Behavioral evidence for brain-based ability factors in visuospatial information processing

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Abstract

The present study examined possible parallels between the structure of human visuospatial abilities and the organization of the neural systems. Forty-eight participants were tested on seven speeded visuospatial tasks. Three of these tasks were constructed so as to rely primarily on known ventral stream functions and four were constructed so as to rely primarily on known dorsal stream functions. Both sets of tasks spanned approximately the same range of difficulty as indexed by both the speed and accuracy of decision making. Factor analysis of response times on the seven tasks revealed only two significant factors. The putative ventral stream tasks all loaded heavily on one factor (mean loading = 0.843) but only weakly on the other factor (mean loading = 0.222); the putative dorsal stream tasks showed the opposite pattern in that they all loaded heavily on the second factor (mean loading = 0.828) but only weakly on the first factor (mean loading = 0.229). These findings are consistent with the hypothesis that human visuospatial abilities can be classified using categories based on the specializations of underlying neural structures and systems. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Visuospatial abilities; Ventral stream; Dorsal stream

1. Introduction

In recent years, two separate neural systems with specialized visuospatial functions, known as the ventral and the dorsal processing streams, have been identified [29]. Mishkin, Ungerleider, and Macko [21] proposed that ventral stream functions are related to stimulus identification whereas the functions of the dorsal stream are related to spatial perception and the control of visually guided movements. Consistent with this view, ventral stream structures (e.g., areas in inferotemporal cortex) contain neurons sensitive to stimulus properties such as shape, color, and texture [5] whereas dorsal stream structures (e.g., areas in posterior parietal cortex) contain neurons sensitive to stimulus properties such as direction of movement as well as to shifts of spatial attention [17]. Moreover, damage to ventral stream structures produces selective deficits on various object identification and discrimination tasks whereas damage to dorsal stream structures produces selective deficits in the ability to recognize spatial relationships [12,23].

Despite the double dissociation in localized brain damage, it is not known whether the two streams are functionally independent enough to account for individual differences in perceptual abilities in intact subjects. The role of the ventral and dorsal streams in normal individuals is open to question because of the cross-talk that occurs along virtually the full extent of the ventral and dorsal streams [30]. Such cross-talk raises the possibility that the two streams are highly interactive, and has led some researchers to caution against overly simplistic classification of neural structures and perceptual processes [18].
In order to examine the roles played by the ventral and dorsal processing streams in normal visual perception, the present study explored possible parallels between the structure of human visuospatial abilities and the organization of the visual system. Participants were tested on seven speeded visuospatial tasks, each constructed to measure primarily a ventral function or a dorsal function, and their response times (RTs) were factor analyzed. If visuospatial abilities can be classified into two categories corresponding to the functions of the two neural processing streams, then analysis should yield two separate factors that group the tasks according to whether they rely primarily on ventral or dorsal stream functions. Such a finding would suggest that even though the two streams may function interactively under some (if not most) circumstances, they are nevertheless sufficiently independent to account for individual differences in visuospatial abilities.

The tasks used in the present study were characterized as using primarily ventral or dorsal stream functions based on evidence from neurophysiological investigations with behaving monkeys and from neuroimaging and neuropsychological studies of humans. Specifically, with respect to the putative ventral tasks, two of these (i.e., the unnameable shapes and puzzle pieces tasks) involve shape constancy, a function that may be tentatively attributed to ventral stream structures based on evidence regarding neural activity in primate inferior temporal cortex. Neurons in inferior temporal cortex may respond selectively to an object’s shape, independent of the object’s size, position, luminance, texture or color [26,27] as well as independent of changes in contrast or even reversal in contrast [4,27]. The third putative ventral task (i.e., abstract matching) was designed to assess the ability to process and integrate color, shape and texture information. Characterization of this task is based in part on reports that some neurons in inferior temporal cortex respond selectively to shape, color, and texture or the combination of these three features [4,28].

