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The Effects of Age and Sex on Mental Rotation Performance, Verbal Performance, and Brain Electrical Activity

Received 10 July 2001; Accepted 15 November 2001

ABSTRACT: *This study examined the effects of age and sex on mental rotation performance, verbal performance, and brain-wave activity. Thirty-two 8-year-olds (16 boys) and 32 college students (16 men) had EEG recorded at baseline and while performing four computerized tasks: a two-dimensional (2D) gingerbread man mental rotation, a 2D alphanumeric mental rotation, of three-dimensional (3D) basketball player mental rotation, and lexical decision making. Additionally, participants completed a paper- and pencil water level task and an oral verbal fluency task. On the 2D alphanumeric and 3D basketball player mental rotation tasks, men performed better than boys, but the performance of women and girls did not differ. On the water level task, men performed better than women whereas there was no difference between boys and girls. No sex differences were found on the 2D gingerbread man mental rotation, lexical decision-making, and verbal fluency tasks. EEG analyses indicated that men exhibited left posterior temporal activation during the 2D alphanumeric task and that men and boys both exhibited greater left parietal activation than women and girls during the 2D gingerbread man task. On the 3D basketball player mental rotation task, all participants exhibited greater activation of the right parietal area than the left parietal area. These data give insight into the brain activity and cognitive development changes that occur between childhood and adulthood.* Dev Psychobiol 40: 391–407, 2002. Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/dev.10039

Keywords: *sex difference; EEG; mental rotation; verbal fluency*

Since the seminal publication *The Psychology of Sex Differences* by Maccoby and Jacklin (1974), the existence of sex differences on cognitive tasks has been staunchly debated. These authors stated that there are sex differences on spatial and verbal tasks. In the case of spatial differences, Maccoby and Jacklin suggested that there were no sex differences until adolescence, whereupon boys gained an advantage that continued through adulthood. In the case of verbal differences, Maccoby and Jacklin suggested that before approximately 3 years of age girls developed more quickly than boys and had better verbal skills. From 3 years until adolescence, boys caught up and there were no sex differences, and then from adolescence into adulthood females again were better than males in verbal skills. Soon after the Maccoby and Jacklin publication, many studies were published both supporting and rejecting the existence of these differences. However, the results of recent meta-analyses have

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documented that, in adult populations, there is an overall male advantage on spatial tasks and an overall female advantage on verbal tasks (Hyde & Linn, 1988; Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995). Researchers using mental rotation tasks and electrophysiological measures have reported that there are brain-activation differences between men and women, but not boys and girls, during task performance (Roberts & Bell, 2000b). The purpose of this study was to examine the relations among spatial ability, verbal ability, and EEG activity in children and college students.

Spatial ability can be generally defined as the skills of generating, transforming, representing, and recalling symbolic, nonlinguistic information (Linn & Petersen, 1985). Although there are numerous individual tasks used to test spatial ability, meta-analyses have concluded that two types of spatial tasks show the most reliable male advantage: mental rotation tasks and spatial perception tasks (Linn & Petersen, 1985; Voyer et al., 1995). *Mental rotation* tasks are broadly characterized as exercises that require the mental repositioning of a two dimensional (2D) or three dimensional (3D) object. Specifically, participants are typically presented with an object that is to be turned in the imagination and matched with one of two or more choices. *Spatial perception* tasks require participants to determine spatial relationships despite distracting information. The classic example of a spatial perception task is Piaget and Inhelder's (1956) water level task (WLT), which requires participants to draw a water line in a glass that is tilted to various degrees.

In adult populations (over the age of 18), the effect sizes for sex differences on tasks of mental rotation ($d = 0.66$; Voyer et al., 1995) and spatial perception ($d = 0.48$; Voyer et al., 1995) are considered the most robust and consistent. Among boys and girls, however, sex differences on such tasks have been less consistently found (Voyer et al., 1995). In the Voyer et al., study, the effect size was calculated for children under the age of 13 (mental rotation, $d = 0.33$; spatial perception, $d = 0.33$). Because children's effect sizes are considerably smaller than those of adults, these data suggest that sex differences on spatial tasks are more reliable in adults.

Verbal ability also has been studied using many different types of tasks. Meta-analyses have concluded that the area of verbal ability with the greatest female advantage is that of speech production (Hyde & Linn, 1988). One specific task in the speech production category is the *verbal fluency* task, in which participants are required to produce words that belong to a specific category in a specific time period. For example, participants may be asked to produce as many words as possible starting with the letter *S* in a 60-s time period. Another method to assess speech production is the *lexical decision-making* task, in which participants are asked to look at a group of letters and determine if the group is a word. For example, "roop" and "room" may be presented, and the participant is required to determine which of the two is actually a word. Sex differences in speech production are the most documented female-advantage sex difference, and Hyde and Linn (1988) concluded that the effect sizes were larger for adults over 19 years of age ($d = 0.45$) than when children and adults were combined ($d = 0.33$). Again, this suggests that the sex difference is more reliable in adult populations.

Because sex differences on mental rotation and verbal fluency appear to develop between childhood and adulthood, an interesting avenue of exploration is to examine possible differences in brain activity that may accompany the sex differences in behavior. For instance, if we know that adults exhibit a sex difference on a specific task and also have accompanying differences in brain activity during task performance, but children exhibit neither the sex difference nor the brain-activity difference, then an interesting line of research would be to determine at what point the sex difference and the accompanying brain differences emerge. However, there are no studies in the literature examining sex differences and accompanying differences in brain activity using both children and adults and both spatial and verbal tasks.

MENTAL ROTATION: BRAIN LOCALIZATION

Researchers using EEG procedures as well as other brain measures have found activation of the right parietal lobe during complex spatial tasks. For example, when research participants completed psychometrically matched verbal and spatial cognitive tasks, the verbal task produced more left central 8- to -13 Hz EEG suppression than right central suppression (indicating left central activation), and the spatial task produced more right parietal 8- to -13 Hz EEG suppression than left parietal suppression (indicating more right parietal activation) (Davidson, Chapman, Chapman, & Henriques, 1990). In a study using the dual measures of EEG evoked potentials (EPs) and regional cerebral blood flow (rCBF), mental rotation task performance was associated with greater activation in the right parietal than the left parietal regions (Papanicolaou et al., 1987). Researchers using functional magnetic resonance imaging procedures reported that both the left and right precentral gyrus, as well as the right superior parietal lobule were the areas most activated in a mental rotation task (Tagaris et al., 1998).

In the literature, there also is a suggestion that rotation of simple stimuli may lead to activation of the left parietal area. In a PET study performed by Alivisatos and Petrides (1997), participants were required to discriminate whether alphanumeric stimuli were ‘‘normal’’ or ‘‘mirror image’’ at various angles. Though this task required mental rotation, the stimuli were simple alphanumeric stimuli, resulting in a ‘‘simpler’’ 2D rotation task. The task elicited activation of the left parietal and right frontal areas. Likewise, a left-hemisphere advantage for the rotation of both alphanumeric characters and figures from the Primary Mental Abilities test has been found (Fischer & Pellegrino, 1988). Roberts and Bell (2000b) noted left parietal and posterior temporal activation in adult males, but not adult females, using a 2D rotation task. In a replication, Roberts and Bell (2001) reported sex differences such that a 2D mental-rotation task was more likely to be associated with left parietal activation in men and right parietal activation in women.

