyping results may indicate that there are genetic differences (in MAOA and COMT) between our performing arts students and the controls. We have already collected DNA from a further set of participants that would allow us to determine whether these differences are statistically significant. Unlike our year 1 results, our year 2 results did not reveal differences between students' brain activity for the Uses of Objects task. We suspect that the differences in our task between the two years are responsible for this outcome. Our analyses of the fMRI data did not reveal differences between the performing arts students and controls. However, our fMRI analyses did reveal significant differences between students who scored high on our test of creativity and those who scored low.

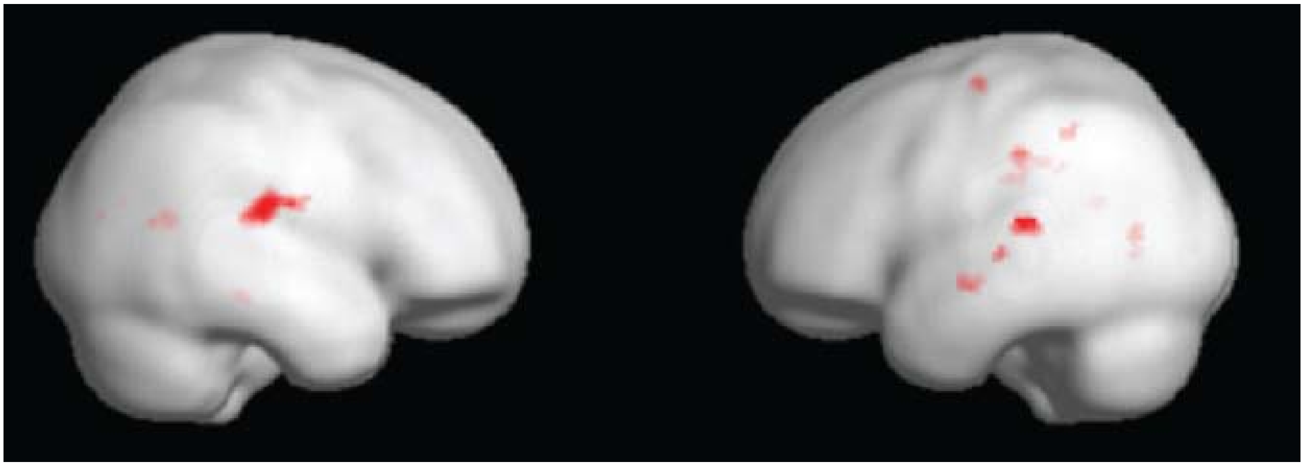


Figure 3

Overall, we found some differences at both the behavioral and genetic level.

Summary Comments and Future Directions

The research conducted by the Dunbar laboratory was concerned with investigating whether there were differences between performing arts students (music and theater students) and non performing arts students. Four main routes were taken to investigate this question. First, we used standardized behavioral tasks such as digit span and the group embedded figures task. Second, we used behavioral tasks that tap the abstract reasoning processes thought to be stimulated by a performing arts education (generation of object uses and generation of analogies). Third, we conducted neuroimaging, using fMRI of students as they performed our behavioral tasks. Fourth, we conducted genetic analyses (DNA genotyping) of our different groups of participants. Overall, we found some differences at both the behavioral and genetic level. At the neural level we found differences between the performing arts students and non-performing arts students in our first year.

In particular we found differences in left hemisphere frontal lobe activation that are consistent with the hypothesis that the performing arts students are more likely to be engaged in the symbolic retrieval than non-performing arts students. When we modified our Uses of Objects task for our year three research, we found no differences in brain activation between the performing arts students and the non-performing arts students. This indicates that it is in the generation of novel ideas, and not the responding to novel ideas, that is the key difference between the two groups.

We plan to analyze the remaining genetic data collected to more definitively determine whether there are differences among our groups at the genetic level. A second avenue would be to increase our sample size, as our sub-group sample sizes are still quite small. A third avenue is to administer the same tasks to a more diverse population in which participants have a wider range of SAT scores and a more diverse socio-economic background. A fourth approach would be to conduct these studies of tasks on a younger population of participants, to determine whether there is a "sensitive period" for the acquisition of the mental processes involved in the performing arts. Finally, we are in the process of developing an epigenetic approach that will allow us to further deliniate potential differences between the performing arts and non-performing arts students.

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Arts Education, the Brain, and Language

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Summary

We conducted two main areas of investigation. One was to study the impact of intensive dance education on higher cognition, including attention and biological motion perception abilities (Part 1). The second was to study the impact of extensive music education in childhood on learning a second language in adulthood (Part 2).

To explore the impact of intensive dance education on higher cognition, we undertook behavioral, brain imaging, and genetic studies. This included the development and pilot-testing of tools for identifying and differentiating expert dancers from non-dancers (and expert musicians and non-musicians). We also assessed dancers and non-dancers' performance on language and other cognitive tasks behaviorally, as well as while they underwent functional Near Infrared Spectroscopy (fNIRS) brain imaging. This brain imaging system detects changes in concentrations of blood oxygen levels that are associated with neural activity in the brain's cerebral cortex. We also developed software for standardizing the analysis and interpretation of fNIRS data, which has been tested in several laboratories.

Artistic education and expertise, such as in dance or in music, requires highly skilled motor control and the ability to selectively attend to, inhibit, and select appropriate sensory cues (such as when performing in a group). Our behavioral studies revealed that dancers were significantly more accurate than non-dancers on an attentional task. This finding suggests that early dance education may positively transfer to other cognitive areas, such as the ability to selectively focus attention and resist interference from competing signals.

Our behavioral studies showed that dancers also were faster on a Biological Motion Perception task. This finding suggests that early dance education benefits the processing of biological motion and benefits the speed of short-term memory processing of motion stimuli. In a separate experiment of dancers and non-dancers, in which both behavioral

and fNIRS data were collected, we found a similar pattern.

To study possible genetic influences on these observed differences between dancers and non-dancers, as well as possible genetic influences on a person's likelihood of pursuing arts education, we identified seven candidate genes that might help to explain such differences. Our research to date on four of the seven candidate genes has shown only one possible relationship, supporting the hypothesis that differences in higher cognitive performance between dancers and non-dancers may be due to their education in the Arts rather than to a genetic predisposition. Research on the remaining three genes is ongoing.

In Part 2 of our research, we tested the hypothesis that monolingual expert musicians would learn a second language better than matched non-musicians. This hypothesis is based on findings that musicians have enhanced selective attention on particular higher cognitive tasks, and learning another language involves the ability to attend to one language, inhibit the other, and rapidly switch between them. We studied monolingual English-speaking students enrolled in introductory Italian or Spanish classes, who were tested at the beginning and end of the academic term.

Musicians (those who received early extensive and continued music education) were compared to non-musicians on English language performance, new language performance, cognitive attentional processing, end-of-term self-evaluation, and class final grade. While the two groups showed no differences in general academic performance measures, or on cognitive attentional assessments, we found that the musicians exhibited significantly increased second language performance (greater improvement in expressive fluency and competence) compared to non-musicians. These results suggest that there may be an enduring cognitive advantage afforded by early and extensive music education on adult learning of a new language in an instructional setting.

Introduction

The overarching goal of the Dana Foundation's Arts and Cognition Consortium is to understand the impact of intensive education in the Arts on the human brain – especially regarding the acquisition and learning of other core content knowledge. For the past three years, the Petitto Laboratory has addressed this question by studying: 1) the impact of intensive education in dance on higher cognition, including attentional and biological motion perception abilities (Part I); and, 2) the impact of extensive music education in childhood on learning a second language in adulthood (Part 2).

… we examined the possible genetic influences on individuals' higher cognitive task performance and their likelihood of pursuing arts education.

We used a variety of populations (e.g., dancers and musicians) and advanced techniques in brain imaging and human genetics. Our methods included the use of behavioral measures, and of the new functional Near Infrared Spectroscopy (fNIRS), a state-of-the-art brain imaging tool that is ideally suited for use in studies of higher cognition. Additionally, as an important design innovation, we conducted crucial co-registration validation checks of the fNIRS system with MRI/anatomical scans.

In the third funding year, we cast an additional exciting lens on our research questions by adding a third level of scientific analysis, the Genetic level, whereupon we examined the possible genetic influences on individuals' higher cognitive task performance and their likelihood of pursuing arts education. Together, our research program offers innovative advances by bringing to bear a trilogy of

three core levels of analysis to assess the impact of intensive education in the Arts on the human brain: mind, brain, and genetics.

Artistic education and expertise (e.g., dance or music) requires highly skilled motor control and the ability to selectively attend to, inhibit, and select appropriate sensory cues, such as when performing in musical groups (e.g., Bever & Chiarello, 1974; Keller, 2001; Large & Jones, 1999; Schellenberg, 2005). Here, we tested the following "transfer of learning" hypotheses: Extensive education in the Arts may yield higher cognitive executive function advantages during the processing of other non-arts information (tested in our Dance study described below)—and/or during the learning and processing of other non-Arts knowledge (our Music and Language Learning study below; referred to as the Music study).

