The Influence of Instruction Modality on Brain Activation in Teenagers With Nonverbal Learning Disabilities: Two Case Histories

Betty Tuller, Kelly J. Jantzen, Dianne Olvera, Fred Steinberg, and J. A. Scott Kelso

Abstract

Teenagers with nonverbal learning disabilities (NLD) have difficulty with fine-motor coordination, which may relate to the novelty of the task or the lack of "self-talk" to mediate action. In this study, we required two teenagers with NLD and two control group teenagers to touch the thumb of each hand firmly and accurately to the fingertips of the same hand, in an order specified by verbal or tactile instruction. Brain activity patterns (measured using functional magnetic resonance imaging) suggest that unlike control participants, the NLD participants used internalized speech to facilitate the novel task only when instructions were verbal. NLD participants also showed activity in a more widely distributed network of neural structures. These findings provide preliminary evidence for remediation strategies that encourage internal speech.

Myklebust (1975) coined the term nonverbal learning disability (NLD) to describe youngsters who are verbally astute but have a wide variety of nonverbal deficits. Nonverbal learning disabilities are less understood than language-based learning disabilities such as dyslexia. In fact, NLD does not appear in any accepted diagnostic nosology; in the fourth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV; American Psychiatric Association, 1994), it retains the category of Learning Disorder Not Otherwise Specified. The purpose of this study is to shed more light on the underlying processing disorder in NLD in hopes of informing remedial strategies.

On the basis of extensive study, Rourke (1987, 1988a, 1988b, 1989, 1991, 1993, 1995a, 1995b, 2000, 2005) and colleagues (Pelletier, Ahmad, & Rourke, 2001; Rourke et al., 2002; Rourke & Conway, 1997) described NLD as being characterized by primary deficits in tactile perception, visual perception, complex psychomotor skills, and the ability to deal with novel circumstances. Secondary deficits may occur in tactile and visual attention and significant limitations in exploratory behavior. Tertiary deficits noted have affected tactile and visual memory, concept formation, problem solving, and hypothesis testing skills. Finally, these deficits may result in significant abstract language difficulties. In the early school years, children with NLD often go undiagnosed because their strong verbal abilities tend to facilitate basic reading and writing activities. Nevertheless, these children's spatial and coordination problems progressively and adversely affect their school performance and daily life. Of particular difficulty are tasks that depend on an appreciation of spatial relations, such as coordinating motor activities, telling time, or orienting work with respect to the page (e.g., O. M. Thompson, 1985; S. Thompson, 1996). Of particular difficulty are mathematics and other subjects that involve higher-order and abstract processing of information. Given the verbose nature of these students, one would anticipate that they would naturally involve language as a means of processing novel or more abstract information. Hence, the present study was designed to determine if teenagers who were diagnosed with NLD based on Pelletier et al.'s (2001) classification rules used internal verbal mediation as a means of facilitating a novel fine motor sequencing task.

The term nonverbal learning disorder has been applied to a wide array of syndromes, such as right hemisphere syndrome, left hemisphere syndrome, Asperger syndrome, developmental Gerstmann syndrome, and developmental right parietal lobe syndrome.
Nonverbal learning disabilities were defined neuropsychologically by a combination of scores on the Wechsler Adult Intelligence Scale—Revised (WAIS-R; Wechsler, 1981) or the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1991), depending on the person’s age and behavioral patterns (problems with fine motor coordination and tactile–perceptual and visuospatial skills, as well as other nonverbal problem-solving skills). Although most importance was given to a Full-Scale Verbal IQ score that is at least 10 points higher than the Performance IQ score (Casey, Rourke, & Picard, 1991; Gross-Tsur et al., 1995; Harnadek & Rourke, 1994; Rourke, 1987, 1988b, 2000; Rourke, Del Dotto, Rourke, & Casey, 1990; Rourke, Young, & Leenars, 1989; Shonkoff, 1997; Tranell et al., 1987), this pattern alone does not uniquely distinguish NLD—Children with Asperger syndrome also have a much higher Full-Scale Verbal IQ than Performance IQ (Klin, Volkmar, Sparrow, Cichetti, & Rourke, 1995; Critchley et al., 2000; Gunter, Ghaziuddin, & Ellis, 2002). Current research (Pelletier et al., 2001; Rourke et al., 2002) places less importance on the differential between Verbal IQ and Performance IQ and relies more on specific subtests that provide evidence of processing strengths and weaknesses. Included in Rourke et al.’s “Rules for Classifying Children” are specific determinants to delineate the neuropsychological assets and deficits of children with NLD, which we follow here.

