SPATIAL ABILITY AND RELATED SOCIO-CULTURAL FACTORS: SEX, COLLEGE MAJOR, AND NATIVE LANGUAGE

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ABSTRACT

The present dissertation focused on preferred strategies during spatial performance, and specifically investigated how sex, college major and native language are related to the strategies used during the Vandenberg and Kuse Mental Rotation Test (the MRT, 1978). The present dissertation involves three studies. In Study I, the mental rotation (MR) strategies used by a group of monolingual native English speakers were examined as a function of their sex and college major via the use of a behavioral dual-task paradigm (i.e., the participants are required to process MR problems while maintaining a verbal or spatial concurrent memory load). In Study II, electroencephalography (EEG) was used to further investigate brain activation patterns among monolingual native English speakers when performing the MRT. Study III used a comparable design to that of Study I to investigate whether monolingual native Chinese speakers and Chinese-English bilinguals would show a stronger tendency towards using a holistic strategy in MRT performance as compared to native monolingual English speakers. The findings from the three studies indicate that for monolingual native English speakers, MR strategies varied according to sex and college major, with physical science males using a holistic strategy and social science males using an analytic strategy. Females, regardless of their college majors, employed a combined strategy. Monolingual native Chinese speakers were found to be highly consistent on MRT accuracy, showing no significant main effect of sex or college major. Moreover, monolingual Chinese speakers in social science used a combined MR strategy, while monolingual Chinese speakers in physical science used either a combined or a holistic strategy. This consistent tendency in MR performance of native Chinese speakers is argued as evidence of the influence of long-term usage of a native logographic language on spatial ability. Chinese-English bilinguals did not show an advantage on the MRT as compared to other language groups, and their strategy preferences were similar to those of monolingual native English speakers. This similarity is argued to be due to the influence of using English as a primary language when living in an English-speaking environment.

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CHAPTER I
GENERAL INTRODUCTION

According to Mazoyer, et al. (2002), human thinking is comprised of two main systems of mental representation: language and visual mental imagery. Spatial ability is the thinking based on visual images, as opposed to verbal coding (words), the latter being an example of thinking based on language. Linn and Petersen (1985) further define spatial ability as “skill in representing, transforming, generating, and recalling symbolic, nonlinguistic information” (p. 1482).

As a critical part of human thinking, spatial ability is essential for success in many physical science related fields such as mathematics, engineering, chemistry, etc. According to Cooper and Mumaw (1985): “The spatial aptitude literature is quite clear in showing that a broadly defined spatial factor exists independently of analytic and quantitative factors and that this spatial factor is more effective than other measures of intelligence in predicting success in certain academic and industrial areas” (p.71). Therefore, it is both practically and theoretically important to investigate how individuals perform spatial tasks and to determine what factors may mediate their spatial ability. The following sections introduce three socio-cultural factors that may contribute to the attainment of high spatial ability: sex, college major and native language.

Sex Difference in Spatial Ability

Studies on sex differences in spatial ability have a long history, tracing back to the early Gestalt studies done by Wertheimer (1913) and Koffka (1935). One of the well established findings from these early studies is that males generally outperform females in many spatial tasks. However, it is not the case that this apparent male advantage in spatial ability consistently manifests itself on all types of spatial tasks. For example, some researchers have found that on spatial location memory tasks, in which participants are required to recall the location of previously viewed item, females outperform males (Kimura, 1999; McBurney, et al., 1997). There are numerous other tests of spatial ability, including Money's Road Map Test, Water-level tasks, Rod and Frame Test, Embedded Figures Test, Mental Rotation, etc. And, these do not always yield the same pattern of sex differences, most likely because they tap into different aspects or subcomponents of spatial ability. Most researchers agree that spatial ability is a complex process that includes many different subcomponents and these subcomponents may function independently from each other in different types of spatial tasks. For example, Kimura (1999) separates spatial ability into six distinct components: (1) targeting (i.e., the ability to judge and respond to the direction and speed of moving object); (2) spatial orientation (i.e., the ability to imagine how an object rotates in a space); (3) spatial location memory (i.e., the ability to memorize the locations of objects in a space); (4) spatial visualization (i.e., the ability to imagine how an object will look like after folding its parts); (5) disembedding (i.e., the ability to separate a simple figure from a complex one); (6) spatial perception (i.e., the ability to locate the horizontal or the vertical in a stationary display while ignoring distracting information). Halpern (2000) also mentions at least five distinctive visuospatial abilities, including spatial perception (i.e., the ability to locate horizontal or vertical while ignoring distracting information, such as in the Rod and Frame Test), mental rotation (i.e., the ability to rotate imagined objects), spatial visualization (i.e., the ability to do complex multistep processing of spatial information, such as the Embedded Figures Test), spatiotemporal ability (i.e., the ability to judge and respond to moving visual displays), and the ability of generation and maintenance of a spatial image. Based on factor analysis, Linn and Peterson (1985) argue that there are at least three categories of spatial ability: spatial perception, spatial visualization and mental rotation.

Interestingly, different cognitive subcomponents may be involved when using different optimal strategies to perform different types of spatial tasks. For example, through conducting a meta-analysis study involving various types of spatial tasks, Linn and Peterson (1985) found that for mental rotation, a holistic strategy (i.e., mentally rotate the figure as a whole in a 'gestalt-like' parallel process) is superior to an analytic strategy (i.e., analyzing the details of the figure in a step-by-step process), and that the optimal spatial visualization performance requires more of an analytic strategy than a holistic one.

When examined closely, studies on spatial ability reveal a general pattern for sex differences: on spatial tasks that emphasize processing static imagery with an analytic strategy, females are no worse or even better than males. On the other hand, on spatial tasks that require active manipulation of a spatial image presumably using a holistic strategy, a large sex difference favoring males is often found (Linn & Peterson, 1985; Paivio, 1971; Paivio & Harshman, 1983, Vecchi & Girelli, 1998; Voyer, et al., 1995). Notably, the largest sex difference favoring males has been found on mental rotation tasks, sometimes with an effect size as large as 1.0 (i.e., the averaged mean for males being one full standardized deviation above the averaged mean for females, see Kimura, 1999), while there is a small or no sex difference found on spatial visualization tasks (Linn & Peterson, 1985).

One possible reason for this pattern of sex difference in spatial performance may be that males and females favor different types of strategies when doing spatial tasks, and their performance levels are affected by how well their strategies match the optimal strategies for performing those tasks. Specifically, males may have a tendency to use a holistic strategy, while females may favor an analytic or a combined analytic/holistic strategy for spatial performance (Richardson, 1991; Linn & Peterson, 1985). This hypothesis is supported in several studies using various mental rotation tasks (Heil & Jansen-Osmann, 2008; Moody, 1998; Moore, 2003; Raabe, et al., 2006). For example, by asking the participants to perform the Vandenberg and Kuse Mental Rotation Test (MRT, 1978) and to fill out an accompanying problem-solving strategy questionnaire, Moody (1998) found that males reported using primarily a holistic strategy, while females reported using an analytic strategy. Moore (2003) used a dual task paradigm (i.e., the participant performed mental rotation while maintaining a concurrent verbal word load or a spatial figure load in memory) to tap into the participants' mental rotation strategies on the aforementioned MRT. She found that males performed better during the verbal load condition than in the spatial load condition, while female performance during both the spatial load and the verbal load condition did not differ. She interpreted these results as suggestive of a holistic strategy used by the male participants (i.e., the concurrent spatial memory load interfered with their MRT performance but not the concurrent verbal memory load) and a combined strategy used by the female participants. In a more recent study, Heil and Jansen-Osmann (2008) asked participants to mentally rotate polygons and found that males' mental rotation speed was not affected by the complexity of the polygons, while females' mental rotation speed decreased with increased complexity of the polygons. They interpreted these results as indicating a holistic strategy used by the males and an analytic strategy used by the females during mental rotation performance.

Importantly, this sex difference in spatial strategy is not limited to mental rotation tasks alone. In studies on spatial navigation, for example, females were found to rely on analytic strategies (i.e., memorizing landmarks) to find their way, while males mostly rely on holistic strategies (i.e., utilizing Euclidean cues, such as distances and cardinal directions) to keep themselves on track (Choi, 2001).

Based on the current literature, Study I of the present dissertation investigated how males and females used different strategies when performing the well documented 3-D Vandenberg and Kuse Mental Rotation Test (the MRT, 1978, see Appendix A). Participants' spontaneous strategies were assessed using a dual-task paradigm (e.g., the participants were asked to perform mental rotation while maintaining a concurrent verbal or spatial load in their memory). The hypothesis was that males would outperform females on MRT because they have a tendency to use a holistic strategy to solve the problems, while females have a tendency to use an analytic or a combined analytic/holistic strategy for the MRT.

College Major and Spatial Ability

Another important factor related to spatial ability is college major. Visuospatial ability is critical to success in physical science. For example, in a study with a large sample (1648 college students), spatial ability was found to be a significant predictor for success in a college chemistry course (Carter, et al., 1987). College students majoring in physical science (e.g. engineering, chemistry, physics, etc.) were found to outperform those majoring in social science (e.g., English, history, philosophy, etc.) on various spatial tasks, such as the Piagetian water-level task, the Embedded Figure Test, and the Vandenberg and Kuse MRT (Kalichman, 1986; Lavach, 1991; Leslie, 1979; Martino & Winner, 1995; Zegas, 1976). Interestingly, high spatial ability test scores obtained from high school students were found to predict choices of physical science majors in college (Humphreys, et al., 1993) and in graduate school (Humphreys & Yao, 2002), suggesting a consistent developmental trend in spatial ability (i.e., those who excel on spatial performance would select spatial ability related academic training and thus enhance their advantage on spatial performance).

Similar to the hypothesis proposed for sex differences in strategy preference during spatial performance, physical science majors' advantage on spatial tasks may be related to their preferred strategies. Specifically, physical science majors may have a tendency to use a holistic strategy, while social science majors may prefer an analytic strategy or a combination of holistic/analytic strategies. This hypothesis was partly supported by some previous studies suggesting that physical science majors have a strong tendency to use a holistic strategy to process spatial problems (Lavach, 1991; Zegas, 1976). For example, Casey, et al. (1990) argued that individuals having a career in mathematics and sciences are particularly adept at actively manipulating spatial images in mind (i.e., holistically processing images in a gestalt way), which is different from memorizing static visual images in a piece-by piece way (i.e., sequentially coding image details). In support of this argument, she found that female college students majoring in physical science had a stronger tendency to rely on holistic manipulation of images to solve spatial tasks than female college students majoring in non-physical sciences (Casey & Brabeck, 1989). Moreover, among physical science majors, those who obtained the highest performance scores on an image generation task were found to be those who preferred a holistic strategy rather than an analytic one. The same result was replicated in a subsequent study with 7th-9th graders, suggesting a developmental continuity in preferred strategies for spatial processing (Casey, et al., 1993). Therefore, in Study I of the present dissertation, college major was considered with the hypothesis that it would significantly predict the participants' MRT strategy (i.e., physical science majors would prefer a holistic strategy and social science majors would use an analytic or a combined analytic/holistic strategy to solve the mental rotation problems).

Neural Basis for Sex and College Major Differences in Spatial Strategy

It is well known that the two hemispheres of the brain function differently during cognition. The left hemisphere is characterized by a step-wise, sequential style and is primarily in charge of language processing, while the right hemisphere is characterized by a parallel, synthetic style and dominates spatial processing (for a review, see Springer & Deutsch, 1998). Studies have shown that the verbal working memory system is primarily supported by a leftward asymmetrical temporal and inferior frontal cortical networks, while spatial working memory is supported by a bilateral occipito-parieto-frontal network (Mazoyer, et al., 2002; Mesulam, 2000; Wager & Smith, 2003). These hemispheric functional differences may be a physiological basis for different strategies used in spatial performance. For example, if a participant prefers a holistic strategy for spatial performance, then he/she will be likely to activate the right hemisphere to process such information. On the other hand, if an analytic strategy is preferred, then the participant may be biased towards activating the left hemisphere to aid in such processing. No difference in activation levels between the left and the right hemisphere may be suggestive of a combined holistic/analytic strategy being used. Based on this theorizing, Study II of the present dissertation extended Study I by investigating the neuroanatomical basis for native monolingual English speakers' spatial performance with the use of electroencephalography (EEG) to search for evidence of distinct brain activation patterns for different strategies during the MRT.

It has been known for some time that sex differences exist in functional lateralization of the two hemispheres (Kimura & Harshman, 1984; Levy & Heller, 1992; Witelson, 1976; Voyer, 1996). Specifically, males show greater lateralization than females. The former tend to have language functions localized to the left hemisphere, and spatial functions to the right hemisphere. In comparison, females show a more bilateral pattern: they tend to activate both hemispheres for language and oftentimes for spatial processing. This sex difference in brain functioning lateralization may be the neuroanatomical basis for the aforementioned sex difference in strategy preference: females may prefer a combined holistic/analytic strategy for spatial performance because they activate both hemispheres during processing, while males may prefer a holistic strategy because they rely more on the right hemisphere for such processing. This was the hypothesis examined in Study II of the present dissertation.