With respect to the tasks tentatively characterized as relying on dorsal stream functions, the first putative dorsal task (i.e., the dot location task) assessed the ability to judge distances between dots. This task was characterized based in part on the observation that damage to the parietal and dorsal prefrontal cortex results in an inability to judge the relative distance among objects [20] as well as the fact that comparison of receptive field sizes and topographic organization in the two processing streams suggests that location information is more accurately preserved in dorsal stream cortical areas [21]. The second putative dorsal task (i.e., curve tracing) assessed the ability to move attention across space, and was characterized as a dorsal stream task based on reports that neurons in primate parietal cortex are involved in shifts of spatial attention [1,16]. In addition, shifts of attention between spatial locations have been observed to activate regions in superior parietal cortex in neuroimaging studies [24].

The other two putative dorsal tasks involved spatial transformations. The first of these was a 2-dimensional mental rotation task similar to one used by Haxby and colleagues [11] in a neuroimaging study. This task is characterized as relying on dorsal stream functions based in part on their finding that superior parietal cortex showed more activation during this task than during a face matching task whereas the reverse was true for ventral stream areas in occipitotemporal cortex. The remaining putative dorsal task involved 3-dimensional mental rotation and was characterized as relying on dorsal stream functions based in part on reports of neurons in the primate posterior parietal cortex that are sensitive to rotation in depth [25] as well as the fact that parietal lobe damage produces deficits in both 2- and 3-dimensional mental rotation in humans [6,22].

2. Methods

2.1. Subjects

Forty-eight young adults from the pool of volunteers maintained by the Department of Psychology at Washington University were tested. All of the participants had normal or corrected-to-normal vision.

2.2. Apparatus

Stimuli were presented on a NEC MultiSynch 2A monitor controlled by a CompuAdd 286 IBM-compatible computer. The software to control the experiment was developed by the third author using routines from the PCX Toolkit (Genus) that enabled stimulus presentation to be synchronized with the video display refresh cycle and permitted RTs to be measured with 1-ms accuracy. The response panel contained three buttons arranged in an inverted triangle: the two upper (right and left) buttons were used to report decisions and the lower center button was used to initiate trials.

2.3. Tasks

Participants performed seven visuospatial tasks. All together, this battery of tasks consisted of 18 conditions, nine conditions from the putatively ventral tasks and nine conditions from the putatively dorsal tasks. For six of the tasks, the conditions each consisted of 24 trials. For the remaining task (3-dimensional mental rotation), one of the three conditions
consisted of 48 trials to maintain an equal number of same and different trials.

2.3.1. Unnameable shapes

Participants had to decide whether or not two irregular polygons had the same shape. The two polygons always differed in color and size, but were the same shape on half of the trials. Colors (red, green, purple, yellow, white, and blue) were randomly assigned with the constraint that the two polygons on any given trial were different in color. Each polygon was created by connecting five points randomly chosen from the coordinates of an invisible 6 × 6 element matrix. The matrix for the left-hand polygon was always 3.3 × 3.3 cm. The matrix for the right-hand polygon was 4.5 × 4.5 cm on half of the trials and 5.4 × 5.4 cm on the other half of the trials. There were two conditions in this task: same shapes and different shapes. A sample of each of the two conditions is shown in panel 1 of Fig. 1.

2.3.2. Puzzle pieces

Participants had to decide whether a puzzle piece would fit the irregularly shaped space in the center of an incomplete puzzle (i.e., whether the piece and the hole were the same shape). The puzzle was a 6 × 6 cm square on the left side of the display, and the hole and puzzle piece were both approximately 2 cm high and 2 cm wide. The puzzle piece and the space in the puzzle both had either two protrusions or four protrusions. The color (randomly sampled from red, yellow, blue, purple, or green) of the puzzle piece and the incomplete puzzle were always the same, and the puzzle piece never had to be turned to fit into the puzzle. There were four conditions (see samples in panel 2 of Fig. 1): (1) same shape, two protrusions; (2) different shapes, two protrusions; (3) same shape, four protrusions; and (4) different shape, four protrusions.

2.3.3. Abstract matching

Participants had to determine which of the top two objects, the left or the right one, was more similar to the object at the bottom. These three objects could differ on three dimensions: shape (sampled from triangle, square, circle, or pentagon), color (sampled from green, red, yellow, or blue), and texture (sampled from textures made up of either straight lines, dashes, crosses, or waves). There were three conditions in this task (see samples in panel 3 of Fig. 1): (1) level one — one of the upper objects was identical to the bottom object; (2) level two — one of the upper objects matched the bottom object on two dimensions, and the other object matched the bottom object on only one dimension; (3) level three — one of the upper objects matched the bottom object on one dimension, and the other object differed from the bottom object on all three dimensions.

