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**Skill at Image Generation:
Handedness Interacts with Strategy Preference
for Individuals Majoring in Spatial Fields**

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Study 1 was designed to identify a subgroup of non-right-handers in spatial fields who excel over right-handers in spatial ability. The study investigated image generation skill in individuals majoring in spatial fields (art, math/science) in college. In order to identify this subgroup, the role of three factors was examined: handedness (non-right-handers vs. right-handers with first-degree relatives who are all right-handed vs. right-handers with at least one non-right-handed first-degree relative), preferred strategy for processing spatial information (visualised spatial metrics vs. verbalised spatial relations), and sex. We found that strategy preference interacted with handedness. The non-right-handers who excelled relative to a right-handed group were those who preferred a visualised spatial metric strategy for processing spatial information. Among visualisers, non-right-handers performed at the highest level, significantly above right-handers with all right-handed relatives. In contrast, among verbalisers, right-handers with right-handed relatives performed at the highest level, significantly above right-handers with non-right-handed relatives. The latter effect for right-handers was replicated in Study 2, for a sample of mathematically precocious youth. We concluded that determination of strategy preference is critical in identifying the handedness

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group that excels at image generation. Effective use of a strategy may depend on a compatibility between preferred processing style and brain organisation.

INTRODUCTION

There has been conflicting evidence on the question concerning the spatial ability of non-right-handers. Some studies have found an advantage for non-right-handers on spatial tasks relative to right-handers (e.g. Hermann & Van Dyke, 1978). Some show no differences between right-handers and non-right-handers (e.g. Fennell, Satz, Van Dell Abell, Bowers, & Thomas, 1978), whereas others have even found that non-right-handers perform *worse* than right-handers on spatial tests (e.g. Levy, 1969; Miller, 1971). The issue is complicated even further, since it also has been reported that spatial abilities of non-right-handers interact with both sex and level of reasoning ability (Harshman, Hampson, & Berenbaum, 1983).

Geschwind and Galaburda (1987) suggest that non-right-handers are not a unitary group either in pattern of brain organisation or in spatial ability, since their brains develop in unpredictable ways. Geschwind and Galaburda (1987) propose that non-right-handers are biologically predisposed towards atypical brain organisation, with more symmetrical hemispheres and more diffuse functions than right-handers. The particular atypical pattern that develops in some non-right-handers may provide them with an advantage on spatial tasks, whereas atypical development in others may produce spatial deficits. Consequently, Geschwind and Galaburda propose that non-right-handers are likely to fall at *both* extremes of spatial ability.

Most of the research on handedness and spatial ability has focused on college populations, and it is likely that researchers have included in their studies a majority of individuals from nonspatial fields (e.g. psychology majors). We have shown in our prior work that individuals majoring in spatial fields outperform those majoring in nonspatial fields on a variety of spatial tasks (Winner & Casey, 1992). If Geschwind and Galaburda's (1987) theory is correct, the subset of non-right-handers with spatial talent may gravitate toward spatial fields, whereas the subset with spatial deficits may avoid these types of fields. The non-right-handers with spatial talent who major in spatial fields, therefore, may have been under-represented in the past research on handedness and spatial ability. The present study was designed to investigate the spatial ability of college students who self-select for spatially based majors such as math/science and art.

Consistent with Geschwind and Galaburda's view (1987), Kimura and D'Amico (1989) found that in non-science fields, non-right-handers (including left-handers, ambidextrous individuals, and weak right-handers) were less spatially skilled than those who were strongly right-handed. In contrast, in science fields non-right-handers equalled strong right-handers

in spatial visualisation (the ability to manipulate an image) and spatial orientation (the ability to perceive and monitor one's spatial relationship to the environment). For individuals in art and math/science, we also found no evidence for handedness effects in spatial visualisation ability (Winner & Casey, 1992). Taken together, these studies indicate that on measures of spatial visualisation and orientation, non-right-handers in spatial fields do not excel over right-handers.

Identifying Non-right-handers with Spatial Talent

Nevertheless, we are proposing in this study that there is a subset of non-right-handers within spatial fields who do excel spatially. The failure to identify this subset so far may be due to at least three factors. One factor may be the use of an undifferentiated comparison group of right-handers. A second factor may be the particular spatial measure investigated. A third may be the lack of attention to strategy preferences for spatial problem-solving. We elaborate on each of these issues next.

Choice of Comparison Groups as a Critical Factor

A factor that may have obscured the advantage of non-right-handers in spatial fields is the general practice in prior research of considering right-handers as a unitary group. In the present study, we compared non-right-handers in spatial fields to two types of right-handers: (1) those with non-right-handed immediate relatives, and (2) those with all right-handed immediate relatives. This decision was based on Geschwind and Galaburda's (1987) and Annett's (1985) theories of brain organisation and handedness. The brain organisation of non-right-handers has been argued to differ most from that of right-handers with all right-handed immediate relatives. These are considered to be strongly left-hemisphere dominant for language and to depend on verbalised spatial relation strategies for solving tasks. There is evidence that right-handers with non-right-handed relatives are also less lateralised than right-handers with right-handed relatives (Hardyck, 1976). Therefore, non-right-handers should differ most markedly from right-handers with all right-handed relatives.