To date, no previous studies investigated the brain activation patterns for different college majors on MRT performance. However, as discussed earlier, physical science majors have been suggested to have a stronger tendency than social science majors to holistically process images. Therefore, a hypothesis regarding hemispheric lateralization for different college majors was proposed in Study II: physical science majors would show stronger activation in their right hemisphere for the MRT, while social science majors may show a bilateral activation or a leftward hemispherical activation pattern during the MRT.

Language Experience and Spatial Ability

Most previous studies on spatial ability have been conducted on English speaking populations. Thus, native language is a somewhat unexplored factor in the research on spatial ability. Whorf (1956) proposed that a specific language, with its own unique linguistic structural properties, may determine the way that native speakers of the language perceive the world and analyze incoming information. Although this strong version of Whorf's hypothesis has not always been supported by empirical studies, a "weaker" form of this hypothesis that native language influences some aspects of human thinking has been confirmed in many studies. For example, in the field of color perception, it was found that speakers of Tarahumara, a language in which green and blue colors are categorized together as one, showed no color perception change effect across the blue-green boundary (Kay & Kemption, 1984). In the study of memory, surface structure features of a language (e.g., number of syllables) were found to positively correlate with memory span for words (Naveh-Benjamin & Ayres, 1986). It has also been found that labeling can improve memory for color (Stefflre, et al., 1966) and figures (Santa & Baker, 1975), indicating an influence of language on nonverbal memory. In numerical thinking, Miller, et al. (1995) found that the way numbers are represented in Chinese (e.g., number eleven is represented as "ten one" and number twelve as "ten two", and so on and so forth) contributed to Chinese preschoolers' advanced acquisition of number system as compared to English speaking preschoolers. Gordon (2004) found that lack of a counting system in the language of Pirahã, in which numbers are represented as one, two, or many, produced poor performance of native adult speakers of this language on numerical tasks when such tasks involved numbers more than three. In spatial navigation, Levinson (1996) found that the manner in which spatial relations are defined in a language (e.g., a spatial coordinate system with north/south/east/west for representing spatial relations versus a viewer perspective system with left/right/front/back used to represent spatial relations) affected the way speakers of that language code and represent objects' positions in a space. In the domain of time perception, Boroditsky (2001) reports that a tendency to think of time relationships "vertically" (i.e., as one event happens "up" or "down" another event) causes native Chinese speakers to respond to yes/no questions concerning time relationships (e. g., "Does June come later than September?") more quickly after vertical primes (e.g., "X is above Y") than after horizontal primes (e.g., "X is behind Y"), while native speakers of English (in which time relationship is represented "horizontally", i.e., one event happens "before" or "after" another event) had faster response to the same type of questions after horizontal primes than vertical ones.

Most previous studies on linguistic relativism have focused on the impact of certain categorization or conceptualization characteristics of a language on a native speaker's cognitive performance. In the present dissertation, another aspect of language influence was investigated, specifically, whether the acquisition and long-term use of a particular native language could affect the development of spatial ability. The focus here was on the comparison between native Chinese and native English speakers.

Chinese has two important linguistic features distinct from English that may contribute to spatial processing: tonal (vs. non-tonal in English), and logographical (vs.

alphabetic in English). First, in spoken form, English is a non-tonal tonal language (i.e., tone variation usually does not change the linguistic meaning of words) and its phonological information is processed primarily by the left hemisphere (Lieberman, 2000). In contrast, the language of Chinese has a 4-tone system. A pronunciation in Chinese can represent different semantic meanings based on varying tones. For example, a pronunciation of "shi" can mean "poem" if pronounced in the first tone, while representing "yes" if in the fourth tone. This tonal system in Chinese requires additional tonal differentiation ability compared to normal English phonological processing. Although the processing of tone in Chinese was found to be dominated by the left hemisphere (Van Lancker & Fromkin, 1973), the right hemisphere also plays a critical role, especially in the early stages of word processing (Greenwald, 2002; Luo, et al., 2006).

Secondly, in written from, the letters of English words correspond to phonemes. It is known that in English the phonological information of a word is the primary key to accessing the semantic and syntactic meaning of that word, both of which are processed via the verbal working memory and primarily mediated by the left hemisphere (Damasio, et al., 1996; Lieberman, 2000). In contrast, in Chinese, words are constructed through a combination of ideographic icons. For example, "明" (brightness) is composed of two separate icons: "日" (sun) and "月" (moon). There is no direct phonological cue or phonemes for this word. The pronunciations of "日" (pronounced as "ri") and "月" (pronounced as "yue") are different from that of "明" (pronounced as "ming"). Therefore, different from the processing of English, research has shown that visual-orthographic information of Chinese words can directly activate semantic information, especially for proficient Chinese readers, which appears to be mediated by the right hemisphere (Tzeng, et al., 1979; Wu, et al., 1998; Yan, et al., 2009).

Since language processing for Chinese involves heightened activation of the right hemisphere (Tan, et al., 2000; Tan, et al., 2001; Wu, et al., 1998), which is also presumably in charge of spatial information processing (Mazoyer, et al., 2002; Springer & Deutsch, 1998), it may be expected that native Chinese speakers have an advantage when performing various spatial tasks as compared to native English speakers. This hypothesis has been partially supported by some previous studies. For example, it has been shown that monolingual native Chinese speakers or English-Chinese speakers with the ability to write in Chinese performed better than monolingual native English speakers on several spatial tests, including the nine-dot problem (Li, 1991; Li & Shallcross, 1992), the Piagetian water-level task (Li, et al., 1999), and various other tests of image generation and manipulation (Li & Zhu, 1999). Some researchers argue that it is this constant practice in conducting spatial analyses for processing the language of Chinese that enhances a native Chinese speaker's advantage on spatial tasks (Li & Zhu, 1999).

No study to date has directly investigated the underling mechanism mediating a native Chinese speaker's spatial performance. Some research on native English speakers (Casey, et al., 1993; Linn & Peterson, 1985) suggested a positive correlation between high spatial performance and the use of a holistic strategy. Therefore, it is possible that native Chinese speakers' advantage on spatial performance is related to a tendency to use a holistic strategy. Study III of the present dissertation explored cross-language differences in strategies applied to spatial processing by comparing monolingual native English and monolingual native Chinese speakers' strategies used during the MRT. The hypothesis was that monolingual native Chinese speakers would have a greater tendency than monolingual native English speakers towards using a holistic strategy to solve the MRT problems because they may be biased from the long-term practice on holistically processing their native language.

Beside native language experience, bilingual language experience may also be an important contributor to spatial ability. Bilingual experience has been shown to be associated with certain cognitive advantages. Several studies report that bilinguals possess larger verbal working memory spans (Harrington, 1992; Ransdell, et al., 2006; Veii & Everatt, 2005) and increased metalinguistic awareness than monolinguals (Bialystok, 1991; Bialystok, 1999; Rodriguez-Fornells, et al., 2006). These advantages are thought to be associated with a bilingual's enhanced executive function ability resulting from the acquisition and practice of a second language (Bialystok, et al., 2006). Bilinguals' cognitive advantage related to enhanced executive function ability may not only be limited to verbal task performance. Some studies demonstrated that bilinguals have stronger divergent and creative thinking abilities than monolinguals due to their superior executive function ability (Cummins & Gulutsan, 1974; Lambert, et al., 1973; Kessler & Quinn, 1987). Moreover, according to Miyake, et al. (2001), executive function ability is positively correlated with certain spatial performance abilities: largest with spatial visualization and smallest with perceptual speed. In support of this argument bilinguals were found to show advantages on some spatial visualization tasks and imagery manipulation tasks comparing to monolinguals (Diaz, 1982; Mcleay, 2003). In another study, Mcleay (2003) tested a group of Welsh/English bilinguals using a knotted rope test (a type of mental rotation test, in which pairs of knotted rope at varying orientations are presented and a participant is required to decide whether or not each pair consists of two alike knotted rope in different orientations) and found that bilinguals were better than monolinguals in both speed and accuracy on the test, especially when the knots became more complex. Importantly, bilinguals' advantage on spatial performance may be related to a stronger tendency to use a holistic strategy during spatial processing as compared to monolinguals. For example, Ransdell and Fischler (1991) asked bilinguals to finish a series of self reported measures on vividness of visual imagery and a Space Relation Test in which the participants were required to imagine how a 2-dementional figure can be "unfolded" into 3-dimentional shapes. Based on self reports, they found that bilinguals had a greater tendency than monolinguals to rely on imagery when coding such information, which helped them excel on the Space Relation Test. Notably, thinking based on mental imagery is thought to be required in spatial manipulation and may indicate the use of a holistic strategy (Richardson, 1991; Shepard & Metzler, 1971).

To date, no previous studies have directly investigated bilinguals' strategies on spatial tasks. Study III of the present dissertation included a bilingual group in search of the impact of bilingual experience on mental rotation performance and strategy use. Specifically, Chinese-English bilinguals were compared to monolingual native Chinese speakers on their MRT performance and strategy use, with the hypothesis that bilingual language experience might enhance MRT performance by facilitating the use of a holistic strategy.

CHAPTER II

THE PRESENT DISSERTATION

The present dissertation involves three studies. Study I was designed to explore monolingual native English speakers' strategy differences during the performance of the Vandenberg and Kuse MRT (1978) as a function of sex and college major (i.e., physical science vs. social science). Specifically, a group of monolingual native English speakers with different sex and college majors were tested on the MRT with a focus on the strategies they applied to solve the MR problems by using a dual-task paradigm (i.e., participants are required to perform the MRT while keeping a verbal or a spatial load in memory). Study II was designed to use EEG technique to further investigate brain activation differences among monolingual native English speakers during the same MRT performance, this as a corroboration of the behavioral data obtained from Study I. Study III was designed to investigate how language experience might affect MRT performance level as well as MR strategy use. Specifically, a group of monolingual native Chinese speakers and a group of Chinese-English bilinguals were studied on their MRT performance, and their results were compared to those obtained from the monolingual native English speakers. The objective here was to find evidences supporting an advantage of acquiring a native logographic language such as Chinese and the benefit of being bilingual on the MRT performance, as compared to monolingual native English speakers.

Study I

Introduction

The primary goal of Study I was to investigate the influence of sex and college major on the strategies used during mental rotation (MR) among monolingual native English speakers. A group of monolingual native English speakers with different sex and college majors were selected as the participants. The 3-dimensional Vandenberg and Kuse MRT (1978) was used as a measure of spatial ability because the MRT is usually thought as one of the "true" spatial tasks and has been shown to produce the largest effect size between the sexes (Kimura, 1999).

Mental rotation may be performed using different strategies. According to Gluck and Fitting (2003), the strategies employed in MR can be conceived to be on a continuum from an analytic strategy (i.e., verbally labeling and comparing the parts of an object to the parts of a target) to a holistic strategy (i.e., mentally rotate the image of an object to match with the image of a target using no words). In the middle of this continuum would be a combined strategy (i.e., the combination of verbal and imagery processing). Linn and Peterson (1985) argue that a mental rotation test can be performed using either a holistic or an analytic strategy, but a holistic strategy is optimal.

Participants may prefer different strategies for MR depending on their sex and college major. Based on the literature discussed earlier (Casey, et al., 1990; Casey & Brabeck, 1989; Casey, et al., 1993; Heil & Jansen-Osmann, 2008; Lavach, 1991; Moody, 1998; Moore, 2003; Raabe, et al., 2006; Zegas, 1976), it was hypothesized in Study I that male participants would outperform female participants on the MRT by showing a stronger tendency towards using a holistic strategy (i.e., holistically manipulating images).

Similarly, physical science majors were hypothesized to outperform social science majors on the MRT by showing a stronger tendency towards using a holistic strategy.

In a previous study, Quaiser-Pohl and Lehmann (2002) found that sex interacted with college major in predicting participants' performance accuracy on the Vandenberg and Kuse MRT: sex differences on MRT score (i.e., males outperforming females) was largest with college students majoring in social science and smallest with those majoring in physical science. Based on this finding, the present study hypothesized a similar interaction effect between sex and college major on both performance accuracy and strategy preference during the MRT, i.e., there would be a larger sex difference in performance accuracy and preferred strategies (i.e., males outperform females, with males employing a holistic strategy and females an analytic or a combined strategy) on the MRT among social science majors than among physical science.

To study what types of strategy were used by these groups of participants, a dual task paradigm adapted from Moore (2003) was used. All participants were asked to perform the MRT while maintaining a low-demanding verbal or spatial concurrent memory load (see Appendix B and C). By using a dual task paradigm, the priming effect of the concurrent loads (spatial or verbal) on the MRT performance was assessed relative to the MRT performance without a concurrent load. Thus, the underlying MR strategies could be inferred from the following patterns: if a participant uses a holistic MR strategy, his/her MRT performance will be primed during the spatial concurrent load condition, as compared to the no load condition. If he/she uses an analytic MR strategy, his/her MRT performance will be primed during the verbal concurrent load condition, as compared to the no load condition. If he/she uses a combined MR strategy, then his/ her MRT performance during the concurrent load conditions will be the same as that in the no load condition.