VERBAL FLUENCY AND LEXICAL DECISION MAKING: BRAIN LOCALIZATION

Although there is a great deal of literature relating performance on mental rotation tasks to brain areas using EEG measures, the literature relating verbal fluency and lexical decision-making to brain areas using EEG measures is sparse. Hoptman and Davidson (1998) conducted a study relating baseline EEG asymmetries to performance on the Thurstone word fluency test. Participants who exhibited greater left central activation at a baseline state performed at a higher level on the word fluency task. Using a PET procedure, Boivin et al. (1992) found that higher performance on an oral verbal fluency task was related to higher baseline metabolic activity in the left temporal region and lower baseline metabolic activity in both the right and left frontal regions. Boivin et al., suggested that lower baseline metabolic activity may be related to cognitive efficiency, allowing those participants with more efficient frontal areas to perform at a higher level on the verbal fluency task. Finally, using an fMRI procedure, Schlosser et al. (1998) found that participants demonstrated an increase of activation in the left prefrontal cortex during a verbal fluency task. Taken together, the literature suggests that the left frontal and central regions are involved in verbal fluency.

In addition, appears that lexical decision making also may be largely lateralized to the left side of the brain. Using a PET procedure, Rumsey et al. (1997) found that during a lexical decision-making task participants had increased activation of the left frontal region and the left cingulate as well as bilateral activation of the parietal region. In a different study, Wegesin (1998a) examined sex differences in cognitive processing using a lexical decision-making and semantic monitoring (LD/SM) task while recording ERPs. During the LD/SM task, participants watched a computer screen as different words were presented, and the participants were required to detect the presence of pseudowords among the ‘‘real’’ words. In this task, females performed better than males, and there also were sex differences in the N400 component, with men exhibiting greater asymmetry when the target was presented in the left visual field. Finally, reading (which is an important component of lexical decision making) is generally considered to be a left-hemisphere task, a finding that also has been substantiated in the literature (e.g., Kraft, Mitchell, Languis, & Wheatley, 1980; Mattson, Sheer, & Fletcher, 1992).

EEG AGE AND SEX INTERACTIONS

Longitudinal and cross-sectional studies examining the relation among age, sex, and EEG power values indicate several types of findings. First, there is a general finding that interindividual variability in EEG recordings is much greater in children than in adults (Benninger, Matthis, & Scheffner, 1984; Gasser, Verleger, Bacher, & Sroka, 1988; Matsuura et al., 1985). This is probably due to individual differences in maturation rates. Next, women tend to exhibit greater overall EEG alpha power than men both during baseline measures and during performance on a variety of cognitive tasks (Benninger et al., 1984; Gasser et al., 1988; Matsuura et al., 1985). Such findings have been replicated in studies dealing with mental rotation tasks, for which patterns of greater EEG alpha power among women have been reported both during a baseline condition and while performing mental rotation tasks (Arce, Ramos, Guevara, & Corsi-Cabrera, 1995; Corsi-Cabrera, Ramos, Guevara, Arce, Gutierrez, 1993; Roberts & Bell, 2000b). Finally, there is no indication of a sex difference in the alpha band in children between 6 years of age and 11 to 12 years of age (Benninger et al., 1984; Matsuura et al., 1985; Roberts & Bell, 2000b). In light of these data, it is important to covary for baseline EEG when examining EEG sex differences during any type of task performance.

PURPOSE AND HYPOTHESES

The purpose of this study was to examine the effects of age and sex on mental rotation performance, verbal performance, and brain-wave activity (specific hypotheses are detailed later). To accomplish this, tasks that met several criteria were used. First, the tasks previously exhibited a sex difference in performance. Next, the tasks were appropriate for both children and adults (The research participants were 8-year-old children and college-age adults.) Furthermore, tasks that could be performed while having EEG recorded were used. The tasks that were used included three computerized, mental rotation tasks (a 2D gingerbread man mental rotation task, a 2D alphanumeric mental rotation task, and a 3D basketball player mental rotation task), a computerized lexical decision-making task, a oral verbal fluency task, and a paper-and-pencil water level task.

Two groups of hypotheses were addressed in this study:

Task Behavior

Mental Rotation Tasks and Water Level Task. Consistent with previous literature, it was hypothesized that there would be an Age × Sex interaction on task performance, with men performing at a higher level than women and no difference between boys and girls.

Lexical Decision-Making Task and Verbal Fluency Task. It was hypothesized that there would be an Age × Sex interaction on the lexical decision-making and verbal fluency tasks, with women performing at a higher level than men and no difference between boys and girls. These hypotheses were consistent with previous literature.

Task-Related EEG

Four tasks were designed so that EEG recording could be accomplished during task performance. These tasks were the 2D gingerbread man mental rotation, the 2D alphanumeric mental rotation, the 3D "basketball player" mental rotation, and the lexical decision-making tasks. The other two tasks (water level and verbal fluency) were performed without the EEG recording due to task demands that would introduce excessive gross motor artifact in the EEG recording. Overall, it was hypothesized that there would be an Age × Sex Task Type interaction. Within each task, additional hypotheses were made.

Two-Dimensional Gingerbread Man and Alphanumeric Mental Rotation Tasks. It was hypothesized that there would be an Age × Sex interaction in the task EEG data at the parietal scalp locations, with men exhibiting more left parietal activation (lower EEG power values) than women during the 2D mental rotation tasks and no task EEG alpha power differences between boys and girls.

Three-Dimensional "Basketball Player" Rotation Task. It was hypothesized that there would be an Age × Sex interaction in the task EEG data at the parietal scalp locations, with men exhibiting more right parietal activation (lower EEG power values) than women during the 3D mental rotation task and no task EEG alpha power differences between boys and girls.

Lexical Decision-Making Task. It was hypothesized that there would be an Age × Sex interaction in the task EEG data at the left central and left frontal locations, with women exhibiting more left central and left frontal activation (lower EEG power values) than men during the lexical decision-making task and no task EEG alpha power differences between boys and girls.

METHOD

Participants

Eight-Year-Olds. Thirty-two right-handed 8-year-old participants (16 boys, mean age = 8.31; 16 girls, mean age = 8.18) from the community were recruited for this study. Participants were free of medications and neurological diagnoses. For their participation, the children were rewarded with a single trip to a "treasure chest" of small toys at the end of the session, and their name was entered into a random drawing for a $100 savings bond.

College Students. Thirty-two right-handed college students (16 men, mean age = 19.86; 16 women, mean age = 19.82) who were free of medications and neurological diagnosis were recruited through the Introductory Psychology extra-credit pool to participate in this study. Participants were compensated for their participation with extra credit in their Introductory Psychology class.

Procedure

Upon entering the lab, both age groups were given an informed consent form to read and sign. In addition, parents of the 8-year-olds also signed a consent form. Both age groups completed questionnaires to verify handedness (Oldfield, 1971). Testing was counter-balanced within and between computerized and non-computerized tasks. The computerized tasks were always performed with the EEG cap applied and included the 2D gingerbread man mental rotation task, the 2D alphanumeric mental rotation task, the 3D ''Basketball player'' mental rotation task, and the lexical decision-making task. The noncomputerized tasks were always performed without the EEG cap applied and included the water level and verbal fluency tasks.

EEG Recording and Analysis

Participants had the Electro-Cap EEG recording device, as well as EOG electrodes applied. After the cap was in place, Omni-Prep abrasive gel and Electro-Gel conductive gel was inserted in 16 electrodes associated with the international 10/20 system (Jasper, 1958): Fp1, Fp2 (frontal pole), F3, F4 (medial frontal), F7, F8 (lateral frontal), C3, C4 (central), T3, T4 (anterior temporal), T5, T6 (posterior temporal), P3, P4 (parietal), and O1, O2 (occipital). Electrodes were referenced to Cz and grounded anterior to the Fz electrode on the Electro-Cap. Lead-Lok solid gel electrodes were applied to the supra orbit and outer canthus of the right eye after the skin had been wiped with an alcohol pad. This allowed monitoring of the EOG and eyeblinks for later artifact scoring of the EEG data. For all EEG electrodes, impedances were less than 5,000 Ω and less than 500 Ω separated homologous electrode pairs.