Choice of Spatial Measure as a Critical Factor

The spatial measures used in prior handedness studies primarily assessed spatial visualisation and orientation abilities. The choice of measures may have contributed to the failure to demonstrate a non-right-handed advantage. A more critical spatial ability might be the ability to *generate or construct a new image* rather than to transform or manipulate a pre-existing image. Image generation is an important building block in a wide range of spatial tasks (Poltrock & Brown, 1984). Image generation may be useful

for art students as they mentally construct an image and for those in math/science as they convert information into mental images for a problem solution. Thus, in the present study, which focusses on individuals in spatial fields, we investigated the possible advantage of non-right-handers for generating images.

There are few tasks that have been developed to assess image generation ability directly. Instead, this ability is frequently inferred from performance on other types of spatial tasks and from questionnaires in which subjects rate their imagery ability (Ernest, 1977; Lorenz & Neisser, 1985; Poltrock & Brown, 1984). Kosslyn, Berndt, and Doyle (1985) have demonstrated that imagery ability is made up of a number of separate components, such as image maintenance, scanning, rotation, and generation. Image generation involves the re-creation of an image out of long-term memory or the construction of a novel image out of components of familiar images, e.g. an image of a dog with a tail in the front rather than the back. Most image generation tasks have required the generation of simple, familiar images, such as letters (Farah, 1986; Kosslyn et al., 1985). In the present study, a more difficult imagery task was developed in order to detect a wide range of individual differences in performance. The task assessed the ability to convert verbal information into a visual array, the type of image generation ability useful for those in spatial fields.

Strategy Preference as a Critical Factor

A third factor, which may be critical in identifying the non-right-handers in spatial fields who excel spatially, is strategy preference. Most imagery tasks can be solved using different types of strategies (Kosslyn, 1988). Those who use a visually based spatial metric strategy generate a mental image of the figure. They construct the mental picture of the components of the image using precise co-ordinates. However, a second approach circumvents the need to depend entirely on generating a picture to create an image. It is possible to generate an image using a verbalised spatial relation strategy, constructing the image part by part, describing and retaining in words the shapes and locations of components of the image relative to one another (i.e. the circle is on the top left above the triangle).

For any particular visual-spatial task, use of a visualised spatial metric or a verbalised spatial relation strategy is a function of task demands and instructions (Katz, 1983). The strategy used, however, is also a function of a general processing style, i.e. an individual's overall tendency to think in images or to verbalise spatial relations (Katz, 1983; Kosslyn, 1987). Such a general predisposition is best assessed under task conditions in which either a visualised spatial metric or a verbalised spatial relation strategy is equally appropriate without task demands pushing subjects towards one

strategy over another. In this study, we assessed strategy preference using a modification of a sentence-picture verification task, designed originally by Clark and Chase (1972) and further developed by MacLeod, Hunt, and Matthews (1978). The task involves remembering a sentence that specifies a spatial relationship (e.g. "star is above plus") and then comparing the information retained in memory to a picture. Following the task, subjects are asked whether they used a visualised spatial metric or a verbalised spatial relation strategy to retain the information. We borrowed Richardson's (1977) terms, "verbaliser" and "visualiser," to label these subjects. We have found this procedure to be useful in assessing the relationship of strategy preference to two other spatial abilities, spatial visualisation and image retention (Casey, Winner, Hurwitz, & DaSilva, 1991; Winner & Casey, 1992).

Different strategies may tap different areas of the brain. There is evidence of both right- and left-hemisphere localisation of image generation (Farah, 1986; Goldenberg et al., 1989; Kosslyn, 1987; Kosslyn et al., 1985; Sergent, 1989). Kosslyn (1987; 1988) has proposed that different types of spatial information are encoded in different hemispheres, with categorical, language-like relations (such as "next to," or "to the left of") localised in the left hemisphere and spatial metrics information, which generates an exact image (such as "3 cm below"), localised in the right hemisphere.

We propose that an individual's preference for a visualised spatial metric strategy on the strategy assessment task reflects this underlying proclivity to use the right-hemisphere metric system when processing spatial information (i.e. visualisers choose to generate an exact picture of the star placed a certain number of cm above the plus). Similarly, a preference for a verbalised spatial relation strategy reflects an underlying proclivity to use the left-hemisphere categorical system (i.e. verbalisers choose to encode the spatial relationship between the star and the plus using a sentence, as in "the star is above the plus," rather than converting it into a picture).

It has been shown that there are strong individual differences in strategy preferences (Ernest, 1977; Just & Carpenter, 1985; Katz, 1983; Kinsbourne & Hiscock, 1983; Kosslyn, 1987; Lohman & Kyllonen, 1983; Paivio, 1971; Richardson, 1977). It is not yet clear why individuals prefer a particular strategy, as both types of strategies have been shown to be effective for solving spatial tasks (Casey et al., 1991; Winner & Casey, 1992). It is likely that experiential and biological factors combine to determine an individual's predisposition to use a particular strategy. Thus, there should be no consistent relationship between handedness subtype and strategy preference. Both visualisers and verbalisers should be found within all handedness groups. It is important to recognise, however, that the issue of spatial skill is separate from strategy preference.