Notably, in the present study, the concurrent tasks (i.e., the verbal and the spatial memory load) were expected to prime rather than impair the performance on the primary task (i.e., the MRT). This is different from a set of previous findings suggesting an impairing effect of the concurrent task on the primary task, especially when the nature of the concurrent task is similar to that of the primary task (Pelligrino, et al., 1975; Warren, 1977). However, as argued by other researchers (Hellige, 1993; Hellige & Cox, 1976; Kinsbourne, 1973, 1975; Kinsbourne, 1975; Kinsbourne & Cook, 1971; Kinsbourne & Hicks, 1978; O'Boyle, et al., 1987), a concurrent task can actually prime the performance on the primary task if the concurrent task is relatively simple and has low demand on cognitive resources. The rationale is that the low-demanding concurrent task can stimulate neural arousal and thus increase the processing resources and speed of cognitive functioning. In one previous study (Li & O'Boyle, 2008) using dual-task paradigm with the same testing materials as those in the present study, it was demonstrated that the concurrent tasks (both the verbal and the spatial tasks) were relatively easy and primed (rather than impaired) the primary MRT task. Therefore, a priming effect of the concurrent tasks on the MRT performance was expected in the present study.

Methods

Participants

Sixty monolingual native English speakers with an average age of 23.8 (SD = 7.03) were recruited from the Texas Tech University as participants. Within this group, 30 were majoring in social science (15 females and 15 males) and 30 were majoring in physical science (15 females and 15 males).

Materials

Mental rotation problems were 20 items adapted from the Vandenberg and Kuse MRT (1978, see Appendix A). Each MRT problem consists of a target figure followed by four comparison figures. Two of the four comparison figures match the target figure after rotated in 3-D space, with the other two figures serving as distracters. Participants were asked to find out the two correct choices as quickly as possible. Five sets of 6 low-imagery English nouns (see Appendix B) were used as the verbal concurrent load. Each noun in the sets consists of 6 to 8 letters and has a mean imagery (low) rating of approximately 2.75 (Paivio, Yuille, & Madigan, 1968). Five 24-point Vanderplas and Garvin forms (1959) served as the spatial concurrent load. These forms are random shapes with low verbal association value according to the Vanderplas and Garvin association value scale (1959). Following a similar design by O'Boyle, et al. (1987), "exploded" shapes were created by visually splitting the original random shapes into quadrants (see Appendix C). Participants were shown the split figure on a 3 cm x 3 cm index card and asked to imagine what the original intact shape might look like when mentally pulling the quadrants together towards the center to form a whole. Later, participants were asked to point out the original intact figure on a 17 cm x 12 cm card with 30 similar figures in total.

Procedure

Prior to the test, participants were seated at a table and completed a consent form and a handedness questionnaire (Edinburgh Handedness Inventory, Oldfield, 1973). They were then provided with written instructions describing the MRT task and were subsequently asked to complete three practice MRT items. After practice, the formal test started.

In the no load condition, 20 MRT problems were presented one at a time, and participants were given a 20 sec time limit to solve each MRT problem. In the concurrent verbal load condition, an index card with six nouns printed on it was presented for 60 sec and participants were asked to memorize the words. They were then asked to complete a block of four MRT problems with a 20 sec time limit for each problem. Afterwards, they were asked to orally report the six nouns memorized before the MRT performance. This sequence was repeated 5 times for a total of 30 words and 20 MRT items. In the concurrent spatial load condition, participants were given 10 sec to memorize a split random shape and then complete a block of four MRT problems. After the MRT problems, they were asked to find out the intact shape corresponding to that split random shape from 30 similar figures presented on a card. This sequence was repeated 5 times for total of 5 split random shapes and 20 MRT items.

The sequence of these three experimental conditions (i.e., no load, verbal load, and spatial load) was presented to the participants in a randomized way to eliminate an order effect.

Data Coding

For the MRT problems, the participants received one point if they correctly identified the two test objects that match the rotated target object; zero points otherwise (score range: 0-20). For the concurrent verbal and spatial tasks, the participants received one point for each word or figure correctly retrieved (score range for word: 0-30; for figure: 0-5).

Results

There were eight left handed participants (5 social science majored females, 1 social science majored male, and 2 physical science majored males) in the data. Preliminary analysis did not show a significant main effect for handedness or age. Therefore, all the data entered a 2 (Sex: female vs. male) x 2 (Major: social science vs. physical science) x 3 (Condition: no load, verbal load, and spatial load) mixed ANOVA analysis with the participants' MRT score as the dependent variable. Sex and Major were the between-subject variables and condition was the within-subject variable. The means and standard deviations were shown in Table 1.

Table 1. *Means and SDs for monolingual English speakers' performance on the MRT across the three experimental conditions*

Sex	**Major**	**No load**		**Verbal load**		**Spatial load**	
		Mean (max=20)	SD	Mean (max=20)	SD	Mean (max=20)	SD
Female	Social Science	8.07	3.17	8.73	3.65	7.87	4.03
	Physical Science	8.20	1.86	10	2.67	9.67	2.53
Male	Social Science	6.67	3.06	10.67	4.40	7.60	3.89
	Physical Science	12.33	2.94	11.33	4.10	15.20	2.86

One significant main effect was found for Sex {F (1, 56) = 5.57, $p < .05$; partial eta^2 = .09}, showing that males outperformed females on the MRT. Another significant main effect was found for Major {F (1, 56) = 12.87, $p < .01$; partial eta^2 = .19}, showing that the physical science majors outperformed the social science majors on the MRT. Condition was also significant {F (2, 112) = 13.83, $p < .001$; partial eta^2 = .20}, showing that, overall, the participants had better performance on the concurrent verbal load and the concurrent spatial load conditions than on the no load condition {t (59) = 3.71, $p < .001$; t (59) = 3.81, $p < .001$, respectively}, while no significant performance difference existed between the two concurrent load conditions.

One significant two-way interaction effect was found for Sex x Major {F (1, 56) = 5.05, $p < .05$, partial eta^2 = .08}, showing physical science males' averaged MRT score across the three experimental conditions being significantly higher than physical science females' {F (1, 28) = 14.57, $p < .01$, partial eta^2 = .34}, while there was no significant sex difference on the MRT scores among the social science majors.

Two more significant interaction effects were found for Condition x Major {F (2, 112) = 20.76, $p < .001$, partial eta^2 = .27} and for Condition x Sex x Major {F (2, 112) = 19.52, $p < .001$, partial eta^2 = .26}. To explore these interaction effects, follow-up 2 (Major) x 3 (Condition) mixed ANOVAs were done separately for females and males.

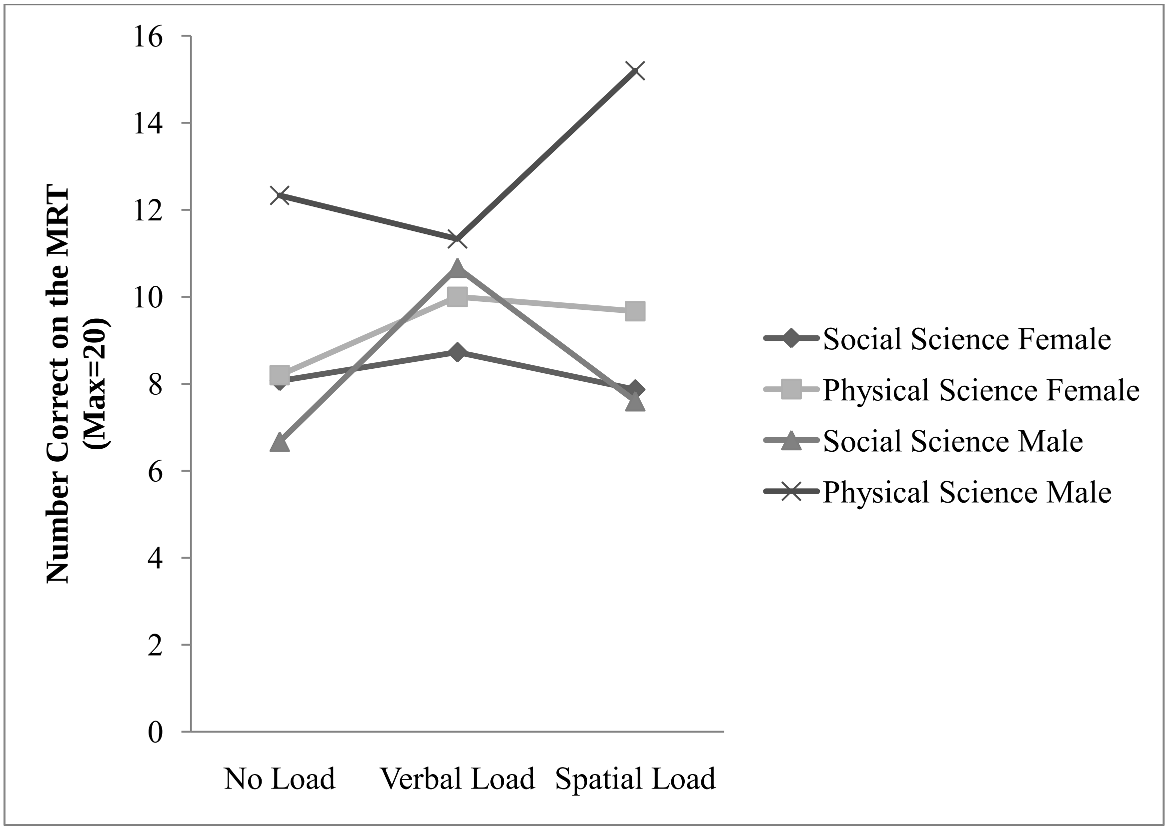
Data for Females

The data for all the females entered a 2 (Major) x 3 (Condition) mixed ANOVA. Only one significant main effect for Condition was found: F (2, 56) = 4.78, $p < .05$; partial eta^2 = .15}. Post-hoc t tests found that this significant main effect was solely driven by the female participants significantly better MRT performance on the concurrent verbal load condition than on the no load condition {t (29) = 3.54, $p < .01$}, while no difference was found for their MRT scores between the concurrent spatial load and the no load conditions, or between the concurrent verbal load and the concurrent spatial load conditions.

Data for Males

The data for all the males entered a 2 (Major) x 3 (Condition) mixed ANOVA. One significant main effect was found for Major {F (1, 28) = 14.51, p < .01; partial eta^2 = .34} and for Condition {F (2, 56) = 11.36, p < .001; partial eta^2 = .29}. One significant two-way interaction effect was found for Condition x Major {F (2, 56) = 36.22, p < .001; partial eta^2 = .56}. Follow-up *t* tests on this interaction effect found that the social science males' MRT performance on the concurrent verbal load condition was significantly better than that on the concurrent spatial load and no load conditions {t (14) = 7.74, p < .001; t (14) = 8.37, p < .001, respectively}, while there was no performance difference between the concurrent spatial load and the no load condition for them. The physical science males showed an opposite pattern. Their MRT performance on the concurrent spatial load condition was significantly better than those on the concurrent verbal load and no load conditions {t (14) = 5.56, p < .001; t (14) = 5.47, p < .001, respectively}, while there was no performance difference between the concurrent verbal load and no load conditions. Different priming patterns for all the participants were shown in Figure 1.

Figure 1. *Monolingual native English speakers' MRT performance across the three experimental conditions*



Concurrent Load Data

2 (Sex) x 2 (Major) ANOVAs on the concurrent loads did not yield a significant difference between the two sexes or the two types of college majors. Descriptive indexes for performance on concurrent load tasks were shown in Table 2.

Table 2. *Means and SDs for monolingual English speakers' performance on the concurrent tasks*

	Verbal		Spatial	
	Mean (max=30)	SD	Mean (max=5)	SD
Female Social science	24.40	2.70	2.93	1.16
Female Physical science	26.73	2.49	2.33	1.18
Male Social science	25.13	3.64	3.13	0.99
Male Physical science	24.27	4.13	2.53	1.46

Discussion

The results from Study I basically supported the hypotheses regarding the influence of the two factors of sex and college major on MRT performance accuracy for monolingual native English speakers. Overall, male participants outperformed female participants, and physical science majors outperformed social science majors on the MRT, replicating previous findings on MR ability. Moreover, the factors of sex and college major were found to interact with each other when predicting MRT performance level. Specifically, males and females in social science were not significantly different from each other on their MRT scores, while physical science males significantly outperformed physical science females. Notably, these results contradict the findings in Quaiser-Pohl and Lehmann' study (2002). According to their report, sex difference on MR scores (i.e., males outperform females) was larger among social science majors than among physical science majors. To understand this contradiction, studies designed to replicate the interaction effect between sex and college major on MR will be needed.

The hypothesis regarding strategy difference as a function of sex and college major was also supported by the data. The participants' MRT performance across the three experimental conditions revealed different strategies employed by them for the MRT. Specifically, social science males' MRT performance was primed by the concurrent verbal task, suggesting the use of an analytic strategy, while physical science males' MRT performance was primed by the concurrent spatial task, indicating the use of a holistic strategy. Females, regardless of their college major, had best performance on the MRT when doing a concurrent verbal task. However, their MRT performance on the verbal concurrent load condition did not significantly differ from that on the spatial concurrent load condition. This fact may imply that they were less "analytic" than social science males when processing the MRT. In other words, the strategy they used for the MRT was more of a combined strategy than a pure analytic strategy.