EEG recordings were made with SA Instrumentation Bio-Amps at a sampling rate of 512 Hz to prevent aliasing. The high-pass filter setting was set at 0.3 Hz, and the low-pass filter setting was at 100 Hz, with a gain of 20,000. Data were collected on a Pentium computer using Snap/Shot acquisition software.

Baseline EEG consisted of 1 min with eyes open, during which participants were instructed to look at a blank computer screen and think about a ''walk in the woods.'' Participants were instructed to sit quietly without motor movements. After baseline EEG was recorded, the computer-based tasks began. All computer-based tasks were counterbalanced within sex and age groups, and performance of the computer-based block of tasks and the noncomputer-based block of tasks also was counter balanced.

Using software developed by the James Long Company, the EEG data were re-referenced via software to an average reference configuration. Average referencing, in effect, weighted all the electrode sites equally and eliminated the need for a noncephalic reference. The data were re-referenced because distances between active and reference electrodes vary across the scalp, and without re-referencing, power values at each active site may reflect interelectrode distance as much as they reflect electrical potential. Data were artifact scored using EOG as a guide, with gross motor and muscle movements removed through artifact scoring. The visual representation of gross motor and muscle artifact was obvious because artifact occurs at frequencies greater than 90 Hz. Artifact-free EEG data were analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1-s width and 50% overlap. Mean voltage was subtracted from each data point prior to analysis to eliminate any power results due to DC offset. Power values for the high alpha band (11–13 Hz) were computed. In a review of the ontogeny of EEG during childhood, Bell (1998) noted that EEG power values of 8-year-old children are within the adultlike 8- to -13 Hz range.

Recent studies have indicated that the standard 8- to -13 Hz alpha EEG band actually may be comprised of two distinct (high and low) bands (Crawford, Clarke, & Kitner-Triolo, 1996; Crawford & Vasilescu, 1995; Klimesch, 1996). Particularly, studies have found that the lower alpha band (8–10 Hz) is associated with states of alertness and emotions, and the high alpha band (11–13 Hz) is associated with cognitive workload (Crawford et al., 1996; Klimesch, Schimke, Ladurner, & Pfurtscheller, 1990). In light of this research, the high alpha band was of interest to this study. Because the tasks used were cognitively demanding, it was expected that EEG activation during both tasks would be found in the high alpha band.

Computerized Tasks

Two-Dimensional Gingerbread Man Mental Rotation Task. Participants were seated in front of a computer and shown the Overman Mental Rotation Test (Epting, Barbour, & Overman, 1996; Epting & Overman, 1998). This mental rotation task consisted of a gingerbread man (later referred to as ''figure'') presented at the top of the computer screen, with two choices—one of which matched the original—presented at the bottom of the screen (see Figure 1, top). Figures, original and choices, were computer generated in such a manner so that each had the same amount of area

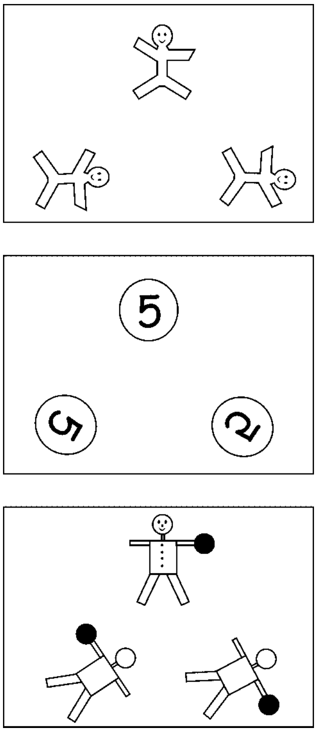

FIGURE 1 Samples of the 2D gingerbread man, 2D alphanumeric, and 3D basketball player mental rotation tasks.

within its borders. The figure had four possible positions. While either the left or right arm was extended straight out, the opposite arm was either in an "up" or "down" position. During task performance, the participant was asked to match the original figure at the top to one of two figures at the bottom. The original figure was always in an upright position, and the subsequent "choice" figures at the bottom were rotated 90, 180, or 270 degrees. Participants were asked to choose which choice figure was the same as the original figure.

Two-Dimensional Alphanumeric Mental Rotation Task. Participants were seated in front of a computer and shown the alphanumeric rotation task. This task was similar to the task used by Alivisotos and Petrides (1997), and consisted of a single alphanumeric stimulus presented at the top of the computer screen, with two choices—one of which matched the original and one of which was a mirror image of the original—presented at the bottom of the screen (see Figure 1, middle). The stimuli were the upper-case letters *G*, *F*, and *R*, and the Arabic numerals 2, 5, and 7. During task performance, the participant was asked to match the original stimuli at the top to one of two stimuli at the bottom. The original stimulus was always in an upright position, and the subsequent choice figures at the bottom were rotated 60, 120, 180, 240, or 300 degrees. Participants were asked to choose which choice stimuli was the same as the original stimuli. In all cases, the choice stimuli were either identical to the original stimuli or a mirror image of the original stimuli, and both choices were rotated to the same degree.

Three-Dimensional Basketball Player Mental Rotation Task. Similar to the methods used in the 2D dimensional rotation tasks described earlier, participants were seated in front of the computer and shown the 3D task. This task utilized a basketball player presented at the top of the computer screen. The basketball player consisted of a silhouette image of a person holding a basketball in either the right or left hand (see Figure 1, bottom). The original figure was always in an upright position and facing the participant, and the subsequent choice figures at the bottom were rotated 60, 120, 180, 240, or 300 degrees. In addition, in half of the trials the choice figures also were rotated so that they were facing away from the participant, resulting in a 3D rotation. Participants were asked to choose which choice figure was the same as the original figure.

Lexical Decision-Making Task. Participants completed a lexical decision-making task that was similar to the task used by Wegesin (1998a, 1998b). In this task, word stimulus pairs were presented on the computer screen, with one word on each side of screen. Each pair included one "pseudoword" and one "real word." The pseudowords were created by combining two real English words (e.g., book + lick = blick) and were matched to the real words in length. All of the real words were at a 2nd-grade or lower reading level, as verified by two local 2nd-grade teachers. The word pairs were comprised of word pairs used by Wegesin (1998a, 1998b) as well as from words suggested by the 2nd-grade teachers. After the word pair was flashed on the screen, participants were asked to decide which word was a real word. Participants pressed the button (right or left) corresponding to the real word.

For *all* tasks, the entire keyboard was covered except for two keys, one on the right side of the keyboard and one on the left side of the keyboard, which the participants used to choose the figure which correctly matched the original (For the lexical decision-making task, participants were asked to choose which string of letters was a real word.) Additionally, the space bar was used to let participants self-pace time between trials. To minimize motor movements, hands were rested in such a manner that only finger movements were required. All trials were randomized such that correct responses were equally divided between the right and left choices.

To control for general attentional and/or reaction-time differences on each of the mental rotation tasks, a match-to-sample task utilizing the same stimuli was randomly mixed within the testing session. These trials were the same as those previously mentioned except that the figures at the bottom of the page were not rotated, but remained in a 0-degree rotation condition. This match-to-sample task assured that differences in rotation ability were due specifically to the ability to mentally rotate objects. For example, latency to respond during the match to sample could be considered baseline response for reaction time.

Performance on all tasks was measured by number of correct trials as well as mean latency to respond. Participants' responses were recorded automatically by the computer and saved for later analysis. The computer program was set up in such, that the participant could respond any time after the choice figures or words were displayed on the screen. After making a choice, the computer screen displayed feedback to the participant to inform if the response was correct or incorrect. The participant then started the next trial by pressing the space bar.