Immediately below is a brief summary of Part I research during Years 1 and 2, including (i) innovations, (ii) key personnel/collaborations, and (iii) results. Extensive detailed discussion of these studies was provided previously. Thereafter, we describe our third-year research, a Mind-Brain-Genetic study of dancers versus non-dancers. At the close of this section is a list of the Tangible Products emanating from year three of this research, while similar lists from the first two years were provided in earlier reports. Thereafter, we briefly summarize Part 2 of the research, the Music Study, which explored the impact of extensive music education in childhood on learning a second language in adulthood. This study was described in detail in earlier reports.

Part I: Brief Summary of Dance Research in Years 1 and 2

Year 1: Dance Research Design and Methods

Innovations

Petitto and team both designed and extensively piloted all: (i) Dance/Music screening and background questionnaires (to be used as one of the standardized tools to identify and differentiate expert, compared to novice, experimental groups); (ii) language screening and background questionnaires; and, (iii) language and cognitive tasks to be administered both behaviorally and during brain scanning. Additionally, Petitto and team completed the (i) scripting, filming, and editing of the experimental video clips to be used for the Dance study, and (ii) creating/designing of the selection criteria for differentiating expert compared to novice participants, as another key tool to establish participant groups. Petitto and team then began recruiting, screening, and studying participants for both the Dance and Music studies, and they also started data analyses for the Music study.

Key Personnel

Professor Laura-Ann Petitto, graduate student Ioulia Kovelman, and undergraduates Rachael Degenshein, Ryan Gramacy, Aekta Shah. We further held several outside meetings with Dartmouth College Professor Scott Grafton and graduate student Emily Cross (Dana consortium members). Importantly, other Dana consortium collaborations that were invaluable during the first two years of our research included consultation with Professor John Jonides (University of Michigan), who provided feedback on and input to our criteria for "expert" vs. "novice" participant groups. Professor Jonides also shared his Stimulus Response Compatibility (SRC) task with us. Further, Professor Michael

Posner (University of Oregon) generously shared his Flanker Task/attention network task.

… the fNIRS system … comes with no standard means for enabling cognitive neuroscientists to analyze its data output.

Year 2: Dance Research Design and Methods

Innovations

Petitto and team completed the behavioral part of the Dance study, the Music study, and also completed all of the data analyses for both of these studies. Further, Petitto and team received a new fNIRS brain imaging system, and completed piloting of the fNIRS brain imaging part of the Dance study. While the fNIRS system has outstanding brain imaging and recording capabilities, remarkably, the system comes with no standard means for enabling cognitive neuroscientists to analyze its data output. Therefore, it was necessary to search for and hire a new Post-Doctoral Fellow, Dr. Mark Shalinsky, an electroneurophysiologist, to write software that would allow us both to analyze and to interpret the fNIRS system data. Dr. Shalinsky, with Petitto and Ioulia Kovelman, created and tested the new software, which was subsequently tested across several major fNIRS labs over 2006-2007 (Year 3).

We have submitted and revised a paper on this important "first-step" research activity to an international journal, in which we describe this new universal analysis program to analyze/interpret the data that the fNIRS system records. Cognitive neuroscience labs throughout the world that utilize fNIRS can use this analysis system. We also completed MRI/anatomical co-registration with fNIRS, to ensure high confidence in the neuroanatomical precision of our fNIRS probe placements.

Key Personnel

Professor Laura-Ann Petitto, Post-Doctoral Fellows Dr. Melody Berens and Dr. Mark Shalinsky, and graduate student Ioulia Kovelman (see also Year 1 above).

… dancers were significantly more accurate than non-dancers on an attentional task …

Part 1 Results: Dance Foundational Behavioral Studies - Years 1 and 2

As important background to our Year 3 research, our completed behavioral studies of dancers versus non-dancers revealed that dancers were significantly more accurate than non-dancers on an attentional task ($p < .03$). This finding, in turn, suggested that early dance education does benefit (that is, may positively transfer to) other domains of higher cognition, such as attentional processing, or more specifically, resistance to interference from competing signals, compared to participants who were not educated in the Arts.

We also found that dancers were faster on the Biological Motion Perception Task ($p < .001$). This finding suggests that early dance education benefits both biological motion processing and working memory of biological motion stimuli, in terms of the speed with which these stimuli are processed.

Part 1: "Mind-Brain-Gene" Dance Study Year 3

Innovations—Genetics (Genotyping Analyses)

To achieve the goal of studying possible genetic influences underlying observed performance differences on higher cognitive tasks in dancers versus non-dancers, as well as possible genetic influences on the likelihood of pursuing arts education, we collaborated with Dana consortium scholars Drs. Kevin Dunbar and Michael Posner.

Indeed, to answer this question we needed to tackle, head-on, the elusive decades-old question of nature versus nurture.

Year 3 Key Personnel

Professor Laura-Ann Petitto, Post-Doctoral fellows Dr. Melody Berens and Dr. Katherine White (Petitto Lab), Dr. Ioulia Kovelman (now at MIT, John Gabrieli's Lab), Dr. Mark Shalinsky (now at Harvard/MGH, David Boas' Lab) and research assistant Douglas McKenney (now at Jerusalem University). Invaluable assistance and consultation about specific genes *that might be* associated with specific higher cognitive processes were provided by Drs. Kevin Dunbar and Michael Posner. Moreover, Dr. Dunbar also reviewed the Petitto team's proposed list of genes to study and offered important feedback that led to our final list of genes under investigation. We remain grateful to these scholars for their wisdom and time.

As discussed (above) in the summary of Year 1 and 2 Dance study results, we discovered significant performance differences on select higher cognitive tasks in persons with extensive education in the performing arts (dancers) versus those with minimal or no education in the performing arts (non-dancers). One exciting hypothesis that followed from these findings—one of the core hypotheses being tested by the Dana Arts and Cognition Consortium—is that such group differences derived from the impact of education in the Arts on the brain, and its positive transfer to the acquisition/learning and processing of other core content knowledge.

The tantalizing unanswered question from the Petitto team's Year 1-2 Dance Study findings, however, was this: Were such group differences specifically due to one group's extensive education in the arts versus the other group's lack of education in the arts, or were the group differences due to other biologically/genetically-based self-selection factors? Indeed, to answer this question we needed to tackle, head-on, the elusive decades-old question of nature versus nurture. Was it the sustained education—the environmental experience—with the arts that rendered dancers with a greater "cognitive edge" over non-dancers? Or, was it just that people who ended up being dancers were born with a complex composite of genetic predispositions—or "nature"— that generally afforded them select higher cognitive capacities, which, in turn, yielded a greater likelihood of their self-selection to enter this particular life path? Said another way, were such group differences between dancers and non-dancers due to differences in their education, per se, or instead to differences in genetic predispositions that caused one group (the dancers) to choose to undertake the arts?

Significance

Moving beyond the fact that we observed group differences between dancers and non-dancers on select higher cognitive tasks (Years 1-2), in Year 3 we sought to gain new insight into why this finding might be so. Answering this "why" question was not only a scientific imperative—the logical next-step in achieving the most complete answer to the

questions posed in our Dana research program—but it was an educational policy imperative. Only by unraveling the factors that contributed to our group differences can we provide compelling evidence to support educational policy in the United States. It is well known that cuts in school budgets often lead first to cuts in school's arts curriculum (over, say, cuts in the math curriculum). By sorting out whether the higher cognitive performance of dancers in our study was due to educational versus biological factors, we can contribute new evidenced-based knowledge to United States educational policy makers on which they may base decisions about whether to cut arts education from young children's curricula during the developmentally crucial elementary school years.

Participants were tested behaviorally and all were also tested with the fNIRS brain imaging system ...

Background

Recently, Bachner-Melman, Dinal, Zohar, Constantini, Lerer, Hoch, et al., (2005) found that dancers have a particular polymorphism on two of their genes. In addition, consortium member Dr. Michael Posner and collaborators have found evidence of genetic influences on performance on attentional tasks (e.g., Posner, Rothbart, & Sheese, 2007). To study whether there might be possible genetic influences underlying any performance differences during higher cognitive tasks in persons highly educated in the arts versus those not educated in the arts—as well as the likelihood of pursuing an arts education—buccal (cheek) swabs were collected from all participants, both while performing a battery of behavioral cognitive tasks and while simultaneously undergoing fNIRS brain imaging.