Interestingly, different strategies used by the participants seemed to be able to predict their performance scores on the MRT. The physical science males, being the only group employing a holistic strategy, had the highest average MRT scores among all the groups. Using combined strategies, female participants across both social science and physical science majors ranked the second highest on the averaged MRT score. With an analytic strategy, the social science males ranked lowest on the averaged MRT score (it should be noted, however, that while the physical science males significantly outperform both the females and the social science males, the females did not significantly outperform the social science males on the MRT). This pattern supports Linn and Peterson' claim that a holistic strategy is the most suitable strategy for mental rotation tasks (1985).

Study II

Introduction

The objective of Study II was to examine monolingual native English speakers' brain activation during the MRT, in order to search for neuropsychological evidence of different MR strategies employed by monolingual native English speakers as a function of their sex and college majors. EEG is a technique with high temporal resolution (i.e., sensitive to brain wave changes occurring over time) and is thought to be suitable for tapping ongoing activity in the brain for long and complex tasks (Springer & Deutsch, 1998). With these advantages, EEG was used in Study II to monitor participants' brain activation during the MRT.

It is well known that the right hemisphere dominates spatial processing (Springer & Deutsch, 1998, Mazoyer, et al., 2002, Vogel, et al., 2003). The right hemisphere, especially right parietal lobe, is the critical brain area for 3-D imagery, because it plays a primary function in the manipulation and rotation of images (Gill, et al., 1998; Harris & Miniussi, 2003; Podzebenko, et al., 2005). In contrast, the left hemisphere, especially the left frontal lobe, is found to be important for sequential analysis of verbal information (Cohen, et al, 1994; Braver, et al., 1997).

It was hypothesized in the present study that the strategy differences among different groups of monolingual native English speakers (as determined by their sex and college majors) on the MRT observed in Study I would be manifest on different hemispherical activation patterns for these different groups. Specifically, physical science males, being the group that employed a holistic strategy (i.e., holistically processing and rotating the images of stimuli) for the MRT in Study I, would primarily rely on their right hemisphere, especially their right parietal lobe to process the MRT. Social science males used an analytic strategy (i.e., processing the stimuli based on some verbal-naming and step-by-step detail analysis methods) for the MRT in Study I. They were hypothesized to primarily activate their left hemisphere, especially their left frontal lobe for the MRT processing. Females, regardless of their college major, tended to use a combined analytic/holistic strategy for the MRT in Study I, were expected to activate both their left and right hemisphere for the MRT. Notably, even though brain activation differences between males and females (i.e., males have stronger activation in right hemisphere than females) had been reported in some previous studies using various mental rotation tests and different neuroimaging techniques, such as event-related potential (Gootjes, et al., 2008), functional magnetic resonance imaging (Jordan, et al., 2002; Weiss, et al. 2003) and EEG (Gill & O'Boyle's, 1997; 2003; Roberts & Bell, 2000), no studies to date have investigated the brain activation differences during spatial performance between physical science and social science majors. To understand how the factors of sex and college major interact and impact on strategy use during MR in terms of brain activation patterns, Study II was designed to include both sexes in the two types of college majors (i.e., social science and physical science majors) to test the above mentioned hypotheses via the use of EEG.

For this study, a group of monolingual native English speakers were selected to perform both the Vandenberg and Kuse Mental Rotation Test (1978) and a base-line match task (i.e., a visual match task comparable to the MRT but requiring no rotation) while having their brain activity monitored using EEG. Since the base-line match task requires simple visual analysis and no rotation, participants' EEG activation during the

MRT could be compared to that during the base-line task match task to determine the distinct brain areas they relied upon for MRT processing.

EEG waves can be divided into different bandwidths with different frequencies. Among all EEG bands, the beta bandwidth (13Hz-30Hz) has been conventionally used as an index of higher cognition activity (i.e., beta power positively correlates with the effort for a higher cognitive activity, see Haenschel, et al., 2000; Singer, 1993). Therefore, the present study examined the participants' beta band power among different groups across different experimental conditions in search of evidences of different activation patterns for different MR strategies.

Methods

Participants

40 monolingual native English speakers with a mean age of 24.95 (SD = 6.44) were recruited from Texas Tech University. Among them, 20 were majoring in social science (10 females and 10 males) and 20 were majoring in physical science (10 females and 10 males). Among the participants, only two were left-handed (one social science female and one physical science female).

Materials

Adapted from the study done by Gill, et al. (1998), two experimental conditions (a match and a rotation condition) were designed via the use of E-Prime 1.0 software. In the base-line match condition (20 trials, see Appendix D) participants were asked compare a target figure to four choice figures with two figures matching the target and the other two being mirror reversals of the target. In the rotation condition (20 trials), participants were tested on the standard Vandenberg and Kuse (1978) MRT. Each match trial lasts 10 seconds, while each rotation trial lasts 20 seconds. The presentation sequence consists of two match trials followed by two rotation trials with each trial followed by a 2 second blank interval. The total running time for the stimuli presentation sequence was 11minutes and 20 seconds.

Procedure

During the EEG test, the participants were seated in a sound-proof chamber and the visual displays were presented on a computer screen set approximately 60 cm in front of them. After signing a consent form, participants completed a handedness questionnaire (Edinburgh Handedness Inventory, Oldfield, 1973) and a demographic questionnaire. Then a 32-channel (channel assignments were in accordance with the international 10-20 system, Binnie, et al., 1982, see Appendix E) EEG system was set up to connect to the participants' scalp through an elastic EEG cap. The impendence of each electrode was kept under 5 KΩ. Sampling rate was set as 500 Hz. EEG signals were filtered through a low pass of 50 Hz and a high pass of 0.15Hz. Participants were asked to place four fingers (i.e., left middle finger, left index finger, right index finger, and right middle finger) correspondently on a four-button (set from left to right, corresponding to the 4 choices of each test item presented from left to right on the screen) keyboard placed in front of them. They were instructed to press on the corresponding buttons as soon as they decided on the two correct choices for each test item. After instruction and practice, participants EEG signal was collected the same time as they went through the test. Artifacts (segments with power exceeding ±100 microvolts) were examined and removed from the data via the standard off-line analysis procedure in the Scan 4.4 software, with the removed artifact being 3.02% of the total. Beta power was extracted from the EEG data through a standard Fast Fourier Transform (FFT) algorithm (Brigham, 2002) and averaged for each experimental condition (i.e., match vs. rotation).

Results

Behavioral Data

A 2 (Task: Match vs. Rotation) x 2 (Sex: Male vs. Female) x 2 (College Major: Social science vs. Physical science) mixed ANOVA was performed on the participants' behavioral data. Sex and College Major were the between-subject variables, and Task was the within-subject variable. The dependent variable was the total numbers of the participants' correct response on the two tasks (i.e., match and rotation). The descriptive indexes of the behavioral data were shown in Table 3.

Table 3. *Correct numbers of monolingual native English speakers' performance on the base-line match task and the rotation task*

	Match		Rotation	
	Mean (max=20)	SD	Mean(max=20)	SD
Male physical science	19.80	0.42	14.70	2.31
Female physical science	18.30	3.06	7.10	2.77
Male social science	16.30	5.14	5.10	3.18
Female social science	17.50	2.68	8.00	4.08

The results yielded a significant main effect for Task: $F(1, 36) = 178.93$, $p < .001$, partial $eta^2 = .83$, showing that the participants' performance on the base-line match condition was significantly better than that on the rotation condition. A significant main effect for Major was also found: $F(1, 36) = 18.92$, $p < .001$, partial $eta^2 = .35$, showing an overall better performance of the physical science majors than the social science majors on both conditions.

One significant two-way interaction for Major x Sex was found: F (1, 36) = 19.51, $p < .001$, partial eta^2 = .35. One significant three-way interaction for Condition x Major x Sex was also found: F (1, 36) = 7.95, $p < .001$, partial eta^2 = .18. To interpret these interaction effects, follow-up 2 (Major) x 2(Sex) ANOVA analyses were done separately for the Match condition and the Rotation condition.

In the base-line Match condition, a 2 (Major) x 2(Sex) ANOVA yielded no significant results, indicating that all groups of participants performed equally well on the simple match task.

In the Rotation condition, a 2 (Major) x 2(Sex) ANOVA yielded a significant main effect for Major {F (1, 36) = 19.03, $p < .001$, partial eta^2 = .35}, showing better MRT performance of the physical science majors than the social science majors. Sex was also significant {F (1, 36) = 5.56, $p < .05$, partial eta^2 = .13}, showing an advantage of the males on the MRT relative to the females. A significant two-way interaction effect was also found for Major x Sex: F (1, 36) = 27.73, $p < .001$, partial eta^2 = .44. Follow-up t tests on this two-way interaction showed that physical science males significantly outperformed the social science males on the MRT{t (18) = 7.73, $p < .001$}, while the physical science female did not differ from the social science females on the MRT scores.

EEG Data

To focus on the hemispheric areas concerning the hypothesis in Study II, participants' beta power was averaged for the following hemispheric locations: right frontal (F4, F8, FC4), left frontal (F3, F7, FC3), right parietal (P4, P8), left parietal (P3, P7), right temporal (T8) and left temporal lobes (T7) (for the location of each electrode, see Appendix E).

A 2(Task: match vs. rotation) x 2(Hemisphere: left vs. right) x 3(Location: frontal, parietal, temporal) x 2(Sex: male vs. female) x 2(College major: physical science vs. social science) mixed ANOVA was performed with beta power as the dependent variable. Sex and College major were the between-subject variables, and the other three were the within-subject variables. One significant main effect was found for Location {F (2, 72) = 7.61, $p < .01$, partial eta^2 = .17}. Overall, the participants' frontal lobe exhibited stronger beta power than their parietal and temporal lobe {t (39) = 2.64, $p < .05$; t (39) = 2.87, $p < .01$, respectively} across both match and rotation tasks.

Three significant two-way interaction effects were found for Location x Major {F (2, 72) = 3.60, $p < .05$, partial eta^2 = .09}, Task x Location {F (2, 72) = 25.49, $p < .001$, partial eta^2 = .42}, and Hemisphere x Location {F (2, 72) = 15.21, $p < .001$, partial eta^2 = .30}. Six significant three-way interaction effects were found for Hemisphere x Sex x Major {F (1, 36) = 8.26, $p < .01$, partial eta^2 = .19}, Location x Sex x Major {F (2, 72) = 6.32, $p < .01$, partial eta^2 = .15}, Task x Location x Sex {F (2, 72) = 5.10, $p < .01$, partial eta^2 = .12}, Task x Location x Major {F (2, 72) = 14.99, $p < .001$, partial eta^2 = .19}, Hemisphere x Location x Sex {F (2, 72) = 4.19, $p < .01$, partial eta^2 = .10}, and Task x Hemisphere x Location {F (2, 72) = 30.40, $p < .001$， partial eta^2 = .46}. Also, four significant four-way interaction effects were found for Task x Hemisphere x Sex x Major {F (1, 36) = 11.26, $p < .01$, partial eta^2 = .24}, Task x Location x Sex x Major {F (2, 72) = 22.17, $p < .001$, partial eta^2 = .38}, Task x Hemisphere x Location x Sex {F (2, 72) = 34.06, $p < .001$, partial eta^2 = .49}, and Task x Hemisphere x Location x Major {F (2, 72)

= 12.40, $p < .001$, partial eta^2 = .26}. Finally, one significant five-way interaction effect was found for Task x Hemisphere x Location x Sex x Major {F (2, 72) = 15.25, $p < .001$, partial eta^2 = .30}. To clarify these complex interaction effects, the following 2(Hemisphere) x 3(Location) x 2(Sex) x 2(Major) mixed ANOVA analyses were done separately for the base-line match condition and the mental rotation condition.