To simultaneously examine the effects of (a) reaction time on correct trials corrected for reaction time on the nonrotation conditions and (b) number of correct trials, a total score variable was created. This was particularly important because the participants were told to choose ''as quickly *and* accurately as possible.'' Therefore, by taking into account both reaction time and number of correct trials, a better overall picture of task performance was created. Because there were no hypotheses concerning angle of rotation, data were collapsed across rotation angles. The first part of the total score variable was created by subtracting the mean reaction time on the correct trials on the nonrotation 0-degree condition of each task from the mean reaction time on the correct trials on all of the rotation conditions of each task. For example, if a participant had a mean of 1,200 ms on the nonrotation condition of the alphanumeric task, and a mean of 2,200 ms on the 180 degree condition of the alphanumeric task, then 1,000 ms was considered the amount of time unique to the rotating the alphanumeric character 180 degree, hence called the *difference score*. Then, the number of *incorrect trials* on all rotation conditions was computed. Next, the difference scores and the data concerning the number of *incorrect trials* were z-scored separately. Finally, the two z-scores were added together to create one variable (hereafter called the *total score* that encompassed both aspects of the task at all angles (number of correct responses, reaction time on correct ''rotation'' trials corrected for reaction time on correct ''nonrotation'' trials). Because the two variables that comprised the score were reaction time (lower reaction time is better) and number of incorrect trials (fewer incorrect trials is better), a lower total score represented better performance on the task. Therefore, the terms ''lower score'' and ''better score'' are used interchangeably.

The total score was created so that one dependent variable, encompassing all of the aspects of task performance that were of interest, could be used in the analysis. The strength of the total score variable is that this variable allows for the study of different components of the task simultaneously. On the other hand, the weakness of using the total score variable is that any of the components of the variable could be contributing to differences found, and the total score variable does not differentiate as to which components are creating the differences.

Noncomputerized Tasks

Water Level Task. Participants were given a single sheet of paper with a line drawing of a bottle sitting just above a table. The experimenter explained that the top of the figure represented a vertical bottle and the bottom of the figure represented a table upon which the bottle rested. The experimenter used a straight edge and drew a horizontal line representing that the bottle was half-full of water. The experimenter then explained that on the following pages the jar was tilted to various angles, and instructed the participants to use the straight-edge to draw the water line as it should appear at the various angles. The experimenter then gave the participants seven sheets of paper, one at a time. Performance was measured by total number of degrees the water line was drawn from horizontal.

Verbal Fluency Task. A standard verbal fluency task was used, giving the participants 60 s to produce as many words as possible. Participants were tested on the letters *S* and *T*. Responses were videotaped for later analyses. Performance was measured by the total number of different words produced in the 60-s period.

RESULTS

Task Behavior

Mental Rotation and Water Level Tasks. It was hypothesized that there would be an Age $\times$ Sex interaction on task performance such that men would perform at a higher level than women on the mental rotation and water level tasks, but there would be no sex difference between boys and girls. Because each mental rotation task had different characteristics (e.g., different number of rotation angles, 2D vs. 3D rotations), analyses were accomplished independently for each individual task. For each repeated measures ANOVA, the between subjects independent variables were age and sex, and the dependent variable was total score. Three participants had no correct trials in 180-degree rotation conditions (2 in the basketball player and 1 in the alphanumeric). The conservative approach of dropping their data from analyses on the task affected was taken.

Two-Dimensional Gingerbread Man Mental Rotation. Analyses revealed a main effect of age, with adults achieving a better total score than children on all of the rotation conditions of the gingerbread man rotation task, $F(1, 60) = 32.47$, $p \leq .001$. There was no sex main effect or Age $\times$ Sex interactions (see Figure 2).

Two-Dimensional Alphanumeric Mental Rotation. One participant, a boy, had no correct trials at the 180-degree rotation condition. Therefore, this analysis included a total of 31 children (15 boys) and 32 adults (16 men). There was a main effect of age, $F(1, 59) = 17.10$, $p \leq .001$, with adults achieving a better total score than children on the rotation conditions of the alphanumeric rotation task. There was no main effect for sex; however, there was an Age $\times$ Sex interaction, $F(1, 59) = 7.23$, $p \leq .01$, such that men performed better than boys, $t(29) = 5.90$, $p \leq .001$, but there was no difference between women and girls, $t(30) = .89$, $p = .38$ (see Figure 2). The hypothesized interaction was that men would perform better than women, but there would be no difference between boys and girls.

Three Dimensional Basketball Player Mental Rotation. Two participants, a girl and a woman, had no correct trials at the 180-degree rotation condition. Therefore, this analysis included a total of 31 children (16 boys) and 31 adults (16 men). Analyses revealed a main effect of age, $F(1, 58) = 8.63$, $p \leq .01$, with adults scoring higher than children on the rotation conditions of the basketball player rotation task. There was no main effect for sex; however, there was an Age $\times$ Sex interaction, $F(1, 58) = 4.22$, $p \leq .05$, such that men performed better than boys, $t(30) = 3.29$, $p \leq .01$, but there was no difference between women and girls, $t(28) = .68$, $p = .49$ (see Figure 2). The hypothesized interaction was that men would perform better than women, but no difference between boys and girls.

Water Level Task. To assess the effects of age and sex on the water level task, an ANOVA was performed. Correct trials were defined as any trial that

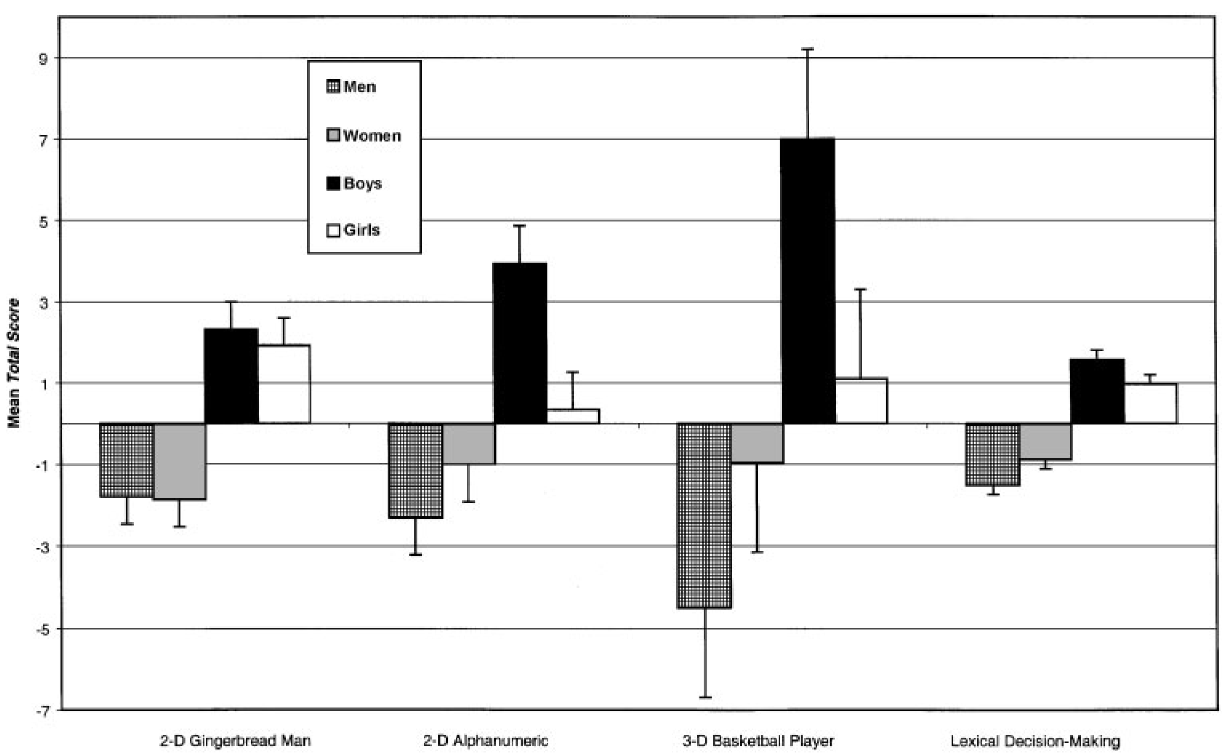

FIGURE 2 Summary of total scores on the computerized tasks.