Seven candidate genes were selected for polymorphism analyses after extensive review of the literature and after important consultation with scholars Drs. Dunbar and Posner. Our particular choice of these seven candidate genes was established on the basis of specific linkages of previously identified genes with specific behavioral profiles. In one such study concerning dance, Bachner-Melman, et al. (2005) found that trained creative dancers had polymorphisms on their serotonin transporter gene SLC6a4 and vasopressin receptor gene AVPR1a—interestingly, polymorphisms not found in athletes and non-dancers.

In such genetics studies concerning attention/higher cognition, consortium scholar Dr. Michael Posner and colleagues have identified polymorphisms in several dopaminergic genes associated with attention and higher cognitive functioning: DAT1, DRD4, MAOA, and COMT. The DAT1 gene has been shown to be related to executive cognitive function and performance on a conflict task (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005). DRD4 and MAOA genes have been shown to be associated with performance on conflict-related tasks (Fan, Fosella, Sommer, Wu, & Posner, 2003). The COMT gene has been associated with performance on attention and working memory-related tasks (Raz, Fan, & Posner, 2006). In genetics studies concerning memory/learning, BDNF (brain-derived neurotrophic factor) has been shown to be associated with episodic memory, LTP (long-term potentiation), and also with learning (Goldberg & Weinberger, 2004).

Participants

Participants in the study were adult English monolinguals who had early (before age 7), sustained, and intensively maintained education in the performing arts (dance) versus participants with very little or no performing arts education (non-dancers). Participants were tested behaviorally

and all were also tested with the fNIRS brain imaging system (a further subset of participants also underwent MRI/fNIRS co-registration).

Methods

Extensive measures were taken to equate our participants across multiple dimensions to ensure that the only major difference between groups was in their arts (dance) expertise. Overall, participants in the study underwent questionnaires for group assignment, followed by the administration of cognitive and perceptual assessment tasks. Two steps were applied to all participants that constituted the basis for expert "dancer" versus novice "non-dancer" group assignment, including an (i) email questionnaire and an (ii) Expert Dance questionnaire or Performing Arts Experience questionnaire. The Performing Arts Experience questionnaire also included a detailed "Personal Pleasure Scale" regarding the performing arts, as well as general information about their propensity to engage in other daily/weekly activities and-or intensive education/training regimes (e.g., house cleaning, shopping activities, sports and exercise education/training regimes, etc.). We collected standardized academic performance measures (SAT scores). Regarding assessment, participants underwent standardized assessments, including measures of non-verbal relational reasoning, language competence, cognitive and attentional processing, and biological motion perception (consisting of whole body dance and walk visual processing).

Selection of those to participate in the dancer, and non-dancer, groups was made on the basis of this information—and following from the Petitto team's rigorous Expert-Novice criteria—as well as in Berens, Kovelman, White, Shalinsky, Gramacy & Petitto, (2007), and in our submitted manuscript for journal submission. Briefly, participants in the "dancers" group had (i) >8 years dance education, (ii) begun education in dance before age 7, (iii) continued dance education/training into adulthood, (iv) extensive professional performance experience, and (v) reported dance as "pleasurable."

Procedures for the "Mind-Brain-Gene" Study

Regarding behavioral assessment of cognitive performance, participants underwent several standardized assessments, including measures of their English language expression and proficiency (language performance assessment), cognitive and attentional processing, and whole body biological motion visual perception processing. Regarding fNIRS brain imaging assessment, participants' brain activity was recorded while they performed the cognitive and attentional processing task and the biological motion perception tasks. Regarding gene assessment, cheek swabs were obtained from all participants immediately prior to the simultaneous behavioral and fNIRS assessments. All swabs were assigned a random, 4-number-4 letter anonymous code, so that no participant could ever be tied to a specific cheek swab. This process also ensured that the genetic study scientists were "blind" to the participants' background during data analyses.

The collected buccal swabs from all dance and non-dance group fNIRS participants were stored in an Isotemp freezer while waiting to be analyzed. Collected buccal swabs from both the Petitto and Dunbar laboratories were then driven to the "Center for Functional Genomics" at SUNY Albany for standard PCR-based amplification and genotyping analyses.

To ensure accuracy and neuroanatomical precision across new fNIRS technology, as compared to existing MRI technology, in Year 3 we completed the collection and analyses of co-registration data between the MRI/anatomical and fNIRS in a subset of our adult participants. This important procedure is required whenever data across two technologies are compared. By doing so, we gain the greatest confidence with regard to recording from the neuroanatomical sites

that precisely correspond to our brain regions of interest (ROI), thus permitting the most accurate study of higher cognitive functions and specific brain regions. During Year 3 (and end of Year 2), entirely new participants were rigorously screened, and new adult dancer and non-dancer groups were established. These participants then participated in our cognitive attentional and Biological Motion Perception behavioral tasks, while undergoing fNIRS brain imaging. In Year 3 we completed fNIRS system imaging of these new participants.

In a striking contrast of neural activity and behavior, both groups exhibited similar activation patterns ...

Preliminary Results and Status of Analyses of fNIRS

First, the behavioral data collected from participants while undergoing this new round of fNIRS brain recordings during the Biological Motion Perception tasks showed a similar pattern of results as those collected without simultaneous scanning (off-line). That is, the present behavioral results replicated the behavioral findings observed in the Year 1-Year 2 study described above.

Second, the fNIRS brain imaging data collected during the visual Biological Motion Perception task showed that dancers had greater right than left hemisphere parietal brain activation, while non-dancers showed the reverse pattern ($p < .02$). In a striking contrast of neural activity and behavior, both groups exhibited similar activation patterns during Biological Motion trials depicting walking, with lateralization differences emerging only on trials depicting dancing.

Third, regarding the genetics data, we have received results for four genes from our target list of seven. Due to the labor-intensive nature of these genotyping analyses, the Center for Functional Genetics (SUNY Albany) is still working on the remaining three genes. Nonetheless, we have now received genotyping results for four of our candidate genes. Most intriguingly, the preliminary results suggest that there are no differences between our dancer and non-dancer groups on COMT, MAOA, and 1 of the DRD4 polymorphisms. (Recall that COMT, MAOA, and DRD4 have been associated with performance on attention and working memory related tasks; Raz, Fan, & Posner, 2006.)

Although exceedingly preliminary, these exciting results suggest support for the hypothesis that the differences between our two groups may be due to their education in the arts, rather than to genetic predispositions. We are currently awaiting the outstanding genotyping data and are in the data interpretation stage of this Mind-Brain-Gene (genotyping) study of dancers versus non-dancers.

Summary and Preliminary Conclusions: Dance Study

The above combined "Mind-Brain-Gene" study of the impact of education in the arts on the mind (as revealed through behavioral measures of cognitive processing), the brain's functional architecture, and genes, may soon have important educational implications. Additional results corresponding to the preliminary results described above have the potential to provide educators, policy makers, and parents with evidence that early and sustained education in the arts may afford young students long-lasting advantages in other core cognitive domains—thereby providing a powerful "translational benefit" from scientists to the greater society.

Year 3 Tangible Products from Dance, fNIRS, and Music Studies

A journal manuscript of the Dance Behavioral study has now been submitted for publication and is under review. A poster of both the Dance Behavioral and the Dance fNIRS studies was presented at the annual Cognitive Neuroscience Society meeting held in New York, NY, May, 2007. Our fNIRS manuscript, in which we offer the discipline a universal analysis method, has been revised and resubmitted. In depth Dance fNIRS analyses are presently in progress. Once data analyses are complete, a journal manuscript of the Dance fNIRS study will be submitted. Over the course of the coming year, we will prepare the genotyping data both for presentation at a major scientific and an educational conference as well as for journal manuscript submission. Clearly, the completion of this important Dana research activity awaits the return of the final genotyping data results from the Center for Functional Genomics scientists at SUNY Albany.

Following from this Dana Foundation genotyping work, Kevin Dunbar (Dana recipient) and Laura-Ann Petitto are writing a manuscript for journal submission in which they lay bare this new method, its theoretical power, and its implications for the study of higher cognition, as well as the arts and education. Final closure on all work (involving, for example, revisions and publication of submitted manuscripts, final analyses of genotyping results, publication of Dance and fNIRS results, presentation and publication of genotyping results, and combined presentation/publication of Dance-fNIRS-Genotyping results) will occur over the next year.

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Research Part 2: Music Education and Its Impact on Second Language Learning

Study Hypothesis

In this Dana Consortium study involving music, our goal was to understand whether extensive childhood musical education impacts higher cognitive attentional abilities and second language learning in adulthood. Because learning another language involves the ability to attend to one language, inhibit the other language, and rapidly switch between them, and because musicians have been shown to have enhanced selective attention on particular higher cognitive tasks (e.g., Crawley, Acker-Mills, Pastore, and Weil, 2002; Schellenberg, 2005), this study tested the following hypothesis: Monolingual expert musicians would learn their new/second language better than non-musicians (equated on all other factors).