In the present study, we were interested in defining how NLD teenagers’ characteristic difficulty with fine motor coordination interacts with their highly developed verbal skills. To this end, we used a bimanual finger–thumb opposition task in which the required sequencing was cued either by verbal or by tactile instruction. Dependent measures included the overall speed and accuracy of performance of the task and the local, task-related changes in blood oxygenation level (BOLD) revealed by using functional magnetic resonance imaging (fMRI). Given the deficits in fine-motor coordination and nonverbal skills characteristic of NLD, we expected the two NLD teenagers to have more difficulty with the task than the two matched control group participants. Moreover, we expected that the difficulty would be greater when the task description was based on nonverbal instruction. We also asked whether task-related changes in the BOLD response could be observed that correlated with any behavioral difficulties with nonverbal instruction.

Previous work in typical adults has used the BOLD response measured by fMRI to examine the effects of handedness, unimanual versus bimanual tasks, executed versus imagined tasks, difficulty of tasks, attentional and memory demands, and so on. Common to all these situations are the coordination of movements in both space and time and the engagement of memory systems that help maintain the correct ordering of components in complex, goal-directed sensorimotor tasks. Typically, sequenced movements of the fingers are positively correlated with fMRI signal intensity in precentral and postcentral gyri (Nair, Purcott, Fuchs, Steinberg, & Kelso, 2003; Porro et al., 1996) as well as in the cerebellum (Lottze et al., 1999; Nair et al., 2003). During bimanual tasks, as used here, significant activity correlated to the task is also noted in the supplementary motor area (SMA), pre-SMA, and cingulate motor areas (Dassonville et al., 1998; Deiber, Honda, Ibanez, Sadato, & Hallett, 1999; Jäncke, Himmelbach, Shah, & Zilles, 2000; Kim et al., 1993; Shibasaki et al., 1993). Furthermore, the superior parietal lobes are selectively activated in complex finger sequencing tasks (Nair et al., 2003; Wexler et al., 1997).

The extent of brain activation and the intensity of activation are also sensitive to movement task difficulty and memory demands. For both unimanual and bimanual tasks produced by typical participants, the area and intensity of brain activation increases with task complexity (Toyokura, Muro,
which has a well-documented role in
for finger sequencing tasks. A pattern has not been observed explic-
tively for finger sequencing tasks.

Given this extensive existing litera-
ture, we can make two predictions:
(a) NLD teenagers should show in-
creased activity in the motor sequenc-
ing network when compared with con-
trols, and (b) each NLD teenager
should show increased signal intensity
from those areas when instructions are
given spatially rather than verbally. If
the NLD teenagers are able to exploit
their verbal skills in overcoming diffi-
culties in producing finely coordinated
movements, it may be that they are
internally rehearsing the required se-
quence—that is, they are able to trans-
late a spatial instruction into a verbally
mediated strategy. Thus, a brain region
of particular interest is Broca's area,
which has a well-documented role in
inner speech (e.g., Baciu, Rubin,
Decors, & Segebarth, 1999; McGuire,
Silbersweig, Murray, et al., 1996; Mc-
Guire, Silbersweig, Wright, et al., 1996;
Smith, Jonides, Marshuetz, & Koepepe,
1998). Converging evidence comes
from case studies of patients who pre-
sent with a complete loss of inner
speech after destruction of the left
inferior frontal area from a stroke
(Levine, Calvano & Popovics, 1982).
Thus, examining activity in Broca's
area may be critical for identifying al-
ternative strategies employed by NLD
teenagers to compensate for difficul-
ties in coordinated motor tasks that are
instructed nonverbally. With respect to
the sequencing task used here, NLD
participants may be able to translate
verbal instructions into inner speech to
rehearse the required sequence but,
when instructions are tactile, may be
unable to use inner speech efficiently
to remember and guide the required
movement sequence.