was within 10 degrees of horizontal. The independent variables were age and sex, and the dependent variable was the total number of correct trials. Analyses revealed a main effect of age, $F(1, 60) = 11.60$, $p \leq .001$, with adults ($M = 2.50$, $SE = .40$) performing better than children ($M = .56$, $SE = .40$). Likewise, analyses yielded a main effect of sex, $F(1, 60) = 5.84$, $p \leq .02$, with males ($M = 2.21$, $SE = .40$) performing better than females ($M = .84$, $SE = .40$). However, there was no interaction between age and sex, $F(1, 60) = 1.74$, $p = .19$. Although there was no interaction between age and sex, post hoc analyses indicated that men performed better than women, $t(30) = 2.05$, $p \leq .05$, whereas there was no difference between boys and girls, $t(30) = 1.33$, $p = .19$.

Lexical Decision-Making and Verbal Fluency Tasks. It was hypothesized that there would be an Age × Sex interaction on the lexical decision-making and verbal fluency takes such that women would perform at a higher level than men, but that there would be no difference between boys and girls.

Lexical Decision-Making Task. To examine the effects of both reaction time and number of correct trials, the total score (similar to the formula described earlier, reaction time data from the correct trials and data concerning the total number of incorrect trials were *z*-scored separately and then added together) was computed. The independent variables were age and sex, and the dependent variable was overall score. These analyses revealed a main effect of age, $F(1, 60) = 113.09$, $p \leq .001$, with adults performing better than children. These analyses did not yield a main effect of sex; however, there was an interaction between age and sex, $F(1, 60) = 7.19$, $p \leq .01$. Post hoc analyses indicated that men achieved a better total score than women, $t(30) = 2.78$ $p \leq .01$, but there was no difference between boys and girls, $t(30) = 1.51$, $p = .14$ (see Figure 2).

Verbal Fluency Task. To assess the effects of age and sex on the total number of words produced on the verbal fluency task, an ANOVA was performed. The independent variables were age and sex, and the dependent variable was the total number of words produced. Analyses revealed a main effect of age, $F(1, 60) = 66.38$, $p \leq .001$, with adults ($M = 26.94$, $SE = 1.07$) performing better than children ($M = 14.63$, $SE = 1.07$). There was no main effect for sex and no Age × Sex interaction.

Task-Related EEG Activity

To ensure that the effects and interactions found for each of the tasks were specific to particular task type and not due to the generalized effects of cognition, EEG data were collected during several different types of tasks thought to elicit activation in different areas of the brain. The use of MANCOVA was particularly important to assure that any effects found in the EEG were due to the specific task being performed and not due to baseline EEG power values differences.

The within-groups independent variables were region (frontal pole, medial frontal, lateral frontal, central, anterior temporal, posterior temporal, parietal, occipital), hemisphere (right, left), and task (2D gingerbread man mental rotation, 2D alphanumeric mental rotation, 3D basketball player mental rotation, and lexical decision making), and the between-groups independent variables were age and sex. The dependent variable was task performance EEG ln power values at 11 to 13 Hz, and the covariate was baseline EEG ln power values at 11 to 13 Hz. There were main effects for task, Wilks's = .77, approximate $F(4, 41) = 4.11$, $p \leq .01$, and region, Wilks's = .73, approximate $F(4, 41) = 14.58$, $p \leq .001$. Interactions included Task × Age, [Wilks's = .72, approximate $F(4, 41) = 5.37$, $p \leq .01$, Region × age, Wilks's = .69, approximate $F(4, 41) = 2.39$, $p \leq .05$, Task × Region, Wilks's = .19, approximate $F(4, 41) = 4.27$, $p \leq .001$, and Task × Hemisphere × Age, Wilks's = .82, approximate $F(4, 41) = 3.02$, $p \leq .04$.

Although the interactions involving task type denoted that the tasks were associated with differential electrical patterns at the scalp locations, performing separate MANCOVAs on the EEG from each of the different tasks allowed for assessment of these interactions. In each of these task-separated MANCOVAs, age and sex were the between-subjects factors and hemisphere was the within-subjects factor. The dependent variable was EEG in power values at 11 to 13 Hz, and the covariate was baseline EEG ln power values at 11 to 13 Hz.

Two-Dimensional Gingerbread Man and Two-Dimensional Alphanumeric Mental Rotation Tasks. It was hypothesized that there would be an Age × Sex interaction in the task EEG data at the parietal scalp locations, with men exhibiting more left parietal activation (lower EEG power values) than women during the 2D mental rotation tasks and no task EEG alpha power differences between boys and girls.

The *F* values for the MANCOVAs on the 2D gingerbread man mental rotation EEG are summarized in Table 1. Testing of the Hemisphere × Sex interaction at the parietal area revealed that males exhibited lower power values (more activation) in the left hemisphere than females, with no right parietal differences between males and females (see Figure 3). Data at the occipital area were in the direction hypothesized for

Table 1. Summary of MANCOVA *F* Values for Analyses of High Alpha (11–13 Hz) During 2D Gingerbread Man Mental Rotation Task Covaried With Baseline EEG

Region	Age	Sex	Age × Sex	Hemi	Hemi × Age	Hemi × Sex	Hemi × Age × Sex
df	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58
Fp1, Fp2							
F3, F4	19.55*** A < C	6.06* M < F					
F7, F8					4.75* R (A < C) L (A = C)		
C3, C4	15.22*** A < C						
T3, T4							
T5, T6	15.38*** A < C						
P3, P4	21.55*** A < C	6.37** M < F				6.17* L (M < F) R (M = F)	
O1, O2	14.97*** A < C	6.96** M < F		5.01* L < R			6.91** L (m < w; b = g) R (m = w; b = g)

Note: Only numbers that were significant at the $p \leq .05$ level are presented. b = boys, g = girls, m = men, w = women, A = Adults, C = Children, M = Males, F = Females, Hemi = Left or Right Hemisphere.
$^{*}p \leq .05$. $^{**}p \leq .01$. $^{***}p \leq .001$.