Skill at Image Generation

An individual's general *preference* to use a strategy may not necessarily indicate greater *skill* at using that particular strategy to generate images. Our hypothesis was that skill at image generation is a joint function of preferred style of processing information and handedness subtype for individuals majoring in spatial fields. Thus, the handedness group that excels at image generation may vary depending on their strategy preference.

Visualisers who Excel at Image Generation

In order to use a visualised spatial metric strategy effectively to solve the image generation task in the present study, subjects must convert verbal information into a visual image. This requires the integration of both hemispheres. Dimond and Beaumont (Beaumont, 1974) propose that the integration and co-ordination of the two hemispheres are useful for solving many complex spatial tasks. Therefore, they argue that the diffuse brain organisation of the non-right-hander provides an advantage on such tasks.

We suggest, however, that this advantage may only occur for visualisers. Verbalisers will sidestep the use of right-hemisphere processing strategies, whenever possible, in order to use their preferred verbalised spatial relation strategy. In contrast, visualisers will use right-hemisphere processing in conjunction with the left hemisphere. Based on the theoretical frameworks of Geschwind and Galaburda (1987), Annett (1985; Annett & Manning, 1990), and Dimond and Beaumont (Beaumont, 1974), we proposed that when subjects prefer a visualised spatial metric strategy, thus using the right-hemisphere metric system to solve complex spatial tasks, those with greater integration between the hemispheres should excel spatially. Consequently, we predicted that for visualisers, the non-right-handers should excel at our image generation task.

This effect was predicted for those in spatial fields, but not for those majoring in non-spatial fields. Incorporating Geschwind and Galaburda's analysis of non-right-handers (1987), we have proposed that some non-right-handers may choose to major in non-spatial fields because of spatial deficits. Thus, no clear handedness predictions can be made for visualisers in verbally based fields.

Verbalisers who Excel at Image Generation

For those who prefer a verbalised spatial relation strategy (and a left-hemisphere categorical system), a different type of brain organisation may be effective at image generation. According to Annett (1985), right-handers with all right-handed relatives are likely to have the optimal pattern of brain organisation for solving verbal/analytic tasks, but should be

at a *disadvantage* on spatial tasks. However, some spatial task solutions allow for verbally based spatial strategies. Therefore, this pattern of brain organisation might actually be *advantageous for verbalisers* when they are presented with spatial tasks that can be solved effectively with a verbalised spatial strategy. Therefore, it is possible that for verbalisers, right-handers with strong left-hemisphere dominance for language may excel at many image generation tasks.

STUDY 1

Purpose of Study 1

In Study 1 we explored two questions about college students majoring in spatial fields of study. First, do non-right-handed visualisers excel at our image generation task, as predicted? Second, do right-handed verbalisers with all right-handed relatives perform poorly on this spatial task or do they excel?

Methods

Subjects

We tested 175 subjects (98 females and 77 males). There were 85 students majoring in the visual arts and 90 students majoring in the math/sciences. The art majors were students at an art school and were majoring in design or studio art. The math/science majors were undergraduates at a liberal arts college. Majors classified as math/science were ones requiring a minimum of 6 courses in math or natural science (e.g. math, physics, chemistry, biology, premedical studies, pre dental studies, computer science). Math and science majors were combined because these 2 groups have previously been shown to perform equivalently on spatial measures (Casey, Winner, Brabeck, & Sullivan, 1990).

Subjects from 3 handedness groups were represented in each major. In the math/science group there were 34 right-handers with all right-handed immediate family members, 31 right-handers with 1 non-right-handed immediate family member, and 25 non-right-handers. In the art group there were 35 right-handers with all right-handed immediate family members, 21 right-handers with 1 non-right-handed immediate family member, and 29 non-right-handers. To obtain our samples, we first screened subjects for handedness and then randomly selected subjects from each of the 3 handedness groups. We were not able to have equal numbers in our actual sample, however. Although we contacted an approximately equal number of subjects in each sex by major by handedness category, an equal number did not show up to participate in our study.

Materials and Procedures

Subjects were tested in groups of 10 to 20. Each subject was given a booklet containing the measures. Proclivity to use a visual or a verbal strategy was assessed through a strategy preference task, adapted from MacLeod et al. (1978). Image generation was assessed by a task developed for this study, described later. Handedness was assessed through the Edinburgh Handedness Inventory (Oldfield, 1971) and a family handedness questionnaire (Casey & Brabeck, 1989). The measures are described here in the order in which they were presented.

Strategy Preference Task. Subjects read three sentences describing spatial relationships between a star and a plus (e.g. "plus is below star"). After each sentence they turn the page to find a picture of a star placed either above or below a plus (e.g. †). Subjects decide whether the sentence just read is a true or false description of the picture. (In this example, the correct response would be *true*.) They are then asked to indicate the strategy they used to solve the task by circling one of the following four statements:

1. I read the words in the sentence, memorised them, turned the page, and compared the sentence in my mind to the picture before me.
2. I read the sentence, converted the words to a picture representing the words, turned the page, and compared the picture in my mind to the picture before me.
3. Sometimes I used strategy 1 and sometimes I used strategy 2.
4. I do not know which strategy I used. (Note: only six subjects chose this option, and they were omitted from the study.)