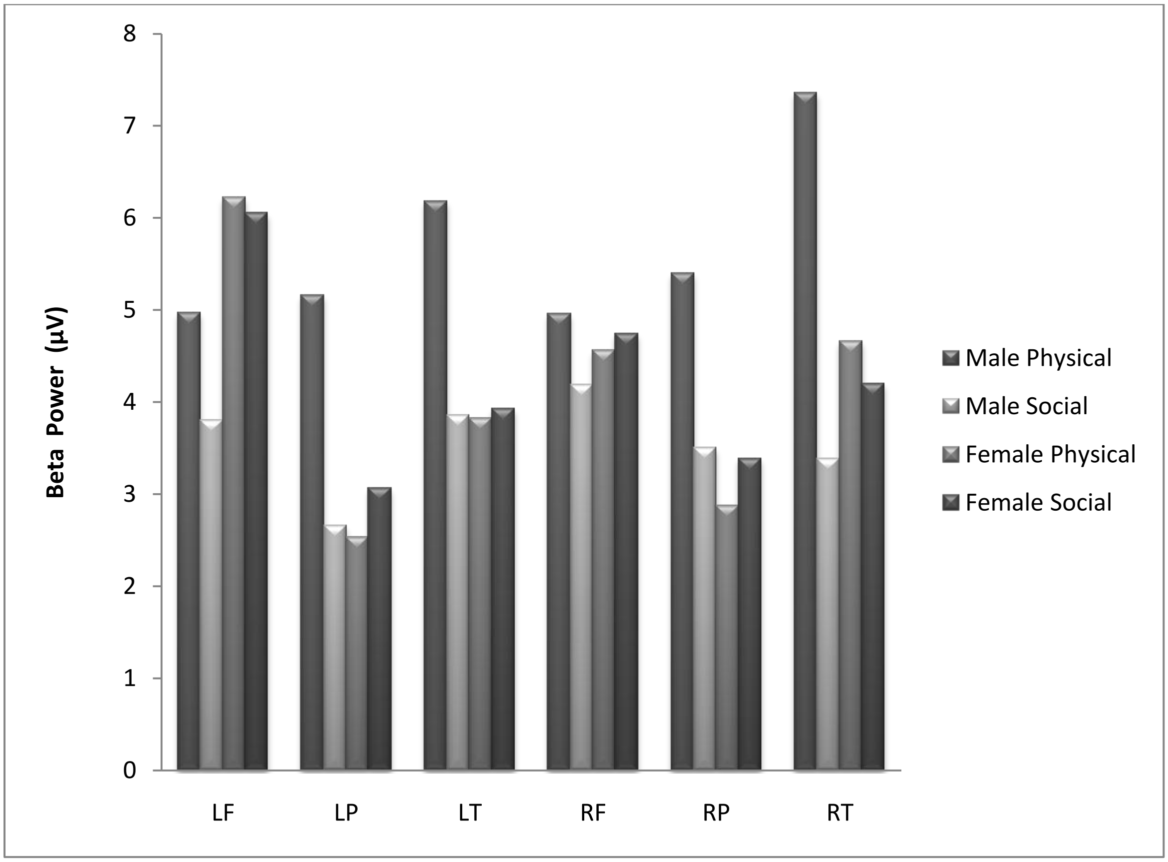
Beta activation on the base-line match task

A 2(Hemisphere) x 3(Location) x 2(Sex) x 2(Major) mixed ANOVA was performed with the Beta power in the base-line Match condition as the dependent variable. Sex and Major were the between-subject variables, and the other two were the within-subject variables.

This analysis yielded one significant main effect for location {F (2, 72) = 5.04, $p < .01$, partial eta^2 = .12}. Overall, participants' beta activation in their frontal lobe and temporal lobe was stronger than that in their parietal lobe for processing the match task {t (39) = 2.57, $p < .05$; t (39) = 2.84, $p < .01$, respectively}.

One significant two-way interaction for Location x Sex was also found {F (2, 72) = 3.38, $p < .51$, partial eta^2 = .09}, showing that the male participants did not have significant beta activation differences across these hemispheric locations, while the female participants' beta activation in their frontal and temporal lobe was stronger than that in their parietal lobe {t (19) = 2.55, $p < .05$; t (19) = 2.26, $p < .01$, respectively} (see Figure 2).

Figure 2. *Monolingual native English speakers' Beta activation patterns on the base-line match task*



Note: LF=left frontal; LP=left parietal; LT=left temporal; RF=right frontal; RP=right parietal; RT=right temporal.

Beta activation on the rotation task

A 2(Hemisphere) x 3(Location) x 2(Sex) x 2(Major) mixed ANOVA was performed with beta power in the Rotation condition as the dependent variable. Sex and College major were the between-subject variables, and the other two were the within-subject variables.

One significant main effect was found for Location {F (2, 72) = 14.22, $p < .001$, partial eta^2 = .28}, showing that, overall, the participants had stronger beta activation in their frontal lobe than their parietal lobe and their temporal lobe {t (39) = 2.28, $p < .05$; t (39) = 4.49, $p < .001$, respectively}.

Three significant two-way interaction effects were found for Hemisphere x Major {F (1, 36) = 8.06, $p < .01$, partial eta^2 = .18}, Location x Major {F (2, 72) = 8.79, $p < .001$, partial eta^2 = .20} and for Hemisphere x Location {F (2, 72) = 32.95, $p < .001$, partial eta^2 = .48}. Four significant three-way interaction effects were found for Hemisphere x Sex x Major {F (1, 36) = 22.01, $p < .001$, partial eta^2 = .38}, Location x Sex x Major {F (2, 72) = 15.21, $p < .001$, partial eta^2 = .30}, Hemisphere x Location x Sex {F (2, 72) = 17.90, $p < .001$, partial eta^2 = .33}, and Hemisphere x Location x Major {F (2, 72) = 4.70, $p < .05$, partial eta^2 = .12}.One significant four-way interaction effect was found for Hemisphere x Location x Sex x Major {F (2, 72) = 9.08, $p < .001$, partial eta^2 = .20}.To separate these complex interaction effects, the follow-up 2(Hemisphere) x 3 (Location) x 2 (Major) mixed ANOVA analyses were done separately for females and males.

Females' beta activation on the rotation

For the female participants, a 2 (Hemisphere) x 3 (Location) x 2 (Major) mixed ANOVA yielded only one significant main effect for Location {F (2, 36) = 6.92, $p < .01$, partial eta^2 = .28}. Females had stronger beta activation in their frontal lobe than in their parietal and temporal lobes {t (19) = 2.66, $p < .05$; t (19) = 2.91, $p < .01$, respectively} for the rotation task.

Males' beta activation on the rotation

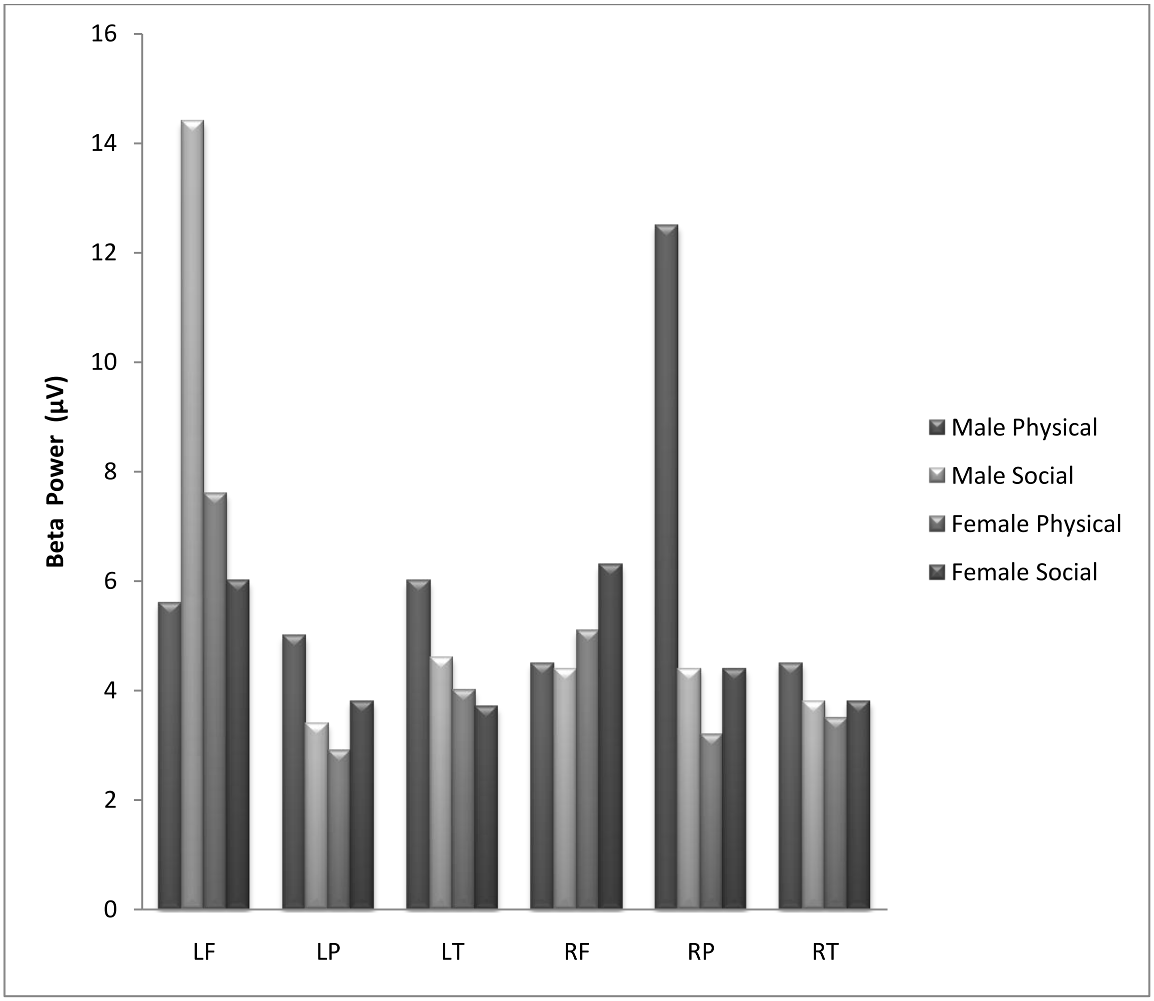
For the male participants, a 2 (Hemisphere) x 3(Location) x 2(Major) mixed ANOVA yielded one significant main effect for Hemisphere {F (1, 18) = 5.52, $p < .05$, partial eta^2 = .24}, showing that, overall, the males had stronger beta activation in their left hemisphere than in their right hemisphere when doing the rotation task. A main effect of Location was also significant {F (2, 36) = 11.31, $p < .001$, partial eta^2 = .24}, showing that males had stronger beta activation in their frontal and parietal lobe than in their temporal lobe {t (19) = 3.10, $p < .01$; t (19) = 2.91, $p < .01$, respectively}. Three significant two-way interaction effects were found for Location x Major {F (2, 36) = 37.79, $p < .001$, partial eta^2 = .68}, Hemisphere x Location {F (2, 36) = 87.31, $p < .001$, partial eta^2 = .83}, and Hemisphere x Major {F (1, 18) = 47.97, $p < .001$, partial eta^2 = .73}. One significant three-way interaction effect was also found for Hemisphere x Location x Major: F (2, 36) = 22.39, $p < .001$, partial eta^2 = .55. To understand these interaction effects, follow-up 2(Hemisphere) x 3(Location) repeated ANOVAs were done separately for the social science males and physical science males.

For the social science males, a 2(Hemisphere) x 3(Location) repeated ANOVA yielded significant main effects for Hemisphere {F (1, 9) = 78.39, $p < .001$, partial eta^2

= .90}, and Location {F (2, 18) = 69.53, $p < .001$, partial eta^2 = .89}. Overall, social science males had stronger beta activation in their left hemisphere than in their right hemisphere during the rotation task. Social science males also had stronger beta activation in their frontal lobe than in their parietal and temporal lobe {t (9) = 8.32, $p < .001$; t (9) = 10.57, $p < .001$, respectively}. One significant two-way interaction effect was found for Hemisphere x Location {F (2, 18) = 91.09, $p < .001$, partial eta^2 = .91}. Post-hoc t tests showed that, for social science males during the rotation task, beta activation in the three locations (frontal, parietal, and temporal) on the right hemisphere did not differ from each other; while beta activation in the left frontal lobe was significantly stronger than that in the left parietal and the left temporal lobes {t (9) = 16.00, $p < .001$; t (9) = 10.30, $p < .001$, respectively}.

For the physical science males, a 2(Hemisphere) x 3(Location) repeated ANOVA yielded significant main effects for Hemisphere {F (1, 9) = 7.22, $p < .05$, partial eta^2 = .45}, and Location {F (2, 18) = 10.28, $p < .01$, partial eta^2 = .53}. The physical science males had stronger beta activation in their right hemisphere than their left hemisphere during the rotation task. In terms of location, they had stronger activation in their parietal lobe than in their frontal and temporal lobes {t (9) = 4.94, $p < .01$; t (9) = 3.31, $p < .01$, respectively}. One significant two-way interaction effect was also found for Hemisphere and Location {F (2, 18) = 35.40, $p < .001$, partial eta^2 = .80}, showing that physical science males had stronger beta activation in their right parietal lobe than their right frontal and right temporal lobe {t (9) = 6.96, $p < .001$; t (9) = 4.77, $p < .01$, respectively}, while there was no difference of beta activation among the three locations (frontal, parietal, and temporal) on their left hemisphere (See Figure 3).

Figure 3. *Monolingual native English speakers' Beta activation pattern on the rotation task*



Note: LF=left frontal; LP=left parietal; LT=left temporal; RF=right frontal; RP=right parietal; RT=right temporal.

Discussion

Study II replicated and extended the findings from Study I. First, the behavioral data from Study II were consistent with the findings in Study I. As expected, on the performance during the base-line match task, no significant differences were observed between the two sexes and the two types of college majors. In contrast, on performance during the rotation task, a significant main effect of sex favoring the males and a significant main effect of major favoring the physical science majors were found. This pattern of the main effects of sex and college major was consistent with the pattern found in Study I, and in line with previous literature. Moreover, the physical science males outperformed the social science males on the MRT, while the female students' MR performance did not differ between the two types of college majors. This interaction pattern between sex and college major was also consistent with the findings in Study I. Overall, the behavioral data in Study II collaborated the findings of Study I suggesting that both sex and college major are important factors interactively influencing MR performance.