Study Participants

Participants in the study were monolingual English-speaking students enrolled in Introductory Italian or Spanish classes (Spanish 001 or Italian 001). Participants were tested twice, once at the beginning of the academic term (T1) and once at the end of the academic term (T2).

Study Procedures

Extensive measures were taken to equate our participants across multiple dimensions to ensure that the only major difference between groups was in their arts (music) expertise. Overall, participants in the study underwent questionnaires for group assignment, followed by the administration of cognitive/linguistic and attentional assessment tasks. Two steps were applied to all participants that constituted the basis for "music" versus novice "non-music" group assignment, including an (i) e-mail questionnaire, and an (ii) Expert Music questionnaire or Performing Arts Experience questionnaire. We collected standardized academic performance measures (SAT scores). Regarding assessment, participants underwent standardized assessments, including measures of language competence, cognitive and attentional processing. Based on responses on these questionnaires about their music education, participants were divided into musician and non-musician groups, with those who received early extensive and continued music education classified as musicians; see summarized details in Dance studies above.

For assessment, participants were measured on their English competence/expressive proficiency (language performance assessment), new language competence/expressive proficiency, cognitive attentional processing, end-of-term self-evaluation, and class final grade. Native Italian, Spanish, and English speakers conducted data transcription, coding, and reliability checks/measures, and all analyses.

Summary of Music Study Results Years 1, 2, 3

Behavioral

Analyses of these data found no differences in general academic performance measures—the SAT, Final Class Grade, and Self-Evaluation. This is what we had predicted. We observed that there were also no differences between groups on the cognitive attentional assessments.

Importantly, our findings demonstrate that

musicians exhibited significantly increased language competence and proficiency in their new (second) language as compared to non-musicians, even after only one term of language instruction ($p < .05$).

… there may be an enduring cognitive advantage afforded by early and extensive music education on adult learning of a new language …

Conclusions

The Music study results suggest that there may be an enduring cognitive advantage afforded by early and extensive music education on adult learning of a new language in an instructional setting. Specifically, musicians showed greater improvement in expressive fluency and competence in their new language than non-musicians.

Tangible Products of Music Study Years 1, 2, 3

A manuscript of the Music study is in progress. A poster of the Music study was presented at the annual Association for Psychological Science conference, held in Washington DC, May, 2007. The Petitto Laboratory recently moved to the University of Toronto, where they will continue research in the Performing Arts and where additional collaborative opportunities exist (e.g., Dr. Glenn Schellenberg's aboratory).

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Effects of Music Training on Brain and Cognitive Development in Under-Privileged 3- to 5-Year-Old Children: Preliminary Results

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Summary

This study tested the hypothesis that music training causes improvements in several diverse aspects of cognition, and that one way music training produces these effects is by improving attention. We tested this hypothesis using a "pre-post" intervention study design, in which we measured children's test scores at baseline, prior to the intervention, and again following the intervention. We enrolled a total of 88 children from Head Start preschools. All were three-to-five years old, from low socio-economic status (SES) families, right handed, monolingual English speakers, and free of neurological or behavioral disorders. The children were randomly assigned to be in either regular Head Start or in one of three smaller groups. Each small group met for instruction within the regular class time for 40 minutes per day, five days per week, over an eight-week period.

The experimental group (N=26 children) had a small class size (a 5:2 student/teacher ratio) and focused on music activities. These included listening to, moving to, and making music, as well as singing. The three control-comparison groups consisted of: 1) a large class control group (N=19), where students received regular Head Start instruction with a student/teacher ratio of 18:2; 2) a small class control group (N=20), where children were

engaged in regular Head Start classroom activities, but in a smaller class, with a student/teacher ratio of 5:2; and 3) a small attention class group (N=23), in which children received training in focusing attention and becoming more aware of details.

Children in each of the four groups were tested prior to and after enrollment in the eight-week period. They were tested on six measures: language fundamentals, vocabulary, letter identification, IQ, visuospatial intelligence (or spatial cognition), and developmental numeracy (numbers used in daily living).

There were strong and significant improvements in non-verbal IQ and numeracy and spatial cognition within a group measured before and after training (i.e., within-group differences) in children who received music training and those who received attention training. The small Head Start class group also displayed large improvements in these same areas from before to after the eight-week period. These improvements were not seen in children who received regular Head Start in the large class control group.

The extent of improvements in non-verbal IQ and numeracy and spatial cognition was similar in children receiving music training, attention training, and regular Head Start instruction in small classes. These findings suggest that increased time in a small group with intense adult attention may be the underlying element in improving children's skills in these cognitive areas, and that music and attention training in these small group classes produces similar beneficial results.

The central and powerful role of adult attention and guidance is also underscored by the results of a separate study conducted by us, in which children did not receive any intervention. Their parents, however, received training that improved parenting practices, which in turn improved children's conduct and produced large and significant improvements in each of the measures reported here (Fanning et al. 2007). These changes were highly significant within the group from before to after training and also when compared to changes made in the large control group (i.e. between-group differences).

Taken together, these findings suggest that attention from adults, including attention focused through providing music training, produces improvements in young children's cognitive abilities in non-verbal IQ, and in numeracy and spatial cognition, with the latter two being important in math abilities.

Learning music requires focused attention, abstract, relational thinking and fluid intelligence (called "executive control").

Introduction

There is universal agreement that learning to make music and experiencing meaningful musical events are inherently and uniquely valuable. Recently, motivated in part by cuts to school budgets for education in arts and music, a burgeoning literature has sought to provide evidence of the potential benefits of music instruction on cognitive and academic development in children.

The vast majority of these studies has assessed cognitive functions in trained musicians compared to people with no musical training. Several studies have reported that musicians have higher scores than non-musicians on tests of verbal, visual-spatial, and "numeracy" skills (those measuring competence in math skills needed for everyday living and for understanding graphs and charts); and that musicians scored higher on IQ tests compared to non-musicians. (These studies are summarized in Schellenberg 2006 and Norton et al. 2005.)

While many such reports interpret these correlations as showing that music **causes**

improvements in cognition, it is equally likely that people with strong cognitive skills are more likely to make the considerable cognitive effort to learn music. Learning music requires focused attention, abstract, relational thinking and fluid intelligence (called "executive control"). It is highly likely, therefore, that a major factor producing the positive correlations between music and cognition is that people with better cognitive skills choose to learn music.

Nonetheless, it is also likely that learning music trains and builds cognitive resources. To test this hypothesis, it is necessary to randomly assign individuals to three groups, receiving: 1) music training; 2) training in some other comparable area; and 3) no special training. Very few studies have taken this approach. Moreover, the few studies that have used this approach typically measured a limited number of cognitive abilities. For example, Rauscher reports that individual piano lessons result in improvements on spatial and spatial- temporal skills in young children (Rauscher et al. 1997, 2002). Gardiner et al. (1996) report that six-year olds who receive music and visual arts training display a larger improvement on standardized tests of reading and arithmetic than children receiving the standard curriculum. Schellenberg (2004) reported that six-year-old children who received music lessons (voice or keyboard) in a small group displayed larger improvements in all verbal and non-verbal subtests of the Wechsler Intelligence Scale than children receiving drama lessons or no lessons.

If these results are upheld in further well-controlled studies, they would suggest that music training causes improvements in cognition. Additionally, they would raise the question of how music training might produce such effects.

The effects reported in the studies described above are not specific to one type of cognitive skill. Rather, they appear across a diverse array of cognitive abilities. These results suggest that music training may result in improvements of cognitive processes that operate to strengthen skills in several areas. One such cognitive process is attention.

In our research, we tested the hypothesis that music training causes improvements in several diverse aspects of cognition and that one way music training produces these effects is by improving attention.

It is important in interpreting our findings to understand what is known about the architecture, development, plasticity, vulnerability, and training of attention. Before describing our results, therefore, we briefly review these issues.

What is Attention?

Over the last several decades, research in the cognitive and neurocognitive sciences has converged on an understanding of the different components of attention (Driver et al. 2001, Raz and Buhle 2006, Shipp 2004). Different research groups, and their models, differ somewhat in the way they subdivide and term components of attention. However, they all recognize the importance of: 1) a basic level of arousal and alerting; and 2) a selective focus on specific stimuli and signals, to further process these signals either transiently or in a sustained manner. Such "attentional" selection involves brain processes that are engaged in increasing the strength of selected signals (called signal enhancement). It also involves suppression of signals that are irrelevant information or distractions. Suppression of distractions is a part of early attentional selection. The brain's suppression of distractions is also considered to be part of its "executive," or inhibitory, control functions, which include self-regulation. The brain's executive control functions are important in suppressing predominant responses generally, and also in switching attention between different sets of signals and in dividing attention between different tasks.

How does Attention Develop?