Subjects were classified as verbalisers if they circled the first statement and as visualisers if they circled the second or third statements. Subjects circling statements 2 and 3 were combined, based on Winner and Casey's (1992) finding that artists reporting statement 2 did not differ on a visual memory test from those reporting statement 3. Using this measure of strategy preference, verbalisers were defined as subjects who code information verbally on *all* trials and reported using *no* images for problem-solution (statement 1 above). Visualisers were defined as subjects who transformed the verbal information presented to them on a page into a visual image for memory coding on some or all of the trials. Among the visualisers, 55% selected statement 2 and 45% selected statement 3.

Image Generation Task. Image generation was assessed through a task in which subjects had to form images of sequentially presented information and then imagine these images arrayed on a 3 × 3 grid. In Phase 1, subjects

were presented with 9 spoken shape names. The names were read aloud twice, for 10 trials, in the same order. On the first trial, as each shape was read, a picture of the shape was shown. the shape names were, in order: *triangle, moon, square, plus, diamond, circle, heart, doughnut, and star*. On each trial, after hearing the list, subjects drew the 9 shapes on a page in the order in which they were read. The shapes were drawn in a vertical list, one under the other. This ensured that in Phase 2 the grid actually had to be created by the subject rather than just reproduced from memory. The purpose of Phase 1 was to have subjects memorise the shapes in the appropriate sequence. This is a necessary condition for imaging the figures on a grid and placing them in order, beginning at the upper left and continuing to the lower right. On each trial, as subjects memorised the list, they were also instructed to picture the image in their mind on a 3 × 3 grid. Based on pilot work, it was ascertained that 10 trials were sufficient for subjects to memorise the shapes in order. (The mean number of trials to criterion was 4.53 trials in Study 1 and 2.18 in Study 2.)

In Phase 2, subjects were given 40 empty grids on 2 sheets of paper. At the top of each grid were 3 randomly selected shapes from the list. The task was to identify the positions of each of the 3 shapes in the mental grid by drawing a line indicating where each shape was located in the grid (an arrow was used to indicate the locations of the first, second, and third shapes respectively). (See Fig. 1.) Effective strategies for constructing the array mentally included: (1) visually generating and remembering an exact mental picture of the grid and locating each shape on that grid, (2) analysing the location of each of the shapes in words, then identifying and

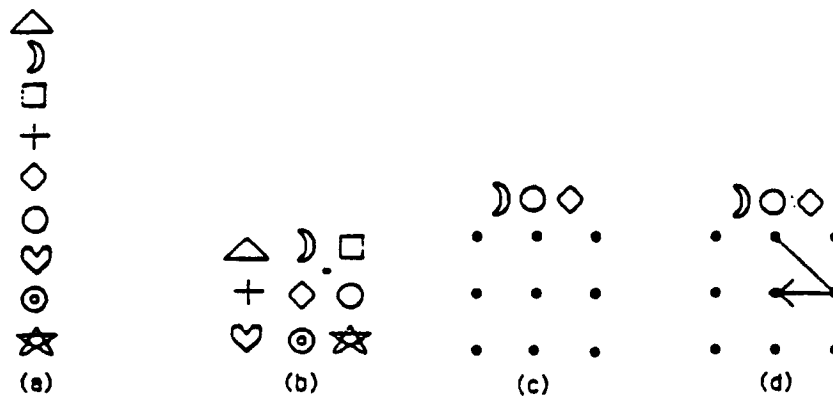


FIG. 1 Image generation task. (a) The shapes in the order in which they were presented in Phase 1. (b) The shapes in the positions they would appear on the subjects' mental grid. (c) Sample test item in Phase 2. (d) Sample test item in Phase 2 with the correct response, i.e., the arrow identifying the placement of the three shapes.

remembering its placement in the imaginary grid (e.g. the triangle is third, so it is the one on the top right).

Subjects were told to work as quickly and accurately as possible. They were given 3 minutes for Phase 2. This time period was determined by pilot work indicating that few subjects could complete the 40 grids in that period of time. A ceiling effect was thus avoided. Responses were scored as correct or incorrect. No partial credit was given. The highest possible score was 40.

Handedness. Handedness was assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), and a laterality quotient (L.Q.) ranging from -100 (strongly left-handed) to +100 (strongly right-handed) was derived for each subject according to the method outlined there. The Inventory consists of 10 items, assessing the hand preference for writing, drawing, throwing, scissors, toothbrush, knife (without fork), spoon, broom (upper hand), striking match (match), and open lid (lid). Subjects with L.Q.s below +41 were classified as non-right-handed (Casey & Brabeck, 1989). This group included both left-handed and ambidextrous individuals. A self-report measure of handedness was used in place of a behavioural measure since overall concordance on the two types of assessment measures tends to be above 90% (Porac & Coren, 1981), and a test-retest reliability score of 0.88 has been obtained in the Edinburgh measure (Casey & Brabeck, 1989).

Subjects were also administered a family handedness questionnaire. Subjects were asked to categorise members of their immediate family (biological parents and siblings) as left-handed, right-handed, and ambidextrous (able to use both hands with ease or switches hands for different tasks). Subjects were asked to base their classifications on activities, like the ones presented in the Edinburgh questionnaire, which they had completed, rather than on handwriting alone. A test-retest reliability of 0.94 on this questionnaire has been reported by Casey and Brabeck (1989). In addition, a 93% rate of agreement was found between subjects' ratings and their parents' ratings of handedness of immediate family members (Casey & Brabeck, 1989).