Moreover, sex and college major were found to predict strategy use during the MRT as evidenced by the neuropsychological findings in Study II. The EEG data in Study II supported the hypothesis that college students prefer different MR strategies based on their sex and college majors. As expected, during the performance on the base-line match task, the participants activated their temporal lobe (which may be involved in determining the meaning related to the test stimuli) and frontal lobe (which may be related to the decision making process for finding the correct solution) but did not active much of their parietal lobe, since no active manipulation or rotation of images was needed for solving the Match problems. In the Rotation task, the physical science males were found to have stronger beta activation in their right hemisphere, particularly their right parietal lobe. This pattern suggests that the physical science males relied primarily on their right parietal lobe to use a holistic strategy for rotating the images in search of the correct solutions for the MR problems. The social science males, as a contrast, activated their left hemisphere, particularly their left frontal lobe during the MRT. This pattern suggests that social science males relied on their left frontal lobe to use an analytic strategy for analyzing or naming the detailed features of the MR stimuli in processing the MR problems. The female students, regardless of their college major, did not show a dominant lateral beta activation pattern (notably, this bilateral tendency for MR processing among the females is consistent with previous reports that females bilaterally activate their hemispheres for various cognitive functions, see Witelson, 1976; Voyer, 1996), indicating the use of a combined strategy for the MRT (i.e., they might have tried to partly rotate the images and partly analyzing detailed features of the MR stimuli). These EEG results supported the findings regarding strategy differences between the two sexes and the two types of college majors as revealed by the dual-task behavioral paradigm in Study I.

Study III

Introduction

The objective of Study III was to see whether monolingual native Chinese speakers have a stronger tendency to use a holistic strategy to process the Vandenberg and Kuse MRT than monolingual native English speakers, and whether Chinese-English bilinguals prefer a holistic MR strategy and show an advantage over both monolingual native Chinese speakers and monolingual native English speakers on the MRT.

Unique characteristics of different languages have been suggested to affect the way native speakers processing various types of information. Study III was designed to investigate how the use of a native language may affect the way a native speaker of that language processes spatial information. Chinese, as a language distinct from English, was studied for its impact on a native speaker's spatial ability by comparing the MRT strategies of native monolingual Chinese speakers to those of native monolingual English speakers.

As discussed in the Introduction, Chinese has two important distinct linguistic features that may contribute to spatial processing: tonal (vs. non-tonal in English), and logographical (vs. alphabetic in English). Both its tonal system and its logographic characteristics may elicit holistic processing and involve enhanced spatial processing by the right parietal lobe (Tan et al., 2001; Wu, et al., 1998), which is known to be an important neural substrate for spatial performance (Mazoyer, et al., 2002). If native Chinese speakers utilize their spatial working memory to holistically process the language they practice every day, it is possible that this long-term and sustained usage of their native language might enhance their tendency to rely upon their right hemisphere to adopt a holistic strategy for various spatial tasks. Based on this reasoning, in Study III, a group of monolingual native Chinese speakers was studied on their MRT performance via the same dual-task paradigm (i.e., participants perform the MRT while keeping either a verbal or a spatial load in memory) as that in Study I with the hypothesis that they would manifest a strong tendency in employing a holistic strategy for the MRT.

Study III also investigated the possible impact of bilingual experience on MR performance. As introduced earlier, bilingual experience can enhance executive function ability (Bialystok, 1991; Bialystok, et al., 2006) and may contribute to superior performance on spatial tasks by enhancing a tendency for a holistic strategy. Study III explored Chinese-English bilinguals' performance and strategy use on the Vandenberg and Kuse MRT and compared their preferred strategy to monolingual native Chinese speakers' with the hypothesis that Chinese-English bilinguals would exhibit a stronger tendency for the use of a holistic strategy on the MRT than monolingual native Chinese speakers.

Sex and college major, as the two important factors that have an impact on the MRT performance level and preferred MR strategy as found in Study I and Study II, were also considered in Study III. A few previous studies found sex and college major do impact on native Chinese speakers' spatial performance in a way similar to that of native English speakers (i.e., males outperform females and physical science outperform social science, see Li & Zhao, 2002; Wang, 1995). Therefore, Study III hypothesized that sex and college major would affect both monolingual native Chinese speakers and Chinese-English bilinguals in the same way as they affected monolingual native English speakers (i.e., males will outperform females, and physical science majors will outperform social science majors).

To address the research questions of Study III, a group of monolingual native Chinese participants and a group of Chinese-English bilinguals with both sex and college major types (i.e., social science and physical science) were selected. The test materials and procedures were the same as those in Study I, except that the verbal load task for the monolingual participants was to memorize equivalent Chinese words as translated from the English version (See appendix B).

Methods

Participants

Sixty Chinese-English bilingual participants with an average age of 28.27 (SD = 4.74) were recruited from the Texas Tech University and 60 monolingual native Chinese participants with an average age of 18.8 (SD = 0.61) were recruited from the South China Normal University. Within each group, 30 were majoring in social science (15 females and 15 males) and 30 were majoring in physical science (15 females and 15 males).

Experimental materials

The test materials were the same as those used in Study I, except in the verbal load task the monolingual native Chinese speakers received equivalent Chinese words translated from the English version (see Appendix B).

Procedure

The test procedure was the same as the one used in Study 1.

Results

There were five left-handed participants (2 bilingual social science males and 3 bilingual physical science males) in the data. Preliminary analysis yielded no significant effect for handedness or age. Therefore, all data entered a 2 (Language: Chinese vs. bilingual) x 2 (Sex: Male vs. Female) x 2 (Major: social science vs. physical science) x 3 (Condition: no load, concurrent verbal load, and concurrent spatial load) mixed design ANOVA. Language, Sex, and Major were between-subject factors and Load Type was the within-subject factor. The means and standard deviations were shown in Table 4.

Table 4. *Means and SDs for both Chinese-English bilinguals' and monolingual Chinese's MRT performance across the three experimental conditions*

Language	**Sex**	**Major**	**No load**		**Verbal load**		**Spatial load**	
			Mean (max=20)	SD	Mean (max=20)	SD	Mean (max=20)	SD
Chinese-English Bilingual	Female	Social science	7.07	3.65	7.27	3.08	6.73	3.75
		Physical science	6.67	3.04	8.33	3.13	7.20	1.86
	Male	Social science	7.93	2.71	10.07	3.33	7.67	3.83
		Physical science	11.13	2.88	11.00	3.40	13.60	1.81
Monolingual Chinese	Female	Social science	9.47	2.50	10.13	1.69	10.13	1.96
		Physical science	8.93	4.11	10.33	3.81	11.67	4.07
	Male	Social science	10.73	2.96	10.60	2.26	11.00	2.73
		Physical science	10.00	2.20	12.73	2.52	12.67	3.27

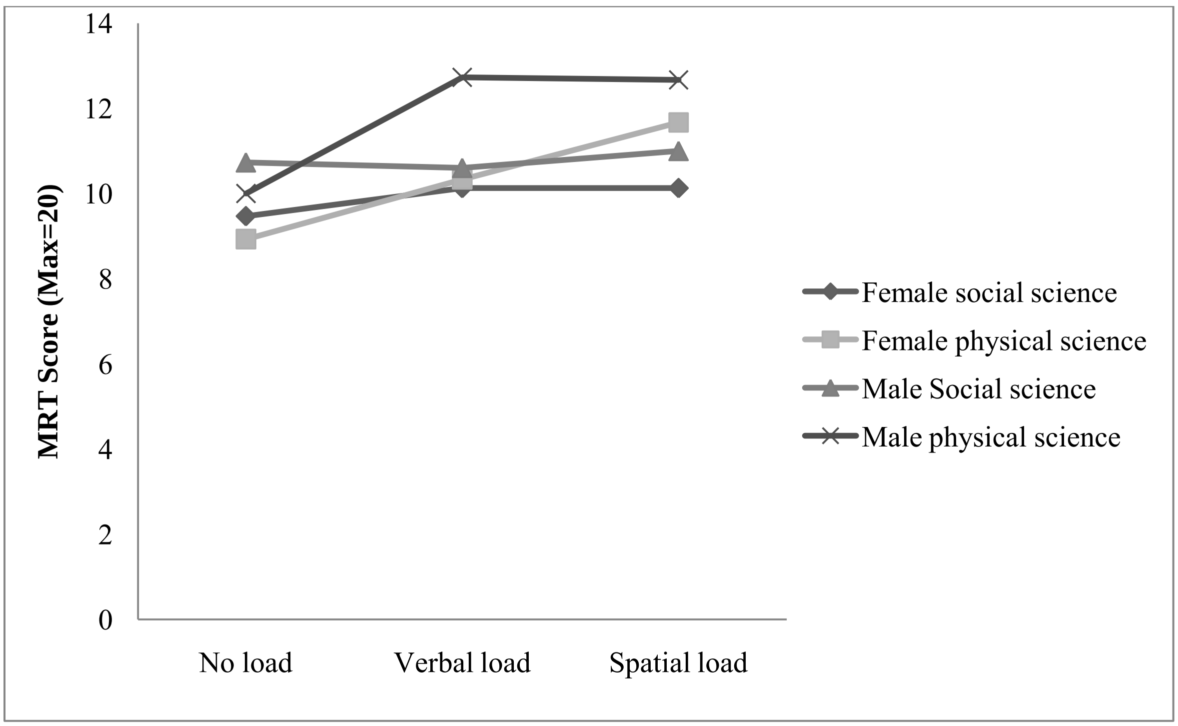
Significant main effects were found for Condition {F (2, 224) = 14.99, $p < .001$, partial eta^2 = .12}, Language {F (1, 112) = 16.57, $p < .001$, partial eta^2 = .13}, Sex {F (1, 112) = 18.68, $p < .001$, partial eta^2 = .14}, and Major {F (1, 112) = 7.04, $p < .01$, partial eta^2 = .06}. Overall, the participants had better performance on both the concurrent verbal load and the concurrent spatial load condition than on the no load condition {t (119) = 4.38, $p < .001$; t (119) = 4.12, $p < .001$, respectively}. Among these participants, monolingual Chinese speakers outperformed bilingual Chinese-English speakers. Males outperformed females. Physical science majors outperformed social science majors.

Significant interaction effects were found for Condition x Major {F (2, 224) = 10.12, $p < .001$, partial eta^2 = .08}, Condition x Language x Major {F (2, 224) = 3.28, $p < .05$, partial eta^2 = .03}, and Condition x Language x Sex x Major {F (2, 224) = 9.20, $p < .001$, partial eta^2 = .08}. To explore these interaction effects, follow-up 2 (Sex) x 2 (Major) x 3(Condition) mixed ANOVA analyses were done separately for monolingual Chinese and Chinese-English bilinguals.

Monolingual Chinese

One 2 (Sex) x 2 (Major) x 3(Condition) mixed ANOVA on the monolingual Chinese MRT data yielded one significant main effect for Condition {F (2, 224) = 13.94, $p < .001$, partial eta^2 = .20}, showing that the monolingual Chinese had better performance on both the concurrent verbal load and the concurrent spatial load condition than on the no load condition {t (59) = 3.82, $p < .001$; t (59) = 4.13, $p < .001$, respectively}. One significant two-way interaction effect was also found for Condition x Major {F (2, 112) = 7.26, $p < .001$, partial eta^2 = .12}. Follow-up analysis on this two-way interaction effect showed that the physical science majors' MRT performance was primed by both the concurrent verbal and spatial load as compared to their MRT performance in the no load condition {t (29) = 4.60, $p < .001$; t (29) = 4.90, $p < .001$, respectively}, while the social science majors' MRT in the concurrent verbal and spatial load conditions showed no significant difference from that in the no load condition (See Figure 4).

Figure 4. *Monolingual native Chinese speakers' MRT performance across the three experimental conditions*



Chinese-English bilinguals

One 2 (Sex) x 2 (Major) x 3(Condition) mixed ANOVA on the Chinese-English bilingual MRT data yielded significant main effects for Condition {F (2, 112) = 4.30, $p < .05$, partial eta^2 = .07}, Sex {F (1, 56) = 18.47, $p < .001$, partial eta^2 = .25}, and Major {F (1, 56) = 7.04, $p < .05$, partial eta^2 = .11}. Overall, the bilinguals had better performance on the concurrent verbal load condition than the no load condition {t (119) = 4.38, $p < .001$}. Among the bilinguals, male outperformed females, and physical science majors outperformed social science majors.

Significant interaction effects were also found for Sex x Major {F (1, 56) = 4.48, $p < .05$, partial eta^2 = .07}, Condition x Major {F (2, 112) = 6.20, $p < .05$, partial eta^2 = .10}, and Condition x Sex x Major {F (2, 112) = 9.18, $p < .001$, partial eta^2 = .14}. To further explore these interaction effects, follow-up 2 (Major) x 3 (Condition) mixed ANOVA analyses were done separately for the females and the males.