A second reason for examining
Broca's area is its demonstrated role in
preparation (Krams, Rushworth, Dei-
ber, Frackowiak, & Passingham, 1998)
and imagery of arm movement trajec-
tories (Binkofski et al., 2000), albeit in
tasks that do not exclude the use of
inner speech. Activity in Broca's area
has not been reported during the pro-
duction of sequenced bimanual finger
movements in typical individuals—
a coordinated task that is fairly easy for
those people, especially after the se-
quence is produced a few times in suc-
cession. Examination of Broca's area
may also hint at whether mode of
instruction differentially affects NLD
teenagers' ability to image and prepare
the movement sequences, or actually
to produce them.

The question addressed here is
whether we can discern different
neural strategies linked to instruction
modality in typical participants and
whether these patterns are preserved
or disrupted in NLD. There are, to
date, few if any demonstrations of the
effects of modality of task instruction
on the neural patterns required to exe-
cute coordinated movement. This is
particularly important for a popula-
tion, such as individuals with NLD, in
which the mode of instruction plays a
large role in facilitating or obstructing
the performance of everyday tasks.

Method

Participants

Four individuals participated in the
study. Two of the participants, a 17-
year-old girl and a 15-year-old boy,
who had been diagnosed as having NLD
by a licensed neuropsychologist. The
other two participants had no known
learning disorder, performed well in
school, and were age- and gender-
matched to the NLD participants. All
of the participants were strongly right-
headed (by self-report). Because they
were minors, informed consent was
obtained from the participants and
their parents or legal guardians ac-
cording to the regulations of the insti-
tutional review board of Florida Atlan-
tic University. All of the participants
gave an MRI safety questionnaire
required by University MRI, where the
imaging was performed. None of the
participants reported any known neu-
rological damage or cardiovascular ill-
ness, and none was on medication at the
time of testing.

Each participant's NLD status
was evaluated using the neuropsy-
chologist's insights, the participant's
academic and developmental history,
and Pelletier et al.'s (2001) classifica-
tion rules for NLD (see Table 1). Al-
though the participants were referred
from a private practice prior to 2001, as
Pelletier et al. noted, Criteria 2, 3, and
4 (listed in Table 1) serve as a good
starting point for classifying an indi-
vidual as having NLD.

Female Participant With NLD
(NLD-F). The neuropsychologist's in-
sights were as follows: Picture Com-
pletion, Block Design, and Picture
Arrangement showed perceptual orga-
nizational difficulties. Visual percep-
tion, judgment, and reasoning prob-
lems led to missing important details
and problems reconstructing abstract
designs with blocks. Assessment notes
indicated that the participant hates
puzzles. She also attained a low score
in Picture Arrangement, indicating her
inability to sequence a series of mean-
ingful pictures to tell a logical story.
Developmental and academic notes in-
cluded the following: No head trauma.
Normal developmental milestones were
noted. In school, she has difficulties in
math and chemistry; both participants
require higher-level abstract reasoning.

Male Participant With NLD
(NLD-M). The neuropsychologist's in-
sights were as follows: Picture Com-
pletion, Block Design, and Object As-
sembly showed perceptual organiza-
tional difficulties. Visual perception,
judgment, and reasoning problems led
to missing important details and dif-


difficulty reconstructing abstract designs with blocks. Assessment notes indicated that the teen was impulsive when answering test questions and also had difficulty self-monitoring his work. His judgment and insight were also considered “fair” during the testing process. Developmental and academic notes involved the following: No head trauma. Normal developmental milestones. His mother noted that in math, her son forgets what he had studied the day before.

Criteria

Both NLD participants met Pelletier et al.’s (2001) Criteria 2, 3, 4, and 8 (see Table 2 for more complete subtest results). For Criterion 2, the standard score for Reading on the Wide Range Achievement Test (WRAT; Jastak & Jastak, 1978)/Wide Range Achievement Test–Revised (WRAT-R; Jastak, Wilkinson, & Jastak, 1984) was at least 8 points higher than the Arithmetic score. Scores were as follows: NLD-F, Spelling 94th percentile, Math 41st percentile (Comprehensive Test of Basic Skills; CTB, 1996); NLD-M, Reading 78th percentile, Math 55th percentile (Stanford Achievement Test, 9th ed.; Harcourt Assessment, 1996). For Criterion 3, at least two of the WISC/WISC-R sub-scales Vocabulary, Similarities, and Information had to yield the highest scores of the Verbal IQ scale. Scores were as follows: NLD-F, Vocabulary = 11, Similarities = 14, Information = 10; NLD-M, Vocabulary = 12, Similarities = 14, Information = 14. For Criterion 4, at least two of the WISC/WISC-R sub-scales Block Design, Object Assembly, and Coding had to be the lowest of the Performance IQ scale. Scores were as follows: NLD-F, Block Design = 7 (Picture Completion = 7; Picture Arrangement = 7); NLD-M, Block Design = 8, Object Assembly = 4. Criterion 8 was that WISC/WISC-R Verbal IQ should exceed Performance IQ by at least 10 points. Scores were as follows: NLD-F, Verbal IQ = 106, Performance IQ = 94 (12-point difference); NLD-M, Verbal IQ = 114, Performance IQ = 93 (21-point difference). Thus the participants were classified as having NLD using a convergent pattern of Pelletier et al.’s (2001) criteria, with neuropsychological evaluation and assessment, academic and developmental history.