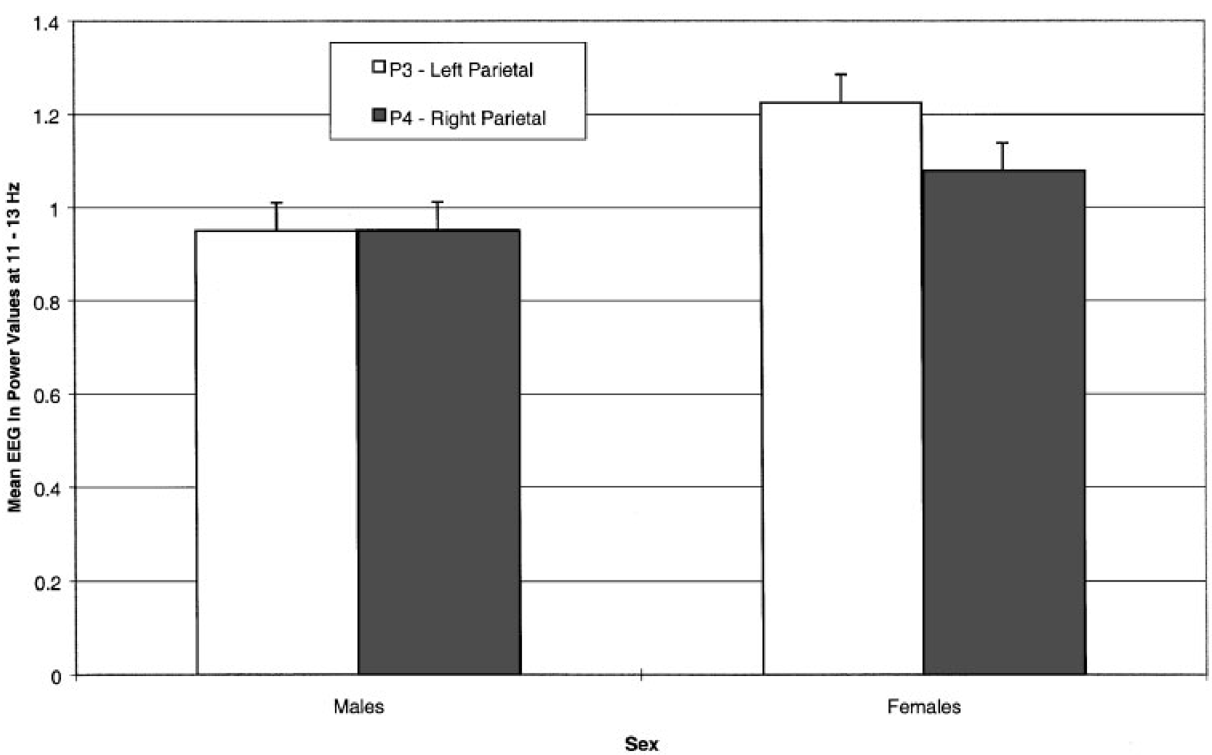

FIGURE 3 Two dimensional gingerbread man mental rotation task EEG (covaried with baseline EEG) at parietal region: Hemisphere × Sex interaction.

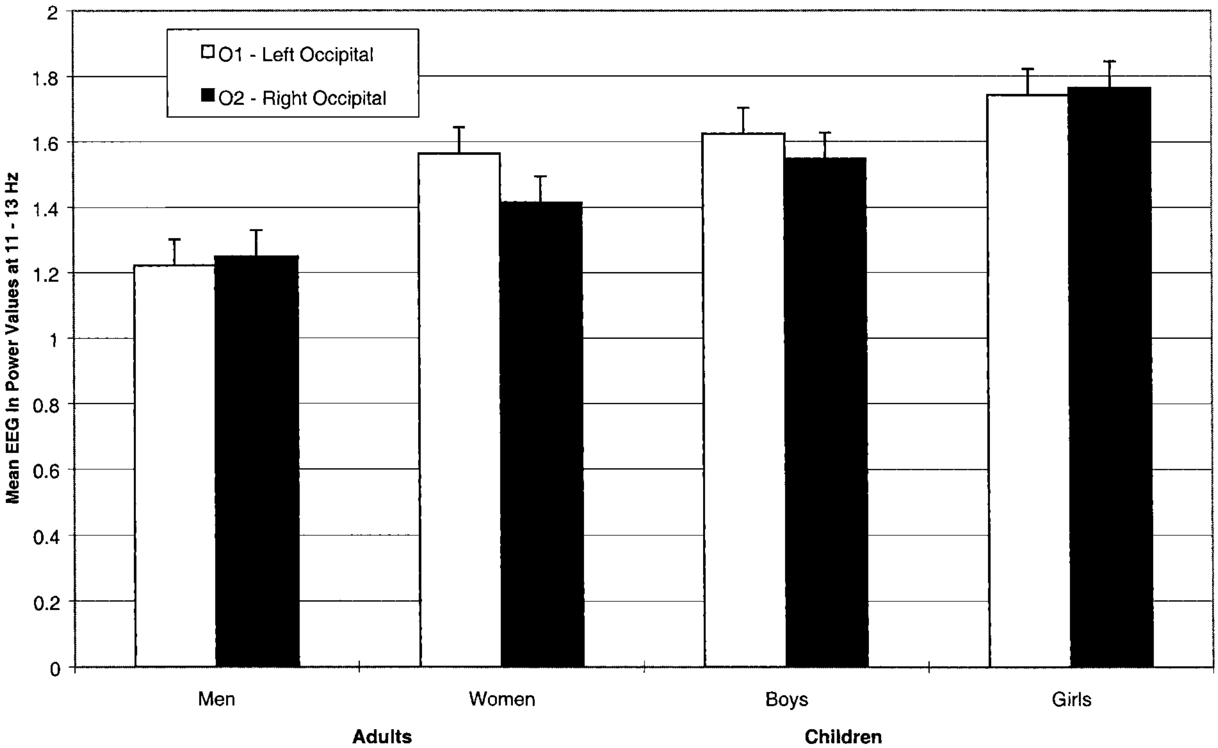

FIGURE 4 Two dimensional gingerbread man mental rotation task EEG (covaried with baseline EEG) at occipital region: Hemisphere × Age × Sex interaction.

the Hemisphere × Age × Sex interaction at the parietal area (see Figure 4).

The *F* values for the MANCOVAs on the 2D alphanumeric mental rotation EEG are summarized in Table 2. Simple effects testing of the Age × Sex interaction at the parietal region revealed that men exhibited lower power values (more activation) than women, but there were no differences between boys and girls. Data at posterior temporal (T5, T6) were in the direction hypothesized for the Hemisphere × Age × Sex interaction at the parietal area (see Figure 5).

Three-Dimensional Basketball Player Mental Rotation Task. It was hypothesized that there would be an Age × Sex interaction in the task EEG data at the parietal scalp locations, with men exhibiting more right parietal activation (lower EEG power values) than women during the 3D mental rotation task and no task EEG alpha power differences between boys and girls.

The *F* values for the MANCOVAs on the 3D basketball player mental rotation EEG are summarized in Table 3. There were no interactions at the parietal or any other posterior location. There was, however, a main effect of hemisphere at the lateral frontal and posterior temporal regions, such that all participants exhibiting right hemisphere activation at these locations.

Lexical Decision-Making Task. It was hypothesized that there would be an Age × Sex interaction in the task EEG data at the left central and left frontal locations, with women exhibiting more left central and left frontal activation (lower EEG power values) than men during the lexical decision-making task and no task EEG alpha power differences between boys and girls. The *F* values for the MANCOVAs on the lexical decision-making task are summarized in Table 4. There were no interactions involving hemisphere at the frontal or central locations.

DISCUSSION

Task Behavior

Past research has indicated that the male advantage on mental rotation tasks and the female advantage on verbal tasks is most robust in adults (Hyde & Linn, 1988; Linn & Petersen, 1985; Voyer et al., 1995). We expected to find the same advantage with our adult populations, but not with our child participants.