Several studies attest to the centrality and relevance that models of attention have to child development in general, and to school readiness in particular (Blair 2002, Early Child Care Research Network 2003, Posner and Rothbart 2000). Studies exploring how the process of attention develops have documented that it matures over a prolonged period of time. This is the case even for aspects of attention that may be present in some form in infancy. Therefore, while alertness is clearly present in infancy, the ability to maintain alertness for effortful processing has a protracted developmental time course that extends into young adulthood (Gomes et al. 2000, Rueda et al. 2004).

This finding suggests that, if given strong attentional cues, children as young as three years old can selectively attend to auditory information.

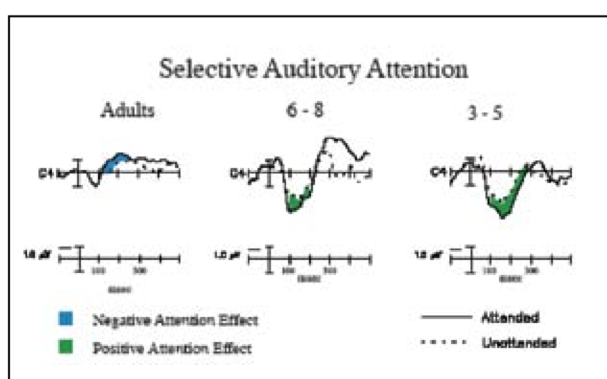
While exogenously driven transient attentional selection may mature within the first decade of life (Rueda et al. 2004), development of endogenous (internal and covert) selection continues until at least the third decade of life (Schul et al. 2003). Our understanding of these maturational differences derives in part from studies of behavior and from "event-related potential" (ERP) studies. In ERP studies, electrodes are placed on the surface of the scalp. Following a visual or auditory stimulus presented to the infant or child, using particular recording paradigms, the electrical currents that are produced by the brain activity can be specifically related to the neural systems important for focused attention.

In a review of both behavioral and ERP studies of the development of selective attention, Ridderinkhof and van der Stelt (2000) proposed that the abilities to select among competing stimuli and to preferentially process the more relevant information are essentially available in very young children. They further proposed that the speed and efficiency of these behaviors, and the systems contributing to these abilities, improve as children develop.

We tested this hypothesis more directly. We adapted the ERP paradigm employed by Hink and Hillyard (1976) to make "dichotic" listening (where each ear hears a different sound) more interesting and engaging for three- to eight-year-old children (Coch et al. 2005; Sanders et al. 2006). As seen in the figure below, the structure of the auditory ERP brain responses to these stimuli differed markedly as a function of age.

Nonetheless, when these listeners were asked to selectively attend to one of two simultaneously presented stories that differed in location (left/right), voice (male/female), and content, children as young as three years of age showed an auditory selective attention effect (an increase of the ERPs in response to the stimuli to which they were asked to attend). Furthermore, the timing at which this selective attention effect is observed was the same for the children as for adults (100 ms after stimulus presentation), as shown in the figure.

This finding suggests that, if given strong attentional cues, children as young as three years



old can selectively attend to auditory information. Moreover, the nature and timing of these effects on processing auditory information are similar to those found in adults.

Plasticity and Vulnerability of Attention

Previously, we have used functional magnetic resonance imaging (fMRI) in combination with behavioral and ERP studies and found that the brain displays considerable plasticity (functional reorganization) of the neural systems that are important in selective attention. For example, we have found that visual selective attention is markedly enhanced in deaf compared to hearing individuals (Bavelier et al. 2000, 2001, Neville and Lawson 1987a, 1987b, 1987c). We have reported similar enhancement of auditory selective attention in congenitally blind adults (Röder et al. 1999, 2003).

However, as we recently reported, there appears to be limits on the time- period during development when the early (100 ms) processes of auditory selective attention can be enhanced. This finding is based on studies that show that people who become blind in later years do not display these same, early enhanced selective attention effects (Fieger et al. 2006).

The finding that particular aspects of selective attention can be modified in congenitally deaf and blind individuals raises the possibility that these aspects of attention may develop relatively slowly and may be particularly vulnerable during development. Using the ERP model of selective attention that we described above, we recently observed deficits in attention in at-risk populations, including children who are "specifically-language impaired" (Stevens et al. 2006) and those from lower socio-economic families (Lauinger et al. 2006).

How do people develop improved attention through training?

Cognitive rehabilitation research undertaken since the late 1980s has assessed the effects of training designed to improve aspects of attention in adults with traumatic brain injury, those treated for brain cancers, and those who have incurred strokes and other cerebral vascular accidents (including Sohlberg and Mateer 1987, 2001, 2003, Niemann et al. 1990). Many of these studies report that patients showed improvements in sustained attention and executive function (Ethier et al. 1989, Finlayson et al. 1987, Gray and Robertson 1989). However, it has been difficult to compare results across studies, since different investigators have focused on training different aspects of attention in order to tailor the training to various specific deficits of individual patients. An analysis of this literature suggests that studies need more stringent comparison of the rehabilitation groups to healthy "control" groups (Park and Ingles 2001).

According to recent studies, healthy adults show pronounced effects of training (video game playing) on virtually every aspect of attention (Green and Bavelier 2003). Additionally, a small number of studies in children with attention deficit/ hyperactivity disorder (ADHD) who were trained in attention and working memory report significant gains following several weeks of daily or every-other-day training (Kerns et al. 1999, Klingberg et al. 2002).

Recently, Posner and colleagues investigated the impact of attention training in typically developing, higher socioeconomic status (SES) preschoolers (Rueda et al. 2005). The computer-based activities were adaptive—they provided progressively increased challenges on attentional skills. The research design was based on a study that showed significant gains in attention skills by non-human primates (Rumbaugh and Washburn 1995). In the Posner study, the group that received

the computer-based activity attention training (the experimental group) for only five days showed significantly greater pre-post experiment change in their executive control and non-verbal IQ scores compared to changes in the control group, which received no special training.

As reported above, the specifically-language impaired children aged six years display deficits on the ERP measures of selective attention described above (Stevens et al., 2006). We recently reported that with daily computerized training over a period of six weeks, measures of receptive language and ERP measures of attention are normalized (Stevens et al., in press).

… research has shown that processes of attention are central to every aspect of cognition and school performance.

Summary of what attention studies show

In sum, research has shown that processes of attention are central to every aspect of cognition and school performance. Moreover, processes of attention display a high degree of neuroplasticity. That is, processes of attention display both enhancements (following sensory deprivation in people who are blind or deaf) and vulnerabilities/deficits in many at-risk populations, including those with developmental disorders and those from lower SES backgrounds. A handful of carefully designed studies suggest that attention can be significantly improved in both at-risk and neurologically intact and typically developing adults and children, following specialized training.

In view of these results, the goal of our Dana Arts and Cognition Consortium research was to determine whether music training in preschoolers would produce significant improvements in cognition and school performance that are comparable to the effects produced by attention training.

The Study Hypotheses

We tested the hypothesis that, following eight weeks of 40 minutes per school day of either music or attention training in small groups, Head Start preschoolers would display gains in a number of cognitive areas, including language, pre-literacy and visual-spatial skills, numeracy and nonverbal IQ; and that these gains would be larger than those observed in preschoolers who were in either large or small control groups who did not receive either of the trainings.

The Study Design

A total of 88 children were included in the study. The children were recruited from local Head Start preschools, which are federally funded and available to children in families with very low household income. All children were from low SES families, three to five years old, right-handed, monolingual English speakers, and free of neurological or behavioral disorders.

One of the four groups was a music intervention class, in which children received eight weeks of music training in a small group (5:2 student/teacher ratio). Music activities included listening to music, moving to music, making music, and singing. Classes ran for 40 minutes a day, four days per week, during the regular Head Start school day.

The other three groups were “control-comparison” classes to enable us to examine whether any effects observed in the music intervention group were specific to music training or whether other types of training would have similar effects.

The control-comparison groups included: 1) a large group of children receiving regular Head Start instruction, with an 18:2 student/teacher

ratio; 2) a small group of children who participated in regular Head Start activities, but in a small group format, with a 5:2 student/teacher ratio; and, 3) a small group of children who received instruction in focusing attention and being aware of details.

All small control-comparison groups (except the large group control) were taught by the same teachers who taught in the music intervention group. The control-comparison classes lasted for the same amount of time as the music intervention class training.

The specificity of the effects of music training can be inferred, depending upon the extent to which students in the three control-comparison groups (including a large comparison group) show different (or fewer) gains in the outcomes measured. If students in control-comparison groups display a similar pattern of outcomes to those observed in the music group, the results would suggest brain processes whereby music training improves cognition. For instance, if learning music trains attention, the effects of these two interventions (music training and attention training) may be similar.

The effects of the interventions in all four groups were assessed employing a range of reliable and valid measures of cognition and literacy. The measures were administered by testers who were blind to the groups to which the children belonged.