Procedure

The experiment consisted of two identical conditions, differing only in mode of instruction (verbal vs. tactile) and in the particular order of the finger movements defining each sequence. In both conditions, the participant’s task was to touch the thumb of each hand firmly and accurately with the fingertip of the same hand, in an order specified by the experimenter. Participants were told to perform the task with both hands in a continuous fashion, at the fastest rate at which they could maintain the accuracy of the order. In the first condition (tactile), the experimenter cued the movement sequence by squeezing the tips of the participant’s fingers in the required (pseudo-random) order; care was taken so that the experimenter did not verbalize during this tactile instruction phase. Two complete cycles of the sequence order were demonstrated to the student before entering the scanning instrument. In the second condition (verbal), participants were told to associate each finger with a number as follows: 1 is the index finger, 2 is the middle finger, 3 the ring finger, and 4 the little finger. The participant was then told a numeric order to follow. The experimenter spoke two complete cycles of the required sequence order (e.g., “1, 3, 4, 2, 1, 3, 4, 2”), while taking care not to touch the participant’s fingers.

A block design was employed, in which a participant lay in the scanner while performing the sequenced movements for four 30-second movement intervals for the tactile instruction condition, then four 30-second intervals for the verbal instruction condition. A 30-second rest segment preceded each movement cycle. The tactile condition was always performed first to guard against suggesting a verbal labeling strategy for the tactile condition. The instructions for the verbal condition were given after the participant completed the tactile condition. No practice trials were included to en-
sure the novelty of each task and to guard against biasing participants to use verbal mediation.

Participants kept their eyes closed during the entire experiment and were instructed to concentrate on the task, opposing fingers to thumb as fast, firmly, and accurately as possible. They held their hands in a semiprone position by their side. Because it was not possible to record the movements for later analysis, two experimenters were always in the imaging room and were able to see the participant's finger movements at all times. Both experimenters monitored movement speed and sequence accuracy, and their notes were compared offline. Interrater agreement with respect to the accuracy of the produced sequences was 98%; recorded average times for a cycle of four movements were within 1 second of each other (the resolution of the timer on the scanner) for 100% of trials.

### Image Acquisition Protocol
Each participant was placed supine on the scanner bed with his or her head fixed by foam supports and a head strap. Task-related changes in neural activity were determined by measurement of changes in local blood oxygenation (BOLD effect) using echo planar imaging on a 1.5-Tesla GE Signa Scanner equipped with real-time fMRI capabilities (General Electric Medical Systems, Milwaukee, WI). Echo-planar images were acquired using a single-shot, gradient-echo, echo-planar pulse sequence, echo time (TE) = 40 ms, flip angle (FA) = 90°, field of view (FOV) = 24 cm, matrix size = 64 x 64. Twenty axial 5-mm-thick slices spaced 2.5 mm apart were selected so as to provide coverage of the entire brain every three seconds (TR = 3 s; voxel size = 3.75 x 3.75 x 7.5 mm). Prior to functional imaging, high-resolution anatomical spoiled gradient-recalled at steady state (SPGR) images (TE = in phase, TR = 325 ms, FA = 90°, FOV = 24 cm, 5-mm thickness, 2.5-mm spacing, number of excitations = 2) were collected at the same slice locations as the functional images. These images served as the background onto which the functional information was displayed and were also used to coregister the functional scans onto anatomical three-dimensional SPGR axial images (TE = 5 ms; TR = 34 ms; FA = 45°, FOV = 24 cm; resolution = 256 x 256; thickness = 2 mm) collected at the end of each experimental session. In the block design employed, 10 images/location were collected during each 30-second rest or movement interval.