Bilingual females

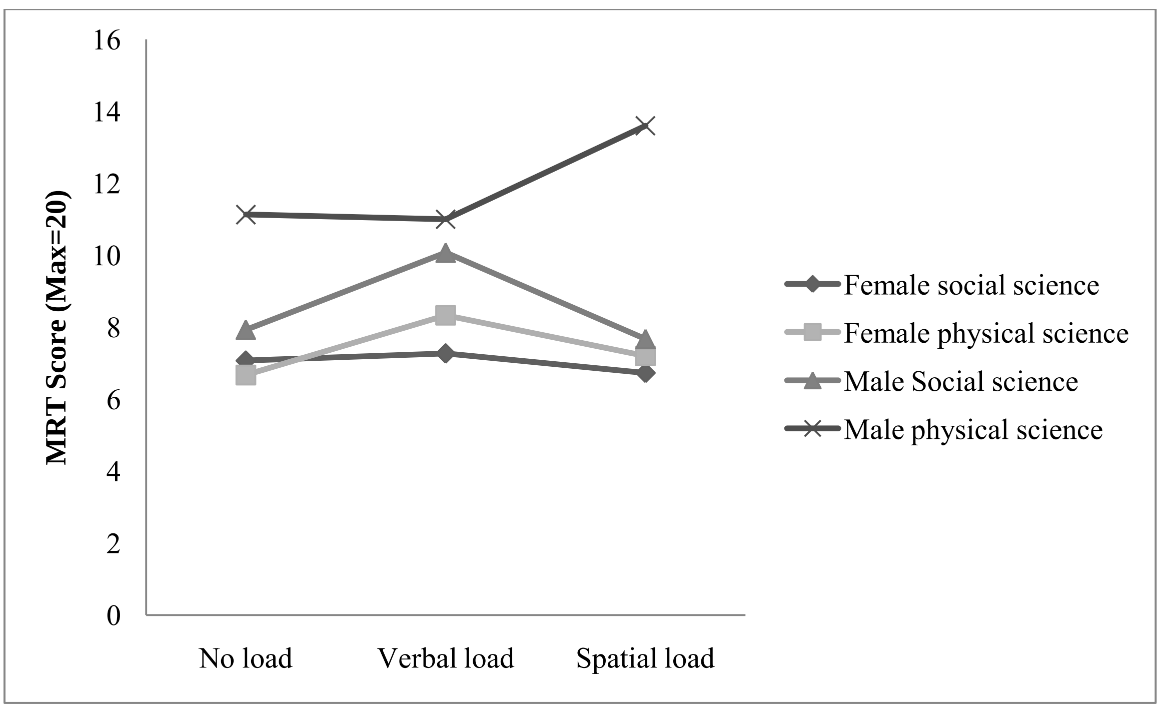
A 2 (Major) x 3 (Condition) mixed ANOVA on the bilingual female data yielded no significant effects.

Bilingual males

A 2 (Major) x 3 (Condition) mixed ANOVA on the bilingual male data yielded significant main effects for Condition {F (2, 56) = 4.51, $p < .05$, partial eta^2 = .14} and Major {F (1, 28) = 10.93, $p < .01$, partial eta^2 = .28}. Overall, the bilingual males' MRT performance on the concurrent spatial load condition was significantly better than on the no load condition {t (29) = 2.50, $p < .05$}. And, the physical science majors outperformed the social science majors.

One significant two-way interaction effect was also found for Condition x Major {F (2, 56) = 19.11, $p < .001$, partial eta^2 = .41}. Follow-up t tests on this interaction effect found that, for the bilingual males, those that majored in the social sciences had better MRT performance on the concurrent verbal load condition as compared to that on the concurrent spatial load and the no load conditions {t (14) = 5.27, $p < .001$; t (14) = 8.34, $p < .001$, respectively}, while those that majored in the physical sciences had better MRT performance on the concurrent spatial load condition as compared to that on the concurrent verbal load and the no load conditions{t (14) = 4.33, $p < .01$; t (14) = 4.63, $p < .001$, respectively}(See *Figure 5*).

Figure 5. *Chinese-English bilinguals' MRT performance across the three experimental conditions*



Concurrent load data

2 (Language) x 2 (Sex) x 2 (Major) ANOVAs on the concurrent verbal load performance and on the concurrent spatial load performance did not yield any significant effect. The descriptive indexes for concurrent load performance were shown in Table 5.

Table 5. *Monolingual native Chinese and Chinese-English bilinguals' performance on the concurrent tasks*

		Verbal Load		Spatial Load	
		Mean (Max=30)	SD	Mean (Max=5)	SD
Bilingual	Female social science	25.07	5.33	2.20	1.27
	Female physical science	25.00	4.38	2.53	0.99
	Male social science	26.67	2.23	2.20	1.27
	Male physical science	24.67	5.00	2.53	0.99
Monolingual	Female social science	28.53	1.92	2.47	1.25
	Female physical science	27.33	3.02	3.13	1.25
	Male social science	28.00	1.93	2.13	1.51
	Male physical science	27.53	3.31	2.93	1.16

Discussion

As an extension of Study I and Study II to test the findings regarding MR strategy use among monolingual native English speakers on other language groups (i.e., monolingual native Chinese speakers and Chinese-English bilinguals), Study III yielded some interesting results: Chinese-English bilinguals and monolingual native Chinese showed very different MR strategy patterns.

First, contrary to the expectation that a bilingual experience would bias a speaker towards the use of a holistic strategy (i.e., thinking based on images) and thus enhance his/her spatial performance, the Chinese-English bilinguals in Study III were actually outperformed by the monolingual native Chinese speakers on the MRT. Moreover, Chinese-English bilinguals showed a MR strategy pattern very similar to that found among monolingual native English speakers in Study I and Study II: bilingual social science males used an analytic strategy (i.e., their MRT performance was significantly primed by a concurrent verbal load rather than a spatial load), and bilingual physical science males used a holistic strategy (i.e., their MRT performance was significantly primed by a concurrent spatial load rather than a verbal load). Bilingual females, regardless of their college major, did not show significant priming effects in the two concurrent load conditions, suggesting the use of a combined strategy. The fact that Chinese-English bilinguals performed similarly to monolingual native English speakers on the MRT may reflect the impact of using English as their primary language in an English-speaking environment; All the Chinese-English bilinguals in Study III had studied English for over 10 years and lived in the USA for over 2 years, during which English would function as their primary language. This language experience may have biased them to process information in a similar way to native English speakers, and thus leading them to employ similar strategies to native English speakers' for the MRT.

Monolingual native Chinese participants in Study III showed a very different pattern of MR accuracy and strategy preference from that of Chinese-English bilinguals and monolingual native English speakers. First, no main effects of sex or college major were found for monolingual native Chinese speakers' performance on the MRT: females and social science males did not differ significantly from physical science males in MRT performance, even though physical science males still scored highest on the MRT. Some previous studies also suggested either no sex difference or a smaller sex difference in native Chinese speakers than in native English speakers on various spatial tasks (Huang, 1993; Keyes, 1979; Wang, 1995; Wang, 2005). This consistency of spatial ability in monolingual native Chinese speakers may be related to the benefit of gaining spatial analysis training/practice from using a logographic native language on a daily basis. That is, the use of Chinese as a native language enhances the "disadvantaged" groups, especially females (who are often found to be less efficient than males on mental rotation tasks) on MR ability and helps them to achieve a performance level equivalent to males in physical science (who would be expected to do well on the MRT as suggested by previous literature).

Secondly, among monolingual native Chinese speakers, social science majors' MRT performance was neither primed nor impaired by the two concurrent tasks (i.e., verbal and spatial concurrent tasks), indicating the use of a combined MR strategy. In contrast, physical science majors' MRT performance was primed by both concurrent tasks. This pattern could be interpreted as a combined analytic/holistic MR strategy being used by monolingual Chinese-speaking physical science majors, which enables their performance to benefit from a concurrent load, be it verbal or spatial. Notably, if this interpretation is true, then it should be stressed that Chinese-speaking physical science majors were quite efficient in making use of a combined strategy for the MRT as compared to participants in other language groups who also used a combined MR strategy, because the latter groups' performance did not benefit from either a concurrent verbal or a concurrent spatial load. This claim is further supported by an additional cross-language analysis showing that monolingual Chinese-speaking physical science majors (both males and females) scored equally on the MRT to English-speaking physical science males, who used the most effective holistic MR strategy and scored highest among native English speakers on the MRT. The effectiveness of using a combined MR strategy by monolingual Chinese-speaking physical science majors could be argued as an unexpected evidence supporting a positive influence on spatial processing by acquiring and using Chinese as a native language (i.e., native usage of Chinese biases its' speakers towards using a highly efficient combined strategy rather than a holistic strategy).

However, there is an alternative interpretation for the dual-priming effect (i.e., primed by both the concurrent verbal and spatial loads) observed for monolingual Chinese-speaking physical science majors. It should be noted that the monolingual Chinese speakers received Chinese words in the concurrent verbal load condition rather than English words and it is known that Chinese words have an intrinsic spatial property by which component icons are arranged spatially according to certain grammatical rules, which in turn convey different semantic meanings. Thus, it is possible that the verbal load for monolingual Chinese speakers functioned as a special type of spatial load, even though it may not be as purely "spatial" as the original spatial load since it consists of both verbal and spatial components. Therefore, the fact the monolingual Chinese-speaking physical science majors' MRT performance was primed by both a special type of verbal load (i.e., partially spatial) and a bonafide spatial load may reflect the use of a purely holistic strategy for the MRT by monolingual Chinese-speaking physical science majors, regardless of their sex or college major. If this interpretation is true, then this finding partially supports the proposed hypothesis that a logographic native language such as Chinese can bias a speaker towards using a holistic strategy for spatial processing. To determine which interpretation is more viable, a future study using neurophysiologic or neuroimaging methods such as EEG or fMRI to monitor brain activation of monolingual native Chinese speakers during MRT performance is needed. If such a study reveals bilateral activation of both hemispheres during MRT performance, it would support the interpretation that monolingual Chinese speakers prefer a combined strategy during MRT. Contrastingly, a strong unilateral activation of the right hemisphere (particularly the parietal lobe) would suggest the use of a holistic strategy. Importantly, in either case, monolingual Chinese speakers exhibited high cross-sex consistency of MRT accuracy and strategy use, which stands in sharp contrast to the significant sex differences observed on the MRT performance by monolingual native English speakers. This cross-sex consistency of MRT accuracy and strategy suggests an influence of native usage of Chinese on spatial performance (i.e., the native use of Chinese may eclipse the sex differences in both MR accuracy and strategy use that were found among the native English speakers in Study I and Study II), and supports the weaker version of Whorfian hypothesis (1956).

CHAPTER III

GENERAL DISCUSSION

The present dissertation investigated the influence of several socio-cultural factors in human spatial performance: sex, college major, and language. Most previous studies in this field have focused on sex differences in spatial ability. A robust finding from those studies is that males usually outperform females on spatial tasks, especially when image manipulation and rotation are required by those tasks. By investigating preferred strategy for the MRT, the present dissertation found that not only sex can impact on spatial performance, but other socio-cultural factors such as college major and language experience also have an important influence on spatial performance. Moreover, these factors interact with each other and influence spatial performance in a complicated way.

Through Study I and Study II, the two factors of sex and college major were found to interactively predict monolingual English speakers' MR strategy and performance level. Specifically, physical science males employed a holistic strategy to manipulate the MR images and their MRT score ranked highest among all participant groups. Social science males used an analytic strategy to compare detailed features of the MR items and obtained the lowest average MRT score among all participant groups. Females' MR performance did not differ between physical science and social science majors and showed a tendency to use a combined analytic/holistic strategy for the MRT. Interestingly, these strategy differences among monolingual English speakers were reflected in their brain activation patterns. By using EEG on another group of monolingual native English speakers, Study II found that physical science males relied on their right parietal lobe (an important brain area for image generation and spatial manipulation) to process the MRT, suggesting the use of a holistic MR strategy, while social science males activated their left frontal lobe (an important brain area for verbal communication and sequential analysis) for the MRT, suggesting the use of an analytic MR strategy. Females showed no dominant lateral activation in either hemisphere, suggesting the use of a combined analytic/holistic MR strategy.

One important theoretical question is whether or not the findings about MR ability and strategy preference among monolingual native English speakers could be generalized to other language groups. Study III addressed this question by testing MR ability and strategy use on another distinct language group: monolingual native Chinese speakers. Chinese is a distinct language from English in at least two ways. One is a tonal system (vs. non-tonal in English) in which different tones for the same pronunciation mark different semantic meanings. The other is its logographic (vs. alphabetic in English) property in which a word consists of icons with specific spatial construction. According to the literature, both the tonal system and the logographic property of Chinese requires its native speakers to additionally activate the right hemisphere for language processing (i.e., holistically processing tone variations in oral expression or spatial construction information of written words), as compared to native English speakers whose language is dominantly processed in the left hemisphere. Monolingual native Chinese' additional training and practice on holistically processing their native language may enhance their spatial ability and bias them towards the use a holistic strategy for spatial information processing. This hypothesis was at least partly supported by Study III. In Study III it was found that monolingual native Chinese speakers were more consistent than other language groups in terms of both MR accuracy (i.e., Chinese monolinguals' MRT scores were equivalent across sex and college majors) and MR strategy preference (i.e., monolingual Chinese-speaking social science majors employed a combined strategy, and monolingual Chinese-speaking physical science majors used either a combined or a holistic strategy). This beneficial consistency among monolingual native Chinese speakers suggests that acquiring and using Chinese as native language can have a positive impact on spatial processing.