Within one month prior to and following the interventions, children were administered the following tests:

1. The Clinical Evaluation of Language Fundamentals-Preschool 2nd Ed. (CELF-P2) (Wiig et al. 2004).

The CELF-P:2 test is an individually administered assessment of language building-blocks that are considered fundamental to the development of effective communication. (We used the "receptive" and "expressive" subtests, which comprise the Receptive and Expressive Language Indices.)

2. Stanford-Binet Intelligence Scales-5th Ed. (SB-5) (Roid 2003).

The SB-5 is an individually administered assessment of intelligence and cognitive abilities. It is normed (i.e. it measures and scores age-appropriate performance) for examinees ranging from two years old through 85 years old. We administered only the Nonverbal Intelligence Scale. This is based on five nonverbal subtests associated with each of five cognitive factors that are measured by the SB-5: fluid reasoning, knowledge, quantitative reasoning, visual-spatial processing, and working memory.

3. The Peabody Picture Vocabulary Test-Third Edition (PPVT-III) (Dunn and Dunn 1997).

The PPVT-III is an individually administered assessment of "receptive" single-word vocabulary knowledge. A target vocabulary word is verbally presented by the tester while the child views a field of four black and white sketch pictures. The child points to the picture that best matches the meaning of the target word. The test is normed for examinees ranging from toddlers aged two years to six months to older children.

4. Letter Identification

This individually administered test assesses the percentage of uppercase and lowercase letters, provided on a page, which a child identifies correctly. The page of letters is from the Observation Survey of Early Literacy Achievement (Clay 1993). The child views the presented page and labels any letters he or she knows.

5. Wechsler Preschool and Primary Scale-3rd Ed. (WPPSI-III) (Wechsler 2002).

One subtest from the WPPSI-III, the "Object Assembly," is used. The tester presents pieces of a puzzle and asks the child to complete the puzzle as quickly as possible. After 90 seconds, the tester can remove the puzzle so that the child does not get frustrated. The Standard Score for the subtest is used, and the cumulative number of seconds taken, and the number of puzzles completed, is tracked.

6. Developmental Numeracy Assessment

We developed a test to screen emerging numeracy abilities in preschool children. The math assessment that we developed is based on educational, cognitive developmental, and cognitive neuroscientific research. We assess digit naming, verbal counting, and magnitude estimation.

Following the music training program, children displayed significant improvements on the CELF tests of … receptive … and expressive language

The Study Outcomes

Since these are preliminary results, based on a small sample size, we begin to analyze the data by looking at changes from before to after training within each group.

Music Training Group (Experimental Group: N=26 children)

Following the music training program, children displayed significant improvements on the CELF tests of language, including receptive language ($p<.01$) and expressive language ($p<.001$). (Results of .05 or better, such as these results of .01 or .001, are considered "statistically significant.") Children also improved significantly in letter identification ($p<.01$) and receptive vocabulary ($p<.01$); and they displayed robust increases on the puzzle assembly subtest of Wechsler Intelligence Test ($p<.01$).

In addition, the music training group improved significantly ($p<.007$) on the test we developed to assess numeracy in preschoolers. The specific subtests in which they improved were verbal counting and estimating magnitudes. Finally, this group also improved on the overall Stanford Binet non-verbal IQ test ($p<.03$), including the fluid and quantitative reasoning subtest of the Stanford Binet IQ test ($p<.03$) and the "knowledge" or "critical thinking" subtest ($p<.01$). An example of an item on the latter subtest is to ask the child what is amiss in a picture showing two children in sunshine who cast shadows in different directions.

Large Group (Control Group: N=19 children)

The children in the regular Head Start classrooms, which have an 18:2 student/teacher ratio, also displayed similar improvements in the CELF tests of receptive ($p<.01$) and expressive ($p<.01$) language, and of phonological awareness ($p<.03$). They showed no significant improvements, however, on the other tests.

Small Group (Control Group: N=20 children)

The children who spent 40 minutes per day in a group smaller than the regular Head Start classroom, but engaging in similar activities, also displayed gains in receptive ($p<.01$) and expressive ($p<.002$) language and in phonological awareness ($p<.01$). In addition, they improved on the object assembly test ($p<.004$), and on overall non-verbal IQ ($p<.001$), including several subtests.

Attention Training Group (Control Group: N=23 children)

The children who were trained in attention displayed gains of comparable magnitude, and in similar areas, as the children trained in music. They improved significantly in receptive ($p<.01$) and expressive ($p<.004$) language and phonological awareness ($p<.01$). They also improved in the object assembly test of visual cognition ($p<.007$), in numeracy ($p<.001$) and in the Stanford Binet subsets of fluid reasoning, quantitative reasoning, visual-spatial and working memory, and critical thinking (all $p<.01$).

Conclusions

Taken together, these results suggest that the gains in language observed in the music group (and also in the control groups) may have been due to Head Start itself, or to test-retest effects. Further controls will be necessary to determine which variables are key to language improvement in children in each of the four groups. While these results are preliminary, one interpretation of the data is that the improvements in spatial cognition (puzzle assembly) and IQ observed in children in all small groups (music, attention, and small Head Start class) but not in children in the large control group in this study may derive from the fact that music training typically involves time being individually tutored, or being in a small group, which may itself increase opportunities for training attention. Alternatively, when the numbers of children in each group are larger, it may show that there are meaningful differences between groups in the magnitude of the effects.

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About the Contributors

Mark D'Esposito, M.D., Professor of Neuroscience and Psychology, Director, Henry H. Wheeler, Jr. Brain Imaging Center, University of California, Berkeley earned his medical degree in 1987 at the SUNY Health Science Center at Syracuse and completed clinical training in Neurology at Boston University Medical Center in 1991. After residency training, he was awarded a NIH Javits Fellowship to pursue research training at the Memory Disorders Research Center at Boston University and Braintree Rehabilitation Hospital. In 1993, he was appointed Assistant Professor of Neurology at the University of Pennsylvania School of Medicine, where he was also the Chief of the Cognitive Neurology Division. In 2000, he was recruited to the Helen Wills Neuroscience Institute and Department of Psychology at the University of California, Berkeley to become Professor of Neuroscience and Psychology, and the Director of their newly created Henry H. Wheeler, Jr. Brain Imaging Center.

Since his first faculty appointment in 1993, Dr. D'Esposito has had a highly productive academic career. He has received numerous competitive research grants from the National Institutes of Health as well as private sources such as the Dana Foundation and the American Federation for Aging Research. For his clinical, teaching, and research skills he has been given many awards and honors such as being cited in "The Best Doctors in America", the Dean's Award for Excellence in Basic Science Teaching, Norman Geschwind Prize in Behavioral Neurology from American Academy of Neurology. He is the Editor-In-Chief of the *Journal of Cognitive Neuroscience*, and he has over 200 research publications and has written and edited five books. Based on these achievements, he has been invited to give lectures throughout the world.

Dr. D'Esposito's research focuses on investigating how the brain creates mental experience, such as forming memories and paying attention. This aim is achieved through several different experimental approaches and methodologies. First, his lab employs a brain imaging method called functional MRI (fMRI) to identify the brain regions and time course of brain activity while healthy

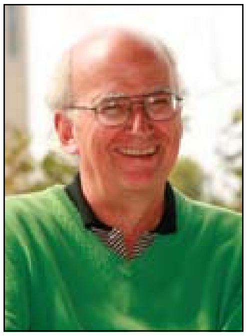
human subjects perform cognitive tasks. A key focus has been on the cognitive functions supported by the frontal lobes. Second, his lab investigates the relationship between brain chemicals, such as dopamine, and frontal lobe function. This aim is achieved by determining the affects of various medications on cognitive abilities in healthy subjects as well as patients with memory loss. Finally, he studies patients who have suffered memory loss from stroke, traumatic brain injury, Parkinson's disease and Alzheimer's disease to further understand the brain mechanisms that underlie memory function. Finally, his lab is attempting to understand normal aging and specifically why individuals become forgetful as they get older. The ultimate goal of this line of research is to both understand how the brain works, as well as to develop new ways to diagnose and treat patients with memory disorders.

Kevin Dunbar, Ph.D., is Professor of Psychology and director of the Laboratory for complex Thinking and Scientific Reasoning at the University of Toronto, Scarborough. For the past 20 years he has been investigating the ways that people think and reason in complex environments and has focused on the effects of education, both in the performing arts and in science, on the brain. He has investigated students and scientists across many domains to achieve a deeper understanding of what and how we learn. He has investigtated leading scientists in the US, Canada, and Italy and has discovered some of the key strategies that scientists use to make discoveries. He also conducts research on scientific thinking in his own laboratory to further probe the scientific thinking strategies that he has seen scientists use "live." In addition, he has also conducted research on the development of scientific thinking abilities in children. Currently, he is using functional Magnetic Resonance Imaging (fMRI) techniques to unravel the ways that the human brain reasons and changes as a function of educational experience. He is also pioneering the use of DNA microarrays (also known as genechips) and DNA genotyping to understand the genetics of learning and cognition. Using these different approaches, Professor Dunbar has been able to articulate the nature of the creative mind and its many facets.