Subjects who were either left-handed or ambidextrous were classified as non-right-handers. The right-handers included two groups: those with at least one non-right-handed (left-handed or ambidextrous) first-degree family member and those who had all right-handed first-degree relatives.

Results and Discussion

The image generation task consisted of two phases, the verbal memory phase and the image generation test phase. Performance in Phase 2 was affected by verbal memory ability in Phase 1. To control for this as well as for differential amounts of rehearsal during Phase 1, verbal memory

performance was covaried out of the ANCOVA performed on the image generation scores with trials to criterion in Phase 1 as the covariate.

On the image generation task, scores were derived by summing the number of correct responses (out of 40). It should be noted that the test was designed so that it would be extremely difficult to complete in the time allotted. The mean score across all subjects was low ($M = 15.05$, $S.D. = 11.34$). Thus, subgroup mean scores should be evaluated in comparison to this overall mean and not against the maximum possible score of 40.

Preliminary Analyses

Results of the first set of preliminary analyses allowed us to combine all non-right-handers into one group. Scores on the image generation phase for the non-right-handers were submitted to a one-way ANCOVA, in which the ambidextrous right-handers (between +40 and 0 on the Edinburgh Handedness Inventory) were compared to the ambidextrous left-handers (between -1 and -40) and the extreme left-handers (between -41 and -100), with trials to criterion in Phase 1 as the covariate. No significant or borderline effect of handedness group was obtained. Scores on the image generation phase for the non-right-handers were then submitted to a one-way ANCOVA, in which the non-right-handers with all right-handed first-degree relatives were compared to the non-right-handers with at least one first-degree non-right-hand relative, with trials to criterion in Phase 1 as the covariate. Again, no significant or borderline effect of handedness group was obtained.

The second set of preliminary analyses allowed us to confirm that visualisers who selected statement 2 did not differ from those who selected statement 3 on the image generation task. A one-way ANCOVA was performed, comparing these two groups of visualisers. Trials to criterion in Phase 1 was used as the covariate. No significant or borderline differences were found between the two groups. Therefore, they were combined to form the visualiser group in the main analysis.

The third set of preliminary analyses allowed us to combine the art majors with the math/science majors. A one-way ANCOVA was performed, comparing these two groups of spatial majors. Trials to criterion in Phase 1 was used as the covariate. No significant or borderline differences were found between the two groups. Therefore, they were considered as a unitary group in the main analysis.

A Comparison of Right-handers to Non-right-handers

In order to relate to the findings to prior research on handedness and spatial ability, scores on the image generation phase were submitted to a simple 2×2 ANCOVA, handedness (non-right-handers vs. right-

handers) by major (art majors vs. math/science majors), with trials to criterion in Phase 1 as the covariate. No main effects or interaction were obtained.

Since no differences in image generation ability between non-right-handers and right-handers were found, these results are consistent with previous research on spatial ability and handedness in spatial fields (Kimura & D'Amico, 1989; Winner & Casey, 1992). Thus, from this analysis one might be forced to conclude that non-right-handers do not differ in image generation ability from right-handers. When we included both family handedness and strategy preference in the main analysis, however, a quite different picture emerged.

Main Analysis

Scores on the image generation phase were next submitted to a $3 \times 2 \times 2$ ANCOVA, family handedness (non-right-handers vs. right-handers with all right-handed relatives vs. right-handers with non-right-handed relatives) by strategy (visualisers vs. verbalisers) by sex (males vs. females), with trials to criterion in Phase 1 as the covariate. There was a significant effect of the covariate, $F(1, 162) = 54.61, P = 0.001$, with those taking fewer trials to criterion on Phase 1 showing better image generation ability in Phase 2. There were no main effects of strategy, or sex. A significant main effect of family handedness was obtained, $F(2, 162) = 3.12, P = 0.047$, however. Least significant difference post hoc comparisons revealed that non-right-handers ($M = 17.12, S.D. = 9.87, N = 54$) significantly outperformed the right-handers with non-right-handed relatives ($M = 12.68, S.D. = 9.89, N = 52$). The right-handers with all right-handed relatives were in between the two groups ($M = 15.21, S.D. = 9.24, N = 69$), and were not significantly different from either.

A significant two-way interaction, strategy by family handedness, was obtained, $F(2, 162) = 4.41, P = 0.014$. (No other interactions were significant.) To clarify this interaction, simple effects analyses were performed separately for visualisers and verbalisers. (See Table 1.)