### Neuroimaging Analysis
MRI and fMRI images were evaluated using Analysis of Functional NeuroImages (AFNI; Cox, 1996; Cox & Hyde, 1997) for analysis and display. SPM99 (Statistical Parametric Mapping, Wellcome Department of Cognitive Neurology, London) was used only for coregistration of the high-resolution background (anatomical) images with the functional images, allowing for more accurate identification of the anatomical structures associated with functional activation. Preprocessing with AFNI included motion detection and correction followed by spatial smoothing by convolution with a Gaussian kernel (FWHM 4 mm) and temporal filtering below 0.1 Hz. Task-related activity was determined by correlating the time series of each voxel with a boxcar reference function (30 s off, 30 s on) that corresponded to the rest–movement cycle of the task but was temporally shifted by 6 s to account for the delay in the hemodynamic response.

All analyses were performed on individual participant data—there was no transformation into a standard coordinate space (e.g., Talairach & Tournoix, 1988) and no intersubject averaging. To facilitate visual comparison among participants, each participant’s data were reoriented in their individual AC-PC aligned space. A neuroradiologist helped to identify regions in the individual brains where significant task-related activity was noted. Comparisons of BOLD activity were performed for individual participants by first normalizing the correlation statistic $r$ for each voxel using Fisher’s $r$ to $z$ transform. At each voxel, the differences between $z$ scores were compared across the tactile and verbal conditions. Corrected significance values of $p < .004$ were obtained for the correlations within individual instruction conditions by three-dimensional clustering with a radius of 5.4 voxels and using a cutoff value of .423 ($p < .0001$, uncorrected). The $z$-score difference between conditions was clustered with a radius of 2.7, resulting in corrected significance values of $p < .01$.

### Results

#### Behavior

Both NLD participants and the matched controls completed each cycle of four movements within 2 s, given either tactile or verbal instruction. However, both observers noted that the NLD participants’ movements were less con-
tinuous and fluid, with multiple sequencing errors that were twice as frequent with tactile instruction than with verbal instruction (34% vs. 17%). Sequencing errors were almost entirely absent from the controls' performance (2%).

**Functional Imaging**

Areas of significant differences in task-related activity between tactile and verbal instruction conditions were identified for each NLD participant. As predicted, higher signal intensity was observed across a broad range of areas when instructions were given tactiley instead of verbally. The one exception was in Broca's area, where higher signal intensity was observed with verbal instruction. For this reason, we will discuss changes in Broca's area separately from task-related changes in other brain areas. For comparison with controls, we identified the closest analogous brain slices in the controls by a combination of locating the same z-axis value relative to the AC-PC line as for the age- and sex-matched NLD participant and by visual inspection.

**NLD Participants.** Figures 1 and 2 show areas (excluding Broca's area) in which the time series of the BOLD responses were significantly correlated with the task–rest cycle, superimposed on the high-resolution structural image. The leftmost column is taken from the tactile instruction condition, the middle column from the verbal instruction condition, and the rightmost column, labeled “tactile-verbal,” shows the difference in the z-transformed correlation of neural activity with movements across the two instruction conditions. As can be seen from Figures 1 (NLD girl) and 2 (NLD boy), both NLD teenagers showed significant task-related activity in bilateral primary sensorimotor cortex (SI/MI), dorsolateral premotor cortex (DLPFC), pre-supplementary motor area (pre-SMA), superior and inferior parietal lobes (SPL and IPL, respectively), and the cerebellum in at least one, if not both, instruction conditions. Interestingly, the supplementary motor area proper (SMA) was active only for the NLD girl and then only in the tactile condition.