Dunbar has served on the editorial boards of *Journal of Experimental Psychology, Cognitive Psychology*, and the *Canadian Journal of Experimental Psychology* and is a member of the steering committee for the Irish Cognitive Science Society. He has spoken at

the National Research Council of the national Academy of Sciences, and given keynote addresses and colloquia at major congresses and in Psychology, Biology, and Medical departments in North America (such as Harvard University, Cornell University, UCLA, UCSB, Georgia Institute of Technology, University of Illinois, University of Pennsylvania, Stanford University, Northwestern University, University of Pittsburgh, University of Texas at Arlington, Vassar College, University of Chicago, University of Toronto, University of Alberta, University of Montreal, Concordia University, Carleton University), Europe (University of Modena, Istituto San Raffaele), and Asia (Aoyama Gakuin in Tokyo). In 2006 he spoke to the Smithsonian Museum in Washington. He gave the plenary address to the International Cognitive Science Society in Tokyo in August 1999, and in April 2000 he was chosen by the American Psychological Society to speak before the heads of all the major scientific societies in North America on his vision of the problems science will face in the next 25 years. Furthermore, he was selected as a member of the APS and Spencer Foundation-sponsored working retreat on "applying the science of learning to the University and beyond" in March 2001). His research has been funded by the National Science foundation, Dana Foundation, US Office of Naval Research, NIH, the Spencer Foundation and the Canadian Natural Sciences and Engineering Council, SSHRC, FCAR, & FRSQ. He has appeared on The Discovery Channel, BBC radio, CBC radio, and his work has been written about in newspapers such as *The New Scientist*, *The Washington Post*, the *APA Monitor*, and the *Times Higher Educational Supplement*. His work on scientific discovery was itself given an award for being one of the most important scientific discoveries of 1993 by the governing scientists of *Québec Science* magazine. His work has been translated into Japanese, Chinese, and Italian.

Kevin Dunbar was born in Birmingham England, but grew up in Ireland. He received his Bachelor's and Master's degree in Psychology from the National University of Ireland. He received his PhD from the University of Toronto in 1985 and was a post-doctoral fellow at Carnegie-Mellon University from 1985-1988. He was at McGill University in Montreal from 1988 to 2001 and was professor of Education and Psychology at Dartmouth College from 2001 until 2007. He joined the faculty at the University of Toronto in 2007.

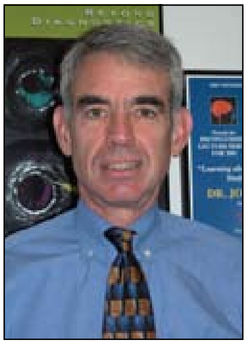


Michael Gazzaniga, Ph.D., is the Director of the Sage Center for the study of Mind at the University of California, Santa Barbara. In 1964 he received a Ph.D from the California Institute of Technology, where he worked under the guidance of Roger Sperry, with primary responsibility for initiating human split-brain research. In his subsequent work he has made important advances in our understanding of functional lateralization in the brain and how the cerebral hemispheres communicate with one another. He has published many books accessible to a lay audience, such as *The Social Brain*, *Mind Matters*, *Nature's Mind,* and *The Ethical Brain*. These, along with his participation in several public television specials have been instrumental in making information about brain function generally accessible to the public. Dr. Gazzaniga's teaching and mentoring career has included beginning and developing Centers for Cognitive Neuroscience at the University of California-Davis and at Dartmouth; supervising the work and encouraging the careers of many young scientists; and founding the Cognitive Neuroscience Institute and the *Journal of Cognitive Neuroscience*, of which he is the Editor-in-Chief Emeritus. Dr. Gazzaniga is also an advisor to various institutes involved in brain research, and is a member of the President's Council on Bioethics. He is a member of the American Academy of Arts and Science and the Institute of Medicine. His upcoming book is *Human: The Science Behind What Makes Us Unique*.

Scott Grafton, M.D., is Professor of Psychology and Director of the Brain Imaging Center at University of California at Santa Barbara. He received B.A.s in Mathematics and Psychobiology from the University of California at Santa Cruz and his M.D. degree from the University of Southern California. He completed a Neurology residency at the University of Washington and a residency in Nuclear Medicine at UCLA. He was a research fellow in Neuroimaging at UCLA where he developed methods for mapping human brain activity using positron emission tomography. He received tenure while at the University of Southern California. He subsequently held positions at Emory University and Dartmouth College, where he was director of the Brain Imaging Center. He joined the UCSB faculty in 2006. Professor Grafton is the author of more than 125 publications. He is action editor for the journal *NeuroImage* and is on the editorial board of *Annals of Neurology*, *Clinical Neurophysiology*,

and the *Journal of Cognitive Neuroscience*. He has been a member of the Board of Scientific Counselors of the NIH intramural branch and an NIH study section member.

Dr. Grafton's research is focused on understanding the neural underpinnings of goal-oriented action. This includes studies of skill acquisition, the development of expertise, observational learning, and the understanding the meaning of actions performed by others. These studies are relevant for understanding patients undergoing therapy to maintain or recover function in the setting of neurologic injury or degeneration and in understanding the normal development of complex human behavior.

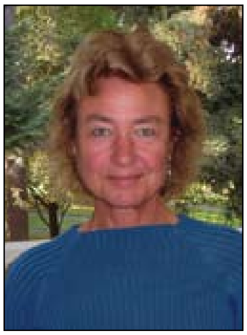


John Jonides, Ph.D., is the Daniel J. Weintraub Professor of Psychology and Neuroscience and co-director of the fMRI Center at the University of Michigan. Dr. Jonides has over 100 referreed publications as well as several edited and authored books. He is widely known for his research using behavioral and neuroimaging techniques studying mechanisms of executive processing and working memory.

For over 20 years, Dr. Jonides' research program has been concerned with understanding many aspects of working memory. Included in that program has been a substantial body of work, still ongoing, to chart the characteristics of information storage in working memory. Also included is more recent research concerning the mechanisms of executive processing, especially as this is reflected in processes involved in switching from one representation in memory to another and in processes used to resolve interference among alternative memory representations, including inhibitory processes. This program of research makes use of behavioral research on both normal and brain-injured humans as well as functional MRI and other imaging modalities as sources of data concerning the mechanisms of working memory.

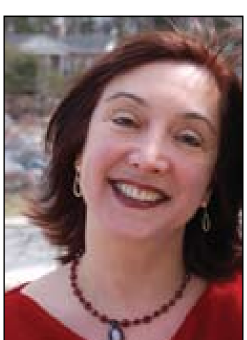
In addition to his research program, Professor Jonides has also been very active in the development and operation of research evaluation programs. In 1988, he developed a basic research funding program at the Air Force Office of Sponsored Research. In 1999, he was a leading figure in developing a new funding program in cognitive neuroscience for the National Science Foundation. He has also served for NSF as a panel member, he has served on four NIH study sections, and he currently chairs a study section for NIH.

Jessica Kieras, Ph.D., received her doctorate in 2006 from Oregon with Mary Rothbart as her committee chair. Her doctoral thesis concerned the influence of motivation on children's attention.



Helen J. Neville, Ph.D., was awarded the B.A. degree from the University of British Columbia, an M.A. from Simon Fraser University and Ph.D. from Cornell University. Her postdoctoral training was at the University of California, San Diego in the Department of Neurosciences. Her major research interests are the biological constraints and the role of experience in neurosensory and neurocognitive development in humans. Methods include behavioral measures and event-related brain potentials (ERPs), and structural and functional magnetic resonance imaging (fMRI). Her work experience includes Director of the Laboratory for Neuropsychology at the Salk Institute and Professor, Department of Cognitive Science, UCSD.

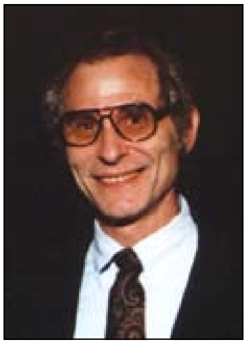
Dr. Neville is currently The Robert and Beverly Lewis Endowed Chair and Professor of Psychology and Neuroscience, Director of the Brain Development Lab, and Director of the Center for Cognitive Neuroscience at the University of Oregon in Eugene. She has published in many books and journals including *Nature, Nature Neuroscience, Journal of Neuroscience, Journal of Cognitive Neuroscience, Cerebral Cortex* and *Brain Research.* She has received many honors including being elected to the American Academy of Arts and Sciences, is a member of the Board of Governors of the Cognitive Neuroscience Society, the Academic Panel of Birth to Three, and is active in many educational outreach programs.