Simple Effects Analysis for the Visualisers

For the simple effects analysis of visualisers, a one-way ANCOVA was performed, comparing the three handedness groups using least significant difference post hoc comparisons. There was a significant effect of family handedness, $F(2, 162) = 3.01, P < 0.05$, with the non-right-handers ($M = 18.30, S.D. = 9.86, N = 36$) outperforming the right-handers with all right-handed relatives ($M = 12.88, S.D. = 9.87, N = 41$). The right-handers with non-right-handed relatives were in between ($M = 14.50,$

TABLE 1
 Mean Image Generation Scores by Strategy, Handedness, and Sex for College Students Majoring in Spatial Fields

		<i>Verbalisers</i>			<i>Visualisers</i>		
		<i>RH/FRH</i>	<i>RH/FNRH</i>	<i>NRH</i>	<i>RH/FRH</i>	<i>RH/FNRH</i>	<i>NRH</i>
Females	M	18.79	12.80	15.17	13.47	14.93	18.82
	S.D.	9.86	10.68	9.72	9.50	9.39	9.48
	N	16	10	11	25	15	21
Males	M	18.21	5.55	15.28	12.15	13.61	17.83
	S.D.	7.83	8.07	7.78	10.41	10.72	10.29
	N	12	10	7	16	17	15

RH/FRH = Right-handers with all right-handed relatives.
 RH/FNRH = Right-handers with at least one non-right-handed relative.
 NRH = Non-right-handers.

S.D. = 9.85, N = 32), and were not significantly different from either group (see Fig. 2).

These results indicate that, for individuals who were visualisers, non-right-handers were significantly better at the image generation task than right-handers with all right-handed relatives. We suggest that among those in spatial majors, non-right-handers who prefer to think in images rather than words capitalise on this proclivity when solving spatial tasks. Within

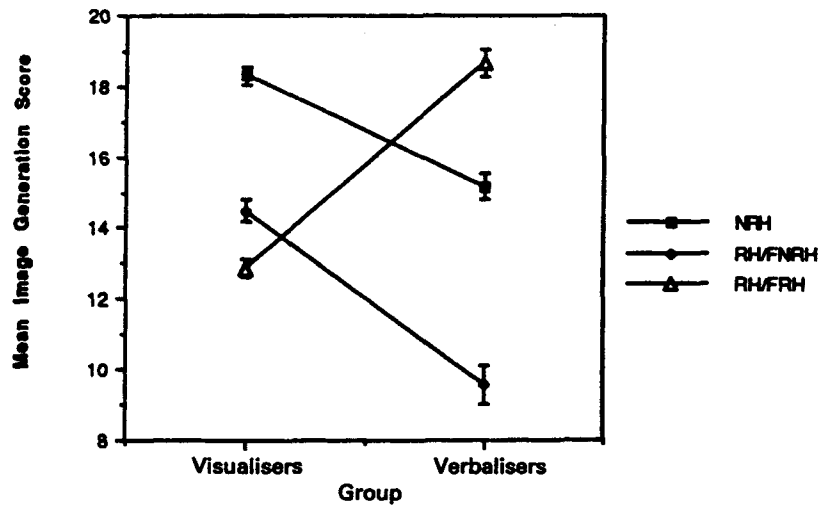


FIG. 2. Mean image generation scores by strategy and handedness for college students majoring in spatial fields.

spatial majors it is often useful to integrate the two types of hemispheric functions by translating verbal information into the visual mode (just as with the imagery task used here). In contrast, non-spatial majors are more likely to depend on analytical rather than spatial processing for success in their field.

Simple Effects Analysis for the Verbalisers

For the simple effects analysis of verbalisers, the same ANCOVA was performed. There was a main effect of family handedness, $F(2, 162) = 4.89$, $P < 0.01$, with least significant difference post hoc comparisons showing right-handers with all right-handed relatives ($M = 18.65$, $S.D. = 9.07$, $N = 28$) significantly outperforming right-handers with non-right-handed relatives ($M = 9.58$, $S.D. = 9.05$, $N = 20$). The non-right-handers ($M = 15.17$, $S.D. = 8.99$, $N = 18$) were intermediate, and were not significantly different from either group (see Fig. 2).

Thus, although the right-handers with all right-handed relatives were the lowest performers among visualisers, these same right-handers were the highest performers among verbalisers, performing significantly better than the other right-handed group. According to Annett (1985), right-handers with all right-handed relatives are more likely to be strongly left-hemisphere dominant for language and to depend on verbal strategies. She assumes that this preference for using verbal strategies would put them at a disadvantage on spatial tasks. Yet, most spatial tasks can be solved through the use of verbalised spatial relation strategies, as well as visualised spatial metric strategies (Bryden, 1982; Lohman & Kyllonen, 1983). This may account for the present findings.

STUDY 2

Since we did not clearly predict the finding relating to verbalisers obtained in Study 1, a second study was designed to replicate this effect using a different sample of subjects likely to excel spatially. We administered the same measures used in Study 1 to a group of right-handed mathematically precocious seventh to ninth graders who had been selected to participate in a summer math/science training programme, based on scores on math and science achievement tests. (Non-right-handers were not included in the study, since there was only a total of three non-right-handed verbalisers and eight non-right-handed visualisers in the sample.)

Based on Study 1, we predicted that family handedness would interact with strategy preference. For the verbalisers, we predicted that the right-handers with all right-handed relatives would outperform those with non-

right-handed relatives on the image generation task. For the visualisers, we predicted no significant difference between the two types of right-handers.