2.3.4. Dot location

Participants had to decide which of two white dots (the left one or the right one) was closer to a central red dot. There were two conditions in this task (samples shown in panel 4 of Fig. 1): (1) shorter distances — one white dot was 2.6 cm away from the red dot and the other one 3.5 cm away from the red dot;
(2) longer distances — one white dot was 3.5 cm away from the red dot and the other 4.6 cm away from the red dot.

2.3.5. Curve tracing

Participants had to decide whether two red dots were on two different criss-crossing curved lines or whether they were both on the same curved line. The two curved lines and three 0.6 cm dots (two red and one blue) were presented in a 8.2 × 6.8 cm box. One of the red dots was 1.2 cm from the left side of the box. Participants were instructed to look at the red dot on the left first, and then follow the curved line it was on until they reached a second dot. If the second dot on this line was also red, they pressed the upper button corresponding to their dominant hand. If the second dot was the blue dot, they pressed the upper button corresponding to their nondominant hand. There were two conditions (samples shown in panel 5 of Fig. 1): (1) short distance — the red dot and the blue dot on the right were both 2.9 cm from the red dot on the left; (2) long distance — the red dot and the blue dot on the right were both 5.8 cm from the red dot on the left.

2.3.6. Two-dimensional mental rotation

Participants had to decide whether the dot in one pentagon with a double line at the bottom had the same location as the dot in the other pentagon after it was mentally rotated until its double line was also at the bottom. There were two conditions in this task (samples shown in panel 6 of Fig. 1): (1) 72° rotation — the pentagon on the right had to be rotated 72° either clockwise or counter clockwise in order to place the double line at the bottom; (2) 144° rotation — the pentagon on the right had to be rotated 144° either clockwise or counter clockwise in order to place the double line at the bottom. Same and different trials were collapsed in both conditions.

2.3.7. Three-dimensional mental rotation

Participants had to decide whether the two buildings in the top view were in the same locations as the two buildings in the side view. In the top view on the left of the display, the building were represented by two 1.2 cm squares (a little shading was added to each to indicate that one building was taller than the other). In the side view on the right of the display, the two buildings were represented by rectangular prisms, 2.9 cm and 2.5 cm high. There were three conditions (samples shown in panel 7 of Fig. 1): (1) same arrangement — the two buildings had corresponding locations in both views; (2) different (untransposed) — the distance between the two buildings in the right display was different from that in the left display; (3) different (transposed) — in addition to the distances between the buildings being different in the two views, the building on the right in the top view appeared on the left in the side view, and vice versa (e.g., if the taller building was on the right in one view, it was on the left in the other view).

2.4. Procedure

Each trial began with the presentation of a fixation point. When the participant pressed the lower button on the response panel, the stimulus for the next trial was presented following a 200-ms delay. The stimulus remained on the screen until the participant pressed one of the two upper buttons or until a 10-s period had elapsed. Errors caused by mistakes or failure to respond within 10 s triggered a 200-ms computer beep. After a correct response or a computer beep, the screen remained blank for 700 ms, and then the fixation point for the next trial was presented. General instructions for all tasks were given before any task started. Prior to beginning each task, specific instructions for that task and six practice trials were given, followed by two buffer trials (which were not included in the analysis) and the experimental trials.

As is typical in factor-analytic studies, each participant performed the tasks in the same order: unnameable shapes, curve-tracing, puzzle pieces, dot location, 3-dimensional mental rotation, abstract matching, and 2-dimensional mental rotation. This order was selected so as to alternate ventral and dorsal stream tasks as well as to prevent the covariation of task difficulty with practice or fatigue.

3. Results

One of our goals in constructing the seven tasks used in the present study was to make the overall difficulty of the set of putatively ventral tasks approximately equal to the overall difficulty of the putatively dorsal tasks. The data presented in Table 1 indicate that we were largely successful in this regard. Both RTs and error rates span approximately equal ranges in both sets of tasks: the ventral task RTs ranged from 782 to 1792 ms, and the dorsal task RTs ranged from 606 to 1823 ms; the error rates on the ventral stream tasks ranged from 0.6 to 8.3%, and the error rates on the dorsal stream tasks ranged from 0.3 to 8.2%.