Analysis of the z-score differences between instruction conditions for each participant reveals that without exception, differences in brain activity are such that movements based on tactile instructions result in greater signal intensity than those based on verbal instructions (the rightmost column in Figures 1 and 2). The female NLD teenager showed higher activation with tactile instruction in pre-SMA (y = -13), and the male NLD teenager showed a nonsignificant trend in the same direction (y = -6). Both NLD teens also showed higher signal intensity with tactile instructions in the right dorsolateral premotor area, the superior parietal lobe (in the right hemisphere, RH, for the girl and the left hemisphere, LH, for the boy), and postcentral gyrus (bilateral for the girl and LH for the boy). The NLD girl also showed higher activation in the right inferior parietal lobe, bilateral postcentral sulcus, right prefrontal gyrus, right caudate, and right cerebellum (culmen) during movements that are instructed via tactile rather than verbal means. The NLD boy showed higher
activation in bilateral sensorimotor cortex and the left cerebellum (tonsil).

Control Participants. Both controls showed within-task correlated activity that was extremely similar across instruction modality (see Figures 3 and 4). For the female control, bilateral sensorimotor cortices and the left culmen were significantly correlated with the movements after tactile instruction (see Figure 3). After verbal instruction, only the culmen was no longer correlated with movement epochs. For the male control, bilateral primary sensorimotor cortices, SMA, pre-SMA, superior parietal lobules, and broad areas of the cerebellum were correlated with the movement epochs after both instruction methods (see Figure 4). More important, analysis of the z-score differences between instruction conditions resulted in no significant differences in task-related brain activity across the two instruction modalities (Figure 4, right column).

Discussion

A well-described network of cortical and subcortical areas supports the memory, spatial, coordination, and timing demands of performing sequenced movements of the fingers of both hands in a predetermined order. In the present study, we examined individual participant’s task-related alterations in brain activity patterns when instructions were either tactile or verbal. Two teenagers without NLD showed expected patterns of brain activity when performing the motor sequencing task, including task-related activation in pre- and postcentral gyri, SMA, inferior parietal lobules, and cerebellum. One suggestive finding is that both male participants, but not the female participants, showed strong activation of superior parietal lobules bilaterally in the verbal instruction condition. Although with only two case studies and two controls one can draw no conclu-
sions on this matter, this apparent sex-related difference in neural patterning is worth pursuing in further research, given the general superiority of young women on tasks of fine motor coordination and on tests of verbal skills and the known association of parietal activity with spatial tasks. That is, one possibility is that the verbally instructed task is relatively more difficult for male teenagers than for female teenagers, both with and without NLD. The positive correlation between parietal cortex activation and task difficulty observed by Wexler et al. (1997) supports this hypothesis.

A primary difference between the two controls and the two teenagers diagnosed with NLD was that for controls, recruitment of brain areas was unaffected by the instruction mode. For both NLD teenagers, on the other hand, several brain areas were recruited to different degrees depending on the mode of instruction. For the tactile instruction condition, in which they made noticeable sequencing errors, higher activation was observed in SMA/pre-SMA, pre- and postcentral gyri, superior parietal cortex, ventral premotor and premotor (middle frontal gyrus) areas, and the cerebellum (especially the culmen). Moreover, the NLD girl showed higher activation in bilateral inferior parietal lobules, the insula, and caudate. These areas are known to increase activity in typical individuals with the difficulty of the motor task (Meyer-Lindenberg, Ziemann, Hajak, Cohen, & Berman, 2002; Nair et al., 2003; Wexler et al., 1997). Earlier work also suggested that SMA is involved in the planning and preparation of action sequences (Stephan et al., 1995), and superior parietal cortex is preferentially engaged when the task involves memory and execution of sequentially ordered components (Crammond, 1997; Jeannerod, 1994; Jeannerod & Decety, 1995; Wexler et al., 1997). Thus, tactile instruction may well increase the difficulty of a fine motor sequencing task for NLD teenagers, perhaps by demanding relatively greater effort or attention on the part of NLD participants when the task is not verbally mediated.

An intriguing pattern is the differential activation of Broca’s area for control and NLD participants. The role of Broca’s area in imagining one’s own speech, also called “inner speech,” is well documented (e.g., McGuire, Silbersweig, Murray, et al., 1996; McGuire, Silbersweig, Wright, et al., 1996). Although Broca’s area is not typically identified as active during the performance or the imagination of sequencing tasks (Nair et al., 2003), it has been shown to be recruited when movements are made sufficiently difficult (Meyer-Lindenberg et al., 2002). Neither of the controls demonstrated activity within Broca’s area during the sequencing tasks, regardless of the instruction method used. This indicates that for these participants, inner speech is likely to be unnecessary in the current task, especially after the first few movement cycles, because the task is quite easy for them. This suggestion is consistent with the dearth of sequencing errors observed for the controls (< 2%).