Mental Rotation and Water Level Tasks. An Age × Sex interaction was found on the water level task, with men outperforming women and no difference

Table 2. Summary of MANCOVA *F* Values for Analyses of High Alpha (11–13 Hz) During 2D Alphanumeric Mental Rotation Task Covaried With Baseline EEG

Region	Age	Sex	Age × Sex	Hemi	Hemi × Age	Hemi × Sex	Hemi × Age × Sex
df	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58
Fp1, Fp2		4.81* M < F					
F3, F4	21.60** A < C	4.38* M < F	4.78* m < w b = g				
F7, F8				10.03** R < L			
C3, C4	18.95*** A < C					4.08* L (M < F) R (M = F)	
T3, T4	8.27** A < C						
T5, T6	30.06*** A < C						6.77** L (m < w; b = g) R (m = w; b = g)
P3, P4	24.36*** A < C		4.55* m < w b = g				
O1, O2	12.41*** A < C					3.88* L (M < F) R (M = F)	

Note: Only numbers that were significant at the $p \leq .05$ level are presented. b = boys, g = girls, m = men, w = women, A = Adults, C = Children, M = Males, F = Females, Hemi = Left or Right Hemisphere.
$^{*}p \leq .05$. $^{**}p \leq .01$. $^{***}p \leq .001$.

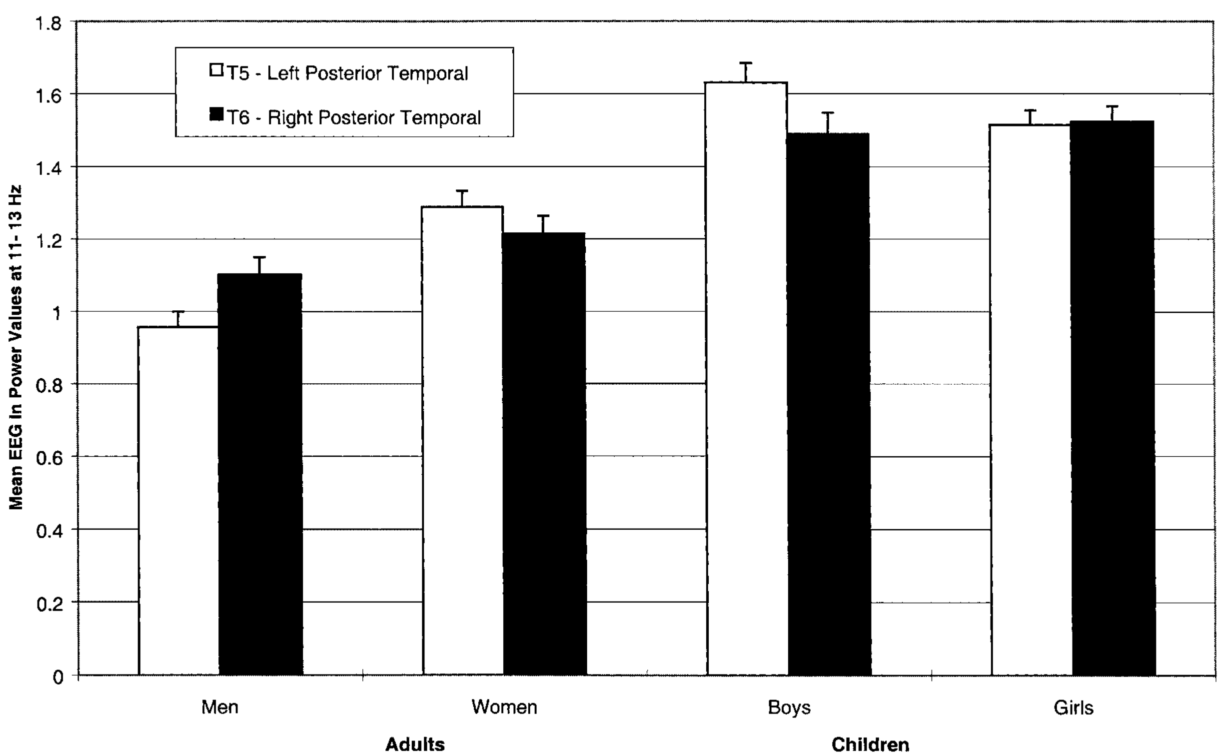

FIGURE 5 Two dimensional alphanumeric task EEG (covaried with baseline EEG) at posterior temporal region: Hemisphere × Age × Sex interaction.

Table 3. Summary of MANCOVA *F* Values for Analyses of High Alpha (11–13 Hz) During 3D Basketball Player Mental Rotation Task Covaried With Baseline EEG

Region	Age	Sex	Age × Sex	Hemi	Hemi × Age	Hemi × Sex	Hemi × Age × Sex
df	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58
Fp1, Fp2							
F3, F4	33.91***	5.18*					
	A < C	M < F					
F7, F8				5.86*	7.51**		
				R < L	R (A = C)		
					L (A = C)		
C3, C4	26.51***					8.23**	
	A < C					L (M < F)	
						R (M = F)	
T3, T4							
T5, T6	24.29***			4.67*			
	A < C			R < L			
P3, P4	21.21***	4.24*					
	A < C	M < F					
O1, O2	9.93**	4.32*					
	A < C	M < F					

Note: Only numbers that were significant at the $p \leq .05$ level are presented. b = boys, g = girls, m = men, w = women, A = Adults, C = Children, M = Males, F = Females, Hemi = Left or Right Hemisphere.
$^*p \leq .05$. $^{**}p \leq .01$. $^{***}p \leq .001$.

Table 4. Summary of MANCOVA *F* Values for Analyses of High Alpha (11–13 Hz) During Lexical Decision-Making Task Covaried With Baseline EEG

Region	Age	Sex	Age × Sex	Hemi	Hemi × Age	Hemi × Sex	Hemi × Age × Sex
df	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58	1, 58
Fp1, Fp2	11.16***	4.45*					
	A < C	M < F					
F3, F4	43.47***		3.94*				
	A < C		m < w				
			b = g				
F7, F8		4.94*	5.03*	4.64*			
		M < F	m < w	L < R			
			b = g				
C3, C4	41.04***						
	A < C						
T3, T4	8.17**						
	A < C						
T5, T6	38.49***		5.93*				
	A < C		m < w				
			b = g				
P3, P4	49.30***						
	A < C						
O1, O2	19.57***	6.34*					
	A < C	M < F					

Note: Only numbers that were significant at the $p \leq .05$ level are presented. b = boys, g = girls, m = men, w = women, A = Adults, C = Children, M = Males, F = Females, Hemi = Left or Right Hemisphere.
$^*p \leq .05$. $^{**}p \leq .01$. $^{***}p \leq .001$.

between boys' and girls' performance. On the 2D alphanumeric task and the 3D basketball player task, there was an Age × Sex interaction, with men performing better than boys and no difference between girls and women.

There was no Age × Sex interaction on the 2D gingerbread man mental rotation task. At least three other studies using this same task have found an adult sex difference on this task, even with a smaller sample size (Epting et al., 1996; Epting & Overman, 1998; Roberts & Bell, 2000b). However, a recent study using this same task found that familiarization with the computer demands of the task may alleviate sex differences on the 2D gingerbread man mental rotation task (Roberts & Bell, 2000a). College students who performed only the 2D gingerbread man mental rotation task exhibited the traditional male advantage. College students who were allowed to practice the computer demands of the task by performing a color-matching task before the 2D gingerbread man mental rotation task showed no sex difference on the mental rotation task.

Previous literature indicates that women have less experience performing computer games than men (Dominick, 1984; Phillips, Rolls, Rouse, & Griffiths, 1995). Likewise, data indicate that men perform at a higher level than women on new computer games (Brown, Hall, Holtzer, Brown, & Brown, 1997; Greenfield et al., 1994). In light of this, the results of the computerized rotation tasks in this study could be explained in the following way. During the first task or two, men may have ''automatized'' quickly and, thus, were only performing one challenging task (the rotation task). On the other hand, the women may not have been as experienced with computer games and were performing the rotation task *plus* the computer manipulation task. As the women began to familiarize themselves with the demands of the computer task, the computer task became ''automatic'' for the women also. After this, the women also were performing only one cognitively challenging task, the mental rotation task. Because the current study counterbalanced all tasks, most participants had completed 100 or more trials of similar computerized tasks before completing the gingerbread man task. This familiarization may have alleviated the adult sex difference.