Laura-Ann Petitto, Ed.D., is a cognitive neuroscientist in the Department of Psychology at University of Toronto. She is full Professor and "Director and Senior Scientist" in The Genes, Mind, and fNIRS Brain Imaging Laboratory for Language, Bilingualism, & Child Development at the University of Toronto Scarborough, and she is a full Professor in the Graduate Studies Program at the University of Toronto, St. George. Dr. Petitto is known for her work on the biological bases of language, especially involving early language acquisition. Her studies of this topic span 30 years, beginning in 1973 with her seminal research at Columbia University in which she attempted to teach sign language to a baby chimpanzee ("Project Nim Chimpsky"). More recently, she is known for her discoveries

concerning how young human children acquire natural language. Taken together, her research points to the existence of specific tissue in the human brain that helps young babies learn language. Presently, Dr. Petitto studies early language development, especially early childhood bilingual language acquisition, using a revolutionary combination of three disciplines: Genetic analyses (polymorphisms in candidate genes and microchip arrays), Behavioral measures of higher cognitive processes from Psycholinguistics and Developmental Science, and a powerful new brain imaging technology, called functional Near Infrared Spectroscopy (fNIRS). Indeed, Petitto's Laboratory is among only a handful in the world who are pioneering the use of these three disciplines under one roof for the study of early brain development, as well as for the very early detection of brain and language disorders. Her new studies of young bilinguals seek to advance our understanding of the biological foundations of bilingualism, when best to expose young bilinguals to their dual languages, how optimal bilingual language acquisition develops, and, crucially, how and when best to teach young bilinguals to read in each of their two languages. Further, these studies have allowed her to explore different reading and teaching techniques with young bilinguals across different types of reading programs (e.g., phonics versus whole word). Petitto has won continuous (non-interrupted) federal and/or foundation funding for her research for the past 25 years. Recently, she is the recipient of significant federal grants from the National Institutes of Health, including both a 5-year research operating grant (R01) and significant funding for her "innovations to science and technology" (R21) to support her pioneering research using fNIRS brain imaging. Most recently, she was awarded a highly esteemed award from the Canadian Foundation for Innovation, involving very significant funding to establish her Genes, Mind, and Brain research laboratory, the first of its kind in the country of Canada. Other recent significant foundation funding includes grants from The Dana Foundation Arts and Cognition Cosortium Study, (2004-2007) and The Spencer Foundation (Major Research Grant, 2000-2003). Petitto received her Masters and Doctoral degrees from Harvard University in 1981 and 1984 (respectively) and built a vibrant laboratory in Cognitive Neuroscience at McGill University (1983-2001; Montreal) and at Dartmouth College (2001-2007) before moving to the University of Toronto in Fall 2007. She is the recipient of over twenty international prizes and awards for her

scientific achievements, including the 1998 Guggenheim Award for her "unusually distinguished achievements in the past and exceptional promise for future accomplishment" in the discipline of Neuroscience.

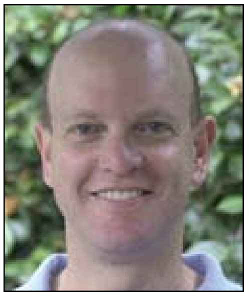


Michael Posner, Ph.D., is currently Professor Emeritus at the University of Oregon and Adjunct Professor of Psychology in Psychiatry at the Weill Medical College of Cornell, where he served as founding director of the Sackler Institute. Posner is best known for his work with Marcus Raichle on imaging the human brain during cognitive tasks. He has worked on the anatomy, circuitry, development and genetics of three attentional networks underlying alertness, orienting and voluntary control of thoughts and ideas. His methods for measuring these networks have been applied to neurological, psychiatric and developmental disorders. His current research involves training of attention in young children to understand the interaction of specific experience and genes in shaping attention. He worked for three years conducting research on the Dana Arts and Cognition Consortium.

Mary K. Rothbart, Ph.D., is a Distinguished Professor Emerita at the University of Oregon. She studies temperamental, emotional and social development, and for the last 25 years has worked with Michael Posner studying the development of attention and its relation to temperamental effortful control. She co-edited the book *Temperament in Childhood*, wrote *Attention in Early Development* with Holly Ruff, and with Michael Posner wrote *Educating the Human Brain*. She has contributed to the education and support of new parents through the Birth to Three organization in Eugene, Oregon. In 2006 she was honored by that group as a "Champion of Children." She and Posner worked together on the Dana Arts Consortium.

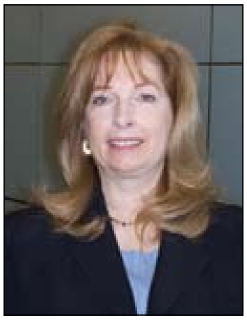
Brad Sheese, Ph.D., is currently Assistant Professor of Psychology at Illinois Wesleyan University. He spent three years as a postdoc at the University of Oregon working with Posner and Rothbart.

Elizabeth S. Spelke, Ph.D., teaches at Harvard University, Cambridge, Massachusetts, where she is the Marshall L. Berkman Professor of Psychology and co-director of the Mind, Brain, and Behavior Initiative. She studied at Harvard and Yale and received her Ph.D. in Psychology from Cornell University in 1978. She studies the origins and nature of knowledge of objects, persons, space, and numbers through research on human infants, children, human adults in diverse cultures, and nonhuman animals. Author of more than 100 research articles, she is a member of the National Academy of Sciences and the American Academy of Arts and Sciences, and a fellow of the American Association for the Advancement of Science. Her honors include the Distinguished Scientific Contribution Award of the American Psychological Association, the William James Award of the American Psychological Society, the IPSEN award in Neuronal Plasticity, and honorary degrees from the University of Umea, Sweden, the Ecole Practique des Hautes Etudes, Paris, and the University of Paris-Rene Descartes.



Brian A. Wandell, Ph.D., is the first Isaac and Madeline Stein Family Professor. He joined the Stanford faculty in 1979 where he is Chair of Psychology and a member, by courtesy, of Electrical Engineering and Radiology. His research projects center on how we see, spanning topics from visual disorders, reading development in children, to digital imaging devices and algorithms. He is the author of the textbook, *Foundations of Vision*. Among various awards and prizes, Wandell was elected to the US National Academy of Sciences in 2003.

The Editors



Carolyn Asbury, ScM.P.H., Ph.D., is a consultant to the Dana Foundation, advising on neuroscience and immunology grant programs and on related Dana publications. She trained in public health at The Johns Hopkins Bloomberg School of Public Health, and in health hystems sciences at the University of Pennsylvania. She is a senior fellow at the University of Pennsylvania's Leonard Davis Institute (LDI). Prior to consulting with Dana, Dr. Asbury developed grant programs, many of them focused on neurological diseases and cognitive neuroscience, at the Robert Wood Johnson Foundation, and was a director of the Pew Charitable Trusts' Health and Human Services division.

Her research, conducted at the LDI, concerns orphan (medically important but commercially unattractive) drugs. She consulted on the Orphan Drug Act, which provides for market incentives and regulatory guidance for rare disease products, and is the author of a book, book chapters, and numerous scientific articles on orphan drugs. She serves on several non-profit boards, including the U.S. Pharmacopeia, and is a fellow of the College of Physicians of Philadelphia, and chair of the College's Public Health Section.

Barbara Rich, Ed.D., a vice president at the Dana Foundation, is responsible for the News and Internet Office and helps oversee arts education at the Foundation. Rich was a co-editor of *Transforming Arts Teaching: The Role of Higher Education*; *Acts of Achievement: The Role of Performing Arts Centers in Education*; and editor of *Partnering Arts Education: A Working Model from Arts Connection*.

Dr. Rich's background in communications and education includes posts at Rutgers University and Marymount Manhattan College, where she was dean and then a vice president. She was senior vice president at the Scientists' Institute for Public Information (SIPI) prior to joining the Dana Foundation.

She has published articles on science and education and has often served as a discussant on both media and arts education. She earned a B.A. from City College of New York, M.A.s from Rutgers University and Teacher's College, Columbia University, and an Ed.D. from Teachers College, Columbia University

Acknowledgements

In addition to the work on this 3-year study by Professor Gazzaniga and the neuroscientists and scientific researchers whose biographies and acknowledgments are included herein, The Dana Foundation and editors Carolyn Asbury and Barbara Rich would like to thank Alexandra Gazzaniga, Jayne Rosenblatt, as well as our following colleagues in New York, Los Angeles and D.C. for their work on this publication: Dr. Guy McKhann, senior scientific consultant; Jane Nevins, editor in chief, and Dan Gordon, managing editor of the Dana Press; Janet Eilber, Dana's Director of Arts Education; Leticia Barnes, Johanna Goldberg, Kenneth Krattenmaker, Rebecca Luib, Tyler Ostrander, Carrie Rubinstein, William Stilwell, Isaac Sashitsky and Ann Whitman.

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