Methods

Subjects

The sample consisted of 51 (20 females and 31 males) 7th to 9th graders who were recruited from a national talent search programme to participate in a summer math/science training programme. Students who met the criteria of scoring at least 20 on the ACT Math or ACT Science Reasoning Tests, or at least 500 on the Math SATs (College Board Aptitude Test) were invited to participate in the programme. These scores indicate that the students have math/science ability representative of only the top 0.5% of students in the USA.

Materials and Procedures

Each subject was given a booklet containing the measures described in Study 1, including a strategy preference task, an image generation task, and handedness and family handedness inventories.

The right-handers were divided into two groups: those with at least one non-right-handed (left-handed or ambidextrous) first-degree family member and those who had all right-handed first-degree relatives.

Results and Discussion

Preliminary Analysis

In order to confirm that visualisers who selected statement 2 did not differ from those who selected statement 3 on the image generation task in Phase 2, a one-way ANCOVA was performed, comparing these two groups of visualisers. Trials to criterion on the verbal memory task in Phase 1 was used as the covariate. No significant or borderline differences were found between the two groups. Therefore, they were combined to form the visualiser group in the main analysis.

Main Analysis

Scores on the image generation task were next submitted to a 2×2 ANCOVA, family handedness (right-handers with all right-handed relatives vs. right-handers with non-right-handed relatives) by strategy (visualisers vs. verbalisers), with trials to criterion in Phase 1 as the covariate. There was a significant effect of the covariate, $F(1, 46) = 6.64, P = 0.013$, with those taking fewer trials to criterion on Phase 1 showing better image

generation ability in Phase 2. There were no main effects of strategy or family handedness.

A significant two-way interaction, strategy by family handedness, was obtained, $F(1, 46) = 5.81, P = 0.02$. To clarify this significant interaction, simple effects analyses were performed separately for visualisers and verbalisers.

Simple Effects Analysis for the Visualisers

For the simple effects analysis of visualisers, a one-way ANCOVA was performed, comparing the two family handedness groups of right-handers. There was no effect of family handedness, with the right-handers with all right-handed relatives ($M = 13.14, S.D. = 7.76, N = 15$) showing no significant difference in performance from the right-handers with non-right-handed relatives ($M = 14.27, S.D. = 7.74, N = 14$). (See Fig. 3.) This replicates the findings in Study 1 for the visualisers.

Simple Effects Analysis for the Verbalisers

For the simple effects analysis of verbalisers, the same ANCOVA was performed. There was a main effect of family handedness, $F(1, 46) = 7.19, P < 0.025$, with right-handers with all right-handed relatives ($M = 20.53, S.D. = 7.96, N = 14$) outperforming right-handers with non-right-handed relatives ($M = 10.82, S.D. = 7.75, N = 8$). (See Fig. 3.)

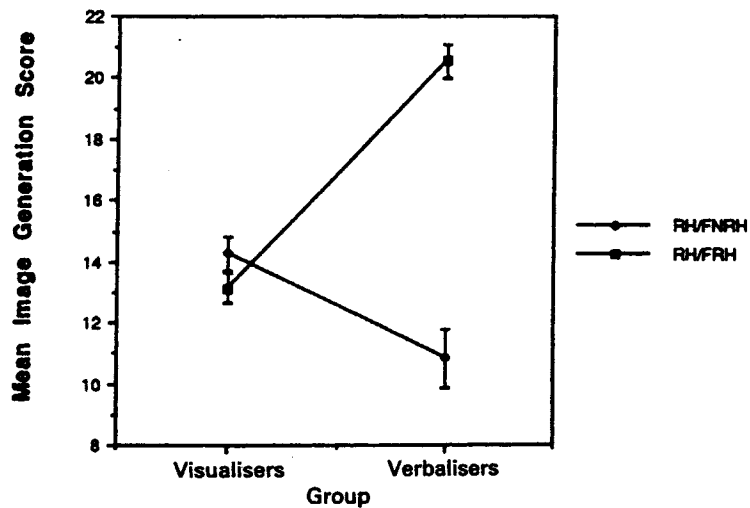


FIG. 3 Mean image generation scores by strategy and handedness for mathematically precocious adolescents.

For the verbalisers, as well as the visualisers, the results of Study 2 replicated the results of Study 1 for the two types of right-handers. This effect was obtained even though a different type of individual with spatial potential was assessed, a group of mathematically precocious adolescents. The same subset of verbalisers excelled at image generation: right-handers with all right-handed relatives.

GENERAL DISCUSSION

The Compatibility Theory

The results of Study 1 show that, among the visualisers in spatial fields, it is the non-right-handers who excel at the type of image generation task used here. The results of Study 1 and 2 show that among the verbalisers in spatial fields, it is the right-handers with all right-handed relatives who excel. These findings lead us to propose a "compatibility" theory. According to this view, the effectiveness of a particular strategy may depend on an individual's brain organisation, as reflected by his/her handedness subtype. For solving our image generation task, a visualised spatial metric approach to spatial processing of images may be more compatible with decreased laterality in brain organisation, whereas a verbalised spatial relations approach may be more compatible with strong left-hemisphere dominance for language.

In order to use a visualised spatial metric strategy effectively to solve our image generation task, subjects must convert verbal information into a visual image. According to the work of Dimond and Beaumont (Beaumont, 1974), this is precisely the type of task at which non-right-handers (with their greater interhemispheric integration) should excel. Thus, for individuals who prefer to use right-hemisphere spatial metrics for solving spatial tasks (i.e. the visualisers), those with decreased laterality would be most skillful at generating this type of complex image.