The proposal that the overall adult sex difference on the 2D gingerbread man mental rotation task was alleviated through computer familiarization raises a question. Why does the overall sex difference still exist on the 2D alphanumeric task and the 3D basketball player task? A male advantage on 3D mental rotation tasks has always been the most robust sex difference (Voyer et al., 1995). Therefore, it would be expected that the sex difference on the 3D task would remain even after computer familiarization. However, this does not explain why the 2D alphanumeric task exhibited a sex difference whereas the 2D gingerbread man task did not. Anecdotally, many of the participants expressed that the alphanumeric task was the most difficult task, despite the fact that it required only a 2D rotation. It may be that participants had difficulty ignoring the properties of the letters/numbers so that they could focus on the rotation task at hand. Therefore, it may be that the sex differences on the computerized 2D alphanumeric rotation task and 3D basketball player rotation task are robust enough to withstand the removal of the initial sex difference in computer-game skills. This hypothesis warrants further exploration with larger sample sizes.

Lexical Decision-Making and Verbal Fluency Tasks. There was an Age × Sex interaction on the lexical decision-making task such that men outperformed women, with no difference between boys and girls. This was opposite of the hypothesis. Particularly among adults, there was a ceiling effect on the number of correct choices (Both men and women averaged over 39 of 40.), so this sex difference was largely due to reaction-time differences. Because there was no ''nonrotation'' condition of the lexical decision-making task, generalized reaction time was not accounted for, and the results of this task are likely due to men having generally faster reaction times than women. The hypothesized sex difference on the verbal fluency task also was not found. This was surprising, but there is no indication of a confound to explain these results. Meta-analyses examining adult sex differences have found that the female advantage on tasks of speech production reach a medium $d = 0.45$) effect size whereas the male advantage on mental rotation tasks reaches a somewhat larger $d = 0.66$) effect size (Hyde & Linn, 1988; Voyer et al., 1995). In the case of the present study, it may be that our sample was large enough to detect sex differences in mental rotation tasks (with their larger effect sizes), but not large enough to detect differences in verbal fluency.

Task-Related EEG Activity. It was hypothesized that on the 2D gingerbread man and alphanumeric tasks, men would exhibit more activation of the left parietal area than women, and that on the 3D basketball player task, men would exhibit more activation of the right parietal area than women. On the lexical decision-making task, it was hypothesized that women would exhibit more activation of the left central and left frontal areas than men. Among children, there were no EEG-related sex differences hypothesized.

Two-Dimensional Gingerbread Man Task. Although the proposed Hemisphere × Age × Sex interaction was not found, a Hemisphere × Sex effect was found at the parietal area. The finding of males exhibiting more left parietal activation than females during the 2D task was not expected to include the child participants, as reports of sex differences in EEG activation during cognitive activity are not common in the developmental literature.

Two-Dimensional Alphanumeric Task. Although the proposed Hemisphere × Age × Sex interaction was not found at the parietal area, it was found at the posterior temporal area. Examination of this interaction revealed that men exhibited more left posterior temporal activation than women during the alphanumeric task. Although mental rotation tasks are traditionally thought to be localized to the parietal area, EEG is a gross measure of brain electrical activity and not a measure that allows for source localization. Thus, finding the effect in the posterior temporal, an area that is adjacent to the parietal area, is not unusual in the EEG literature. Roberts and Bell (2000b) found Hemisphere × Age × Sex interactions at the posterior temporal and parietal areas on a 2D mental rotation task. On a more theoretical level, this finding is difficult because it creates a pattern of the activation of the posterior temporal area during the completion of a 2D mental rotation task. Mental rotation tasks are traditionally considered parietal tasks, and this finding warrants further exploration.

Three-Dimensional Basketball Player Task. The proposed Hemisphere × Age × Sex interaction was not found at the parietal area. However, a main effect of hemisphere at the posterior temporal area was found, such that all participants had more right posterior temporal activation (see Table 3). Research has indicated that complex rotations led to activation of the right parietal areas (e.g., Berfield, Ray, & Newcombe, 1986; Michel, Kaufman, & Williamson, 1994; Papanicolaou et al., 1987). Although the current effect was not in the parietal area, it was in the posterior temporal area, adjacent to the parietal area. In retrospect, our hypothesis may have been misguided, and a better hypothesis may have been for a main effect of hemisphere such that all participants exhibit more activation of the right posterior brain area. More difficult rotation tasks lead to activation of the right parietal area, so we should have hypothesized right activation for all participants, not just the men.

Lexical Decision-Making Task. The proposed Age × Sex × Hemisphere interaction of women exhibiting more activation of the left central and left frontal areas was not found. All participants exhibited more activation (lower power values) of the left lateral frontal area. Lexical decision-making tasks are traditionally thought to lead to activation of the left frontal and left central areas (Rumsey et al., 1997; Wegesin, 1998a), so the generalized finding of left frontal activation during the this task (rather than an Age × Sex interaction) is in concordance with the lexical decision-making literature.

GENERAL CONCLUSIONS

Computer Familiarization Effects

Sex differences on the mental rotation tasks used in this study may have been affected by the randomized order in which the tasks were presented, allowing much computer time before some tasks were presented. Thus, computer familiarization and computer task demands are variables that should be accounted for in future studies of sex differences on computerized tasks. The current study may lend support to the proposal that sex differences on some computer-based tasks can be eliminated through computer familiarization or practice (Roberts & Bell, 2000a). The data from the current study also can be used to demonstrate that the sex differences on some computer-based tasks are robust enough to withstand the removal of computer-familiarization differences (or practice effects) between males and females. We have demonstrated that adult sex differences on mental rotation tasks are present, but the robustness of these sex differences warrants further research.

Overall Findings

The behavioral and EEG results, taken together, suggest that changes which affect both mental rotation task performance and EEG high alpha power values occur sometime between 8 years of age and college age. One possible explanation of these Age × Sex differences could be brain plasticity, with a malleable brain forming to the needs of the body. It may be that male children differentially participate in activities that require the use of spatial skills, their brains become adapted to the tasks, and specialization to spatial tasks occurs within the brain (Baenninger & Newcombe, 1989; Newcombe, Bandura, & Taylor, 1983). Another explanation for the differences in rotation task ability and EEG could be the onset of puberty and the resulting hormonal changes. The body of evidence to suggest that hormonal factors influence spatial abilities is growing (Hampson, 1990a, 1990b;

Hampson & Kimura, 1988; Silverman & Phillips, 1993; Van Goozen, Cohen-Kettenis, Gooren, Fridja, & Van de Poll, 1994, 1995). Additionally, recent experimental research has indicated that hormones also may have a direct effect on EEG (Corsi-Cabrera, Ugalde, Del-Rio-Portilla, & Fernandez-Guasti, 2000). These different lines of research all could be used to explain the results of the current study. Although the results of the current study add to the sex-difference literature, they cannot be used to comment on *why* these sex differences in mental rotation performance and EEG activation occur.

In the case of the two-dimensional gingerbread man task, there were sex differences in the EEG patterns, but no sex differences in performance. Although this may appear troublesome on the surface, it also may be one of the more interesting findings in this study. Despite the EEG data to suggest that men and women processed the gingerbread man task differently, they performed at the same level. This suggests that there may be different means to the same end. That is, even though the material is processed in different ways, the outcomes are the same.

NOTES

We thank Ian Reed for his help designing the computer tasks and assisting in data collection. Additionally, we thank numerous other undergraduates for their assistance in data collection. Special thanks go to William Overman for use of his mental rotation task.

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