In contrast, both NLD participants showed a significant increase in activity within Broca’s area during motor sequencing when the task was verbally instructed rather than when tactile instructions were provided. This suggests that NLD participants may be

FIGURE 3. Control female participant: The closest analogous brain slices to those shown for the female participant in Figure 1 (see text).
using explicit verbal information to rehearse the required sequence silently. Although this is only supposition, it converges with the activation of both Broca's area and SMA in the NLD participants. SMA has been shown to be active during subvocalization in the general population (e.g., Kawashima et al., 2000). However, the NLD participants seemed less able to use inner speech as an aid to remember and guide the required movement sequence when explicit verbal instruction was unavailable. Despite this, it appears that there may still be an attempt to adopt a verbal strategy by recruiting areas involved in aspects of language processing. For example, adults and children older than age 7 years show activation in SMA and left premotor areas during a covert semantic fluency task (Gaillard et al., 2003) and during silent articulation (Kawashima et al., 2000), the same areas activated during silent reading (McGuire, Silbersweig, Wright, et al., 1996). Moreover, the left medial frontal gyrus is active during verbal working memory tasks (e.g., Gabrieli, Poldrack, & Desmond, 1998), as is SMA (Smith et al., 1998). These same areas showed task-related activity for the two NLD participants, suggesting that verbally mediated strategies are attempted to some extent even with tactile instruction. However, if these strategies were used, they were not sufficient to reduce the errors in the participants' behavior. Together, these results suggest that teenagers with NLD may use verbal information when available to make the task easier. When verbal information was not available, an increase in the number of movement errors was accompanied by increased activation in the neural network recruited. For example, the engagement of the superior parietal lobule with tactile instruction may be related to the increased attention and memory resources associated, in the present instance, with coordinating difficult bimanual sequences in the absence of language-mediated information. These results, while preliminary, may have potential implications for diagnosis: People with NLD are often labeled as having high-level autism, Asperger syndrome, or attention-deficit disorder, among other syndromes, because the behavioral descriptions overlap considerably. Investigating the brain activity patterns during carefully constructed tasks may eventually help refine differential diagnosis. Another extremely important aim is to examine people with NLD before and after behavioral intervention strategies to determine whether the strategy used has in fact changed the mode of operation of the underlying neural networks (e.g., Temple et al., 2000, 2001). The present study provides suggestive physiological clues in two case studies for why verbally targeted remediation strategies may prove effective and underscores the potential of combining neuropsychological testing with non-invasive measurement of neural activity patterns.

ABOUT THE AUTHORS

Betty Tuller, PhD, is a professor of complex systems and brain sciences and professor of psychology at Florida Atlantic University (FAU). Her research focuses on phonological learning in adults and extensions into learning disorders. Kelly J. Jantzen, PhD, is an assistant research professor in the Center for Complex Systems and Brain Sciences at FAU. His research uses functional magnetic resonance imaging to understand complex behavior and cognition in terms of large-scale neural dynamics for both healthy and brain damaged individuals. Dianne Olvera, PhD, is a part-time professor in the Education and English departments at California Polytechnic State University. She also is an educational therapist and has a private office in Pismo Beach, California. Her interests focus on learning disabilities and language processing in students who have been diagnosed with autism spectrum disorders and
learning problems. Fred Steinberg, MD, is a research professor in the Center for Complex Systems and Brain Sciences at FAU. He is the medical director of University MRI and Diagnostic Imaging Centers in Boca Raton, Florida. His research interests include clinical applications of functional magnetic resonance imaging and applications of magnetic resonance imaging to neuroimaging. A. Scott Kelso, PhD, holds the Glenwood and Martha Creech Chair in Science at FAU. His current research uses brain imaging technologies and the conceptual framework of coordination dynamics to understand how humans learn and interact socially and how the brain recovers function after traumatic brain injury. Address: Betty Tuller, Complex Systems and Brain Sciences, Florida Atlantic University, 777 Glades Road, Boca Raton FL 33431; e-mail: tuller@ccs.fau.edu

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TITLE: The Influence of Instruction Modality on Brain Activation in Teenagers With Nonverbal Learning Disabilities: Two Case Histories
SOURCE: J Learn Disabil 40 no4 Jl/Ag 2007

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