Moreover, Study III investigated another language factor that may affect spatial ability: bilingual experience. Even though some studies suggested that bilinguals possess enhanced executive function ability which helps them to excel on various verbal and spatial tasks, Study III did not find an advantage of Chinese-English bilinguals on the MRT. Interestingly, the Chinese-English bilinguals in Study III showed a very similar pattern of MR strategy to that among monolingual English speakers. This similarity may indicate the influence of a dominant language on cognition. That is, using English as a dominant language in an English-speaking environment may have biased the Chinese-English bilinguals towards using the same strategies for the MRT as native English speakers.

For many years, researchers have been debating the origin of high spatial ability. One group of researchers propose that a genetic factor, or that hormonal type and level may account for spatial ability differences between the sexes (Gouchie & Kimura, 1991; Kimura, 1996; Van Goozen, et al., 1994; Zechner et al., 2001), while another group of researchers argued that personal social experience influences the development of spatial ability and causes individual differences on spatial performance (Parsons, et al. 1982; Skaalvik & Skaalvik, 2004). However, both biological and social-cultural factors may affect the development of spatial ability. For example, many studies point to the fact that there is a biological root for individual differences in spatial ability. A male advantage in MR has been reported in human infants as young as four-months, who obviously do not have a chance to gain much social training on spatial ability (Moore & Johnson, 2008; Quinn & Liben, 2008). A sex difference favoring males has also been found among congenitally blind people when performing visuospatial working memory tasks (e.g., memorizing tactile information of an object's spatial position and pointing out the objects' new spatial position after being rotated: see Vecchi, 2001). Such a difference has been confirmed in animal studies with male rodents outperforming female rodents on several maze tasks that utilize visuospatial representation (Williams & Meck, 1991). On the other hand, many other studies manifest the importance of environmental factors in the attainment of spatial ability. For example, Newcornbe and colleagues (1983) have argued that spatial ability is positively correlated with spatial activities. In line with such arguing, it has been found that video game playing and computer game experience reduce sex difference in mental rotation task performance (Feng, et al., 2007; Quaiser-Pohl & Lehmann, 2002; Quaiser-Pohl, et al., 2006). Not only a spatial activities related experience can affect spatial performance attainment, but a gender role related self expectation was also found to impair females' performance on rotation related math problems in several behavioral studies (Keller, 2002, Walton & Cohen, 2003; Wigfield, 2002). In a recent fMRI study, negative sex-related spatial ability stereotype primes were found to impair female MR performance presumably by increasing their emotional load (the later as evidenced by the activation of brain areas specialized for emotion processing) as compared to females who received positive sex-related spatial ability stereotype primes (Wraga, et al., 2007).

Even though the origin of high spatial ability was not a research topic in the present dissertation, findings from the present dissertation indirectly supported both the biological and the socio-cultural account of spatial ability development. For example, in Study I and Study II, monolingual English-speaking females in physical science were found not to use a holistic strategy for the MRT, even though they would be expected to as a byproduct of their physics science related courses. This finding suggests that females' spatial information processing may have been biased by certain biological factors towards using a combined strategy. However, this biological tendency is not isolate to the impact of social experience. The finding that monolingual native Chinese-speaking females were consistent with their male counterparts in MR strategy (be it a holistic or a combined), and presumably biased by their native logographic language experience, suggests a subtle socio-cultural influence (i.e., native language) on spatial ability.

One related issue on the nature vs. nurture argument of the development of high spatial ability is the concept of sensitive periods (Knudsen, 2004). It is often found that during early stages of human development, experience can exert a stronger force on the development of various cognitive abilities than it does in later stages. In the same way, the development of spatial ability may be sensitive to the impact of early environmental factors, such as native language. In the present dissertation, enhanced spatial ability among monolingual native Chinese-speaking females may be due to the fact that they were exposed to logographic Chinese since infancy. To monolingual Chinese speakers, the sensitive period of language development may also be an important period for their spatial ability development. A hypothesis like this needs future developmental studies involving different age groups to verify.

One thing that should be noted in the present dissertation is that participants' IQ was not controlled. One may argue that the observed differences on MR performance level and MR strategy were driven solely by different IQ levels. However, it is not likely that there were large IQ discrepancies within or between the groups in light of the fact except that for the monolingual Chinese speakers, all participants were recruited from the same University and thus all had at least the minimum level of college entrance score requirement. Moreover, the Chinese-English bilinguals (all were graduate level college students) would presumably possess higher than average IQ scores given the fact that they have to be top students among native Chinese students to be allowed to pursue graduate level study abroad. Despite having a potentially high IQ level, the Chinese-English bilinguals were still outperformed by the monolingual native Chinese speakers on the MRT, and their MR strategies varied by sex and college majors. Both facts argue against that possibility that high IQ would guarantee high MR performance, or that high IQ would bias a person to use a certain MR strategy (e.g., a holistic MR strategy). These facts are also consistent with the literature showing that spatial ability is independent of verbal ability or other IQ subcomponents and hence not predictable by general IQ measures (Benbow, 1988; Hermelin & O'Connor, 1986; Jaušovec & Jaušovec, 2008; Tan, et al, 2003). Therefore, based on the findings from the present dissertation, MR ability and preferred MR strategy would be a by-product of a participant's sex, college major and native language, rather than IQ level per se.

In conclusion, the present dissertation found that sex and college major are two important factors predicting both MR performance level and strategy preference among the monolingual native English speakers. Different MR strategies could be reflected by distinctly different brain activation patterns as manifested in concurrent EEG measurements. The present dissertation also found evidence suggesting the impact of language experience on MR performance level and strategy preference. The native usage of a logographic language such as Chinese was found to bias females towards using the same MR strategy and achieving equivalent MR accuracy as their male counterparts. Chinese-English bilinguals were found to perform the MRT in a similar way to monolingual native English speakers, which may reflect the influence of using English as their primary language by living in an English-speaking environment.

The findings from the present dissertation may have value for school educators. Even though males and females may be biologically differentiated in terms of their cognitive strength (i.e., males are often reported to excel on spatial tasks, while females are often found to excel on verbal tasks), social experience related to spatial processing such as logographic language learning may enhance females' spatial ability, especially at early stages of development.

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APPENDICES

APPENDIX A SAMPLE MENTAL ROTATION TEST ITEM

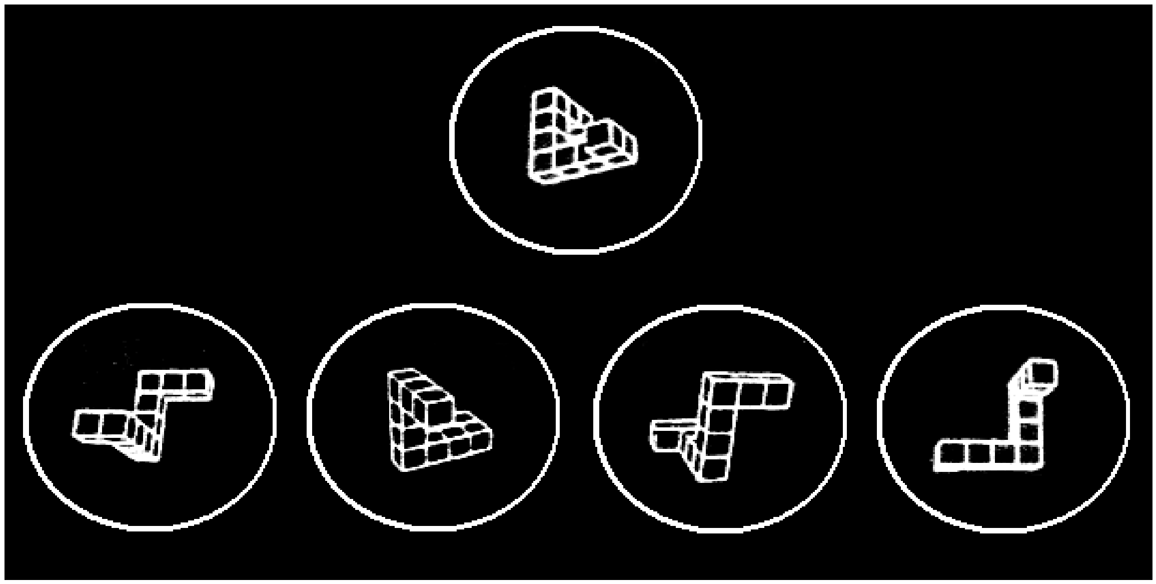
APPENDIX B SAMPLE VERBAL LOAD STIMULI (IN ENGLISH AND CHINESE VERSION)

APPENDIX C SAMPLE 24-POINT VANDERPLAS AND GARVIN (1959) FORM

APPENDIX D SAMPLE MATCH ITEM

APPENDIX E ELECTRODES PLACEMENT ACCORDING TO THE 10-20 SYSTEM

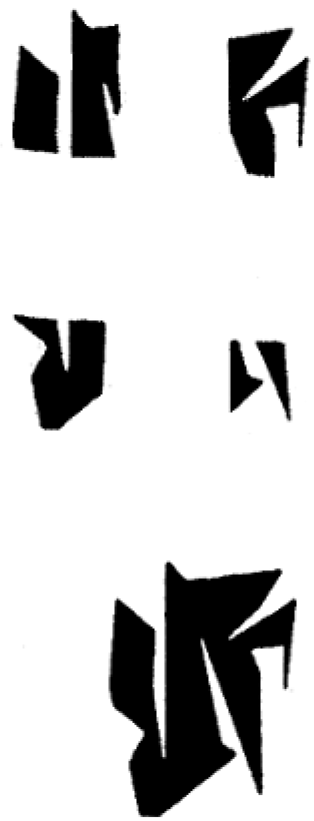
APPENDIX A: SAMPLE MENTAL ROTATION TEST ITEM



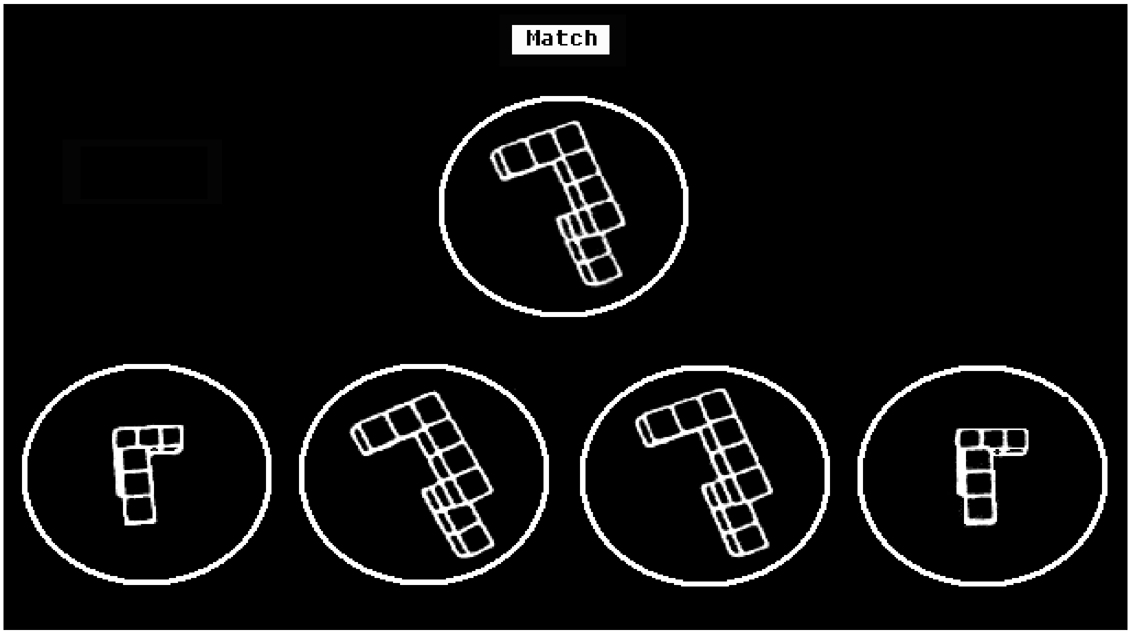
APPENDIX B: SAMPLE VERBAL LOAD STIMULI (IN ENGLISH AND CHINESE VERSION)

origin	justice	起源	正义
interim	Simile	间歇	明喻
aptitude	edition	才能	版本

APPENDIX C: SAMPLE 24-POINT VANDERPLAS AND GARVIN (1959) FORM



APPENDIX D: SAMPLE MATCH ITEM



APPENDIX E: ELECTRODES PLACEMENT ACCORDING TO THE 10-20 SYSTEM