In contrast, we propose that in order to use a verbalised spatial relation strategy effectively to solve our image generation, it is not necessary to integrate both hemispheric functions. Instead subjects must reorganise the sequentially presented verbal information into different verbal propositions. These subjects generate a mental grid, which designates the spatial relationships between the shapes on their mental grid, by coding them in words. This should involve only left-hemisphere functions, at which right-handers with all right-handed families should excel, given their strong left-hemisphere dominance for language. Thus, among those preferring to use left-hemisphere-based verbal propositions for solving spatial tasks (i.e. the verbalisers), those with strong left-hemisphere dominance for language would be most skillful at using this approach on our imagery task.

We have used handedness and family handedness patterns as markers for patterns of brain organisation in the present study. The next step is to examine the neurological basis for these predicted relationships in order to have a more direct test of the theory.

Family Handedness and Sex Effects

It is noteworthy that, among the right-handers who preferred a verbalised spatial relation strategy, family handedness was a critical factor determining image generation ability across two very different samples of individuals with spatial/mathematical talent. Bishop (1990) has recently criticised the use of family handedness as a marker of genetic differences. Her argument, however, relates to the use of familial handedness for distinguishing between inherited left-handedness and left-handedness due to brain damage. The Bishop paper does not address the difference between the familial handedness patterns of right-handers. In fact, she lumps these two types of right-handers together in her analysis. In contrast, we suggest that the critical difference in pattern of brain organisation is between those right-handers who, according to Geschwind and Galaburda (1987), are strongly left-hemisphere dominant for language (equivalent to Annett's *rs++* genotype) and all other right-handed individuals. It is for this group of right-handers that the family handedness effects are critical.

Geschwind and Galaburda's (1987) theory has recently undergone a detailed review by McManus and Bryden (1991). They proposed that such a grand theory has the advantage of generating new and unexpected hypotheses, but also runs the risk of being unfalsifiable. One major direction proposed by the reviewers for clarifying the theory is the study of familial relations, the direction pursued here.

There is increasing evidence that the two types of familial right-handers process information in very different ways. For example, a recent study by Bever, Carrithers, Cowart, and Townsend (1989) found that right-handed adults with all right-handed relatives were more dependent on analysing grammatical structures when reading compared to right-handers with left-handed relatives, who depended more on context and meaning. In a prior study assessing mental rotation ability among female high math achievers, we found that right-handers with non-right-handed relatives were more likely to use a visual rotation strategy than were the right-handers with all right-handed relatives (Pezaris & Casey, *in press*). We have also shown that in this same spatial task, among female math/science majors, right-handers with non-right-handed relatives outperformed the right-handers with all right-handed relatives. The males preferred a visual rotation strategy over a verbal strategy independent of family handedness, and no family handedness effects were found on level of performance (Casey & Brabeck, 1989).

In the present study, we found no sex differences. On a task such as the image generation task used here, in which either verbalisers or visualisers can solve the task effectively, sex differences may be minimal. It is primarily on mental rotation tasks, which cannot be solved easily using a verbalised spatial relation strategy, that sex differences have been obtained (Linn & Petersen, 1985) and found to depend on strategy usage (Pezaris & Casey, in press).

In sum, our own research suggests that no one handedness group has a consistent advantage across different types of spatial tasks. The effects of handedness and family handedness clearly vary as a function of sex, type of task, and strategy used.

The Relation between Task Variables and Strategy Usage

Task variables may interact with preferred strategy in determining both skill at image generation and which hemisphere is implicated in generating images. Kosslyn (1988) showed a left-hemisphere advantage for imaging a letter within a grid, but a right-hemisphere advantage when no grid was present. We found (Casey et al., 1991) that the success of verbalisers on an image recall task varied as a function of the particular figure used. When verbalisers reported an inability to use their preferred verbal strategy due to the nature of the figure to be reproduced, they performed worse than visualisers. Yet, when a slightly different figure was used, they reported being able to use their preferred verbal strategy to recall a figure, and they did as well as visualisers in image recall. We argue that a purely right- or left-hemisphere task is rare, and that whenever possible subjects will manipulate the information given to them on a spatial task in order to use their preferred hemisphere for processing the information. Thus, identification of strategy preference is critical to unravelling the relationship between handedness and spatial ability.

Conclusions

Conflicting claims have been made about the spatial abilities of non-right-handers in spatial fields (Geschwind & Galaburda, 1987; Levy, 1969; Springer & Deutsch, 1989). The results of Study 1 support our hypothesis, that in order to identify the subgroup of non-right-handers in spatial fields who excel spatially, researchers need to: (1) investigate the ability to generate images, not the ability to transform pre-existing images as in standard tests of spatial visualisation and orientation, (2) include strategy preference as a variable, and (3) assess the family handedness of right-handers when making comparisons to non-right-handers. Taken together, the results of Studies 1 and 2 suggest that the effective use of a particular

strategy may depend on a compatibility between an individual's general preference for using that strategy and a pattern of brain organisation that allows the individual to capitalise on that strategy.

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