Covariation in performance on the different tasks was examined first by looking at the correlations between the mean correct RTs from different tasks. As may be seen in Table 2, correlations were generally higher between mean RTs from the same set (ventral or dorsal) of tasks and lower between the RTs on tasks from different sets. The average correlations between RTs on two different ventral stream tasks and
Table 1
Mean RTs (ms), standard deviations (SD), and error rates (%) for young adults on seven tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Condition</th>
<th>Mean</th>
<th>SD</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unnameable shapes</td>
<td>Same</td>
<td>1793</td>
<td>524</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>Different</td>
<td>1544</td>
<td>553</td>
<td>8.2</td>
</tr>
<tr>
<td>Puzzle pieces</td>
<td>Two-protrusions, same</td>
<td>1517</td>
<td>488</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Two-protrusions, different</td>
<td>1282</td>
<td>403</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>Four-protrusions, same</td>
<td>1701</td>
<td>546</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Four-protrusions, different</td>
<td>1520</td>
<td>520</td>
<td>7.1</td>
</tr>
<tr>
<td>Abstract matching</td>
<td>Level one</td>
<td>782</td>
<td>202</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Level two</td>
<td>1186</td>
<td>489</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Level three</td>
<td>1367</td>
<td>532</td>
<td>1.2</td>
</tr>
<tr>
<td>Dot location</td>
<td>Shorter distances</td>
<td>607</td>
<td>125</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Longer distances</td>
<td>700</td>
<td>197</td>
<td>0.3</td>
</tr>
<tr>
<td>Curve tracing</td>
<td>Short distance</td>
<td>1489</td>
<td>415</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>Long distance</td>
<td>1824</td>
<td>474</td>
<td>2.7</td>
</tr>
<tr>
<td>2-D mental rotation</td>
<td>72° rotation</td>
<td>1306</td>
<td>372</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>144° rotation</td>
<td>1679</td>
<td>567</td>
<td>7.0</td>
</tr>
<tr>
<td>3-D mental rotation</td>
<td>Same arrangement</td>
<td>1461</td>
<td>466</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Different (untransposed)</td>
<td>1391</td>
<td>468</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>Different (transposed)</td>
<td>1315</td>
<td>415</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 2
Correlation matrix of the response times between seven visual spatial tasks

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Unnameable shapes</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Puzzle pieces</td>
<td>0.757</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Abstract matching</td>
<td>0.536</td>
<td>0.673</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Dot location</td>
<td>0.206</td>
<td>0.424</td>
<td>0.395</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Curve tracing</td>
<td>0.231</td>
<td>0.308</td>
<td>0.310</td>
<td>0.630</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. 2-D mental rotation</td>
<td>0.138</td>
<td>0.397</td>
<td>0.587</td>
<td>0.625</td>
<td>0.700</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>7. 3-D mental rotation</td>
<td>0.379</td>
<td>0.596</td>
<td>0.495</td>
<td>0.727</td>
<td>0.619</td>
<td>0.599</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*Correlations between two tasks hypothesized to rely on processes from the same stream are in bold type.

between RTs on two different dorsal stream tasks were both 0.65. In contrast, the average correlation between RTs on a ventral stream task and the RTs on a dorsal stream task was 0.37.

The RTs data were factor analyzed using Systat 7.0. The results of this analysis, presented in Table 3, confirm the distinction between the ventral and dorsal tasks that is suggested by the correlation matrix. There were two principal components with eigenvalues greater than 1. All tasks loaded heavily on the first principal component (mean loading = 0.751, minimum loading = 0.587) that accounted for more than 57% of the variance in data space. Thus, this component may represent a general speed factor or a general visuospatial ability factor. The second principal component, on which the ventral tasks loaded positively and the dorsal tasks loaded negatively, accounted for an additional 20% of the variance. When the factors were subjected to a varimax rotation (or when a varimax rotation was performed on these two factors), the ventral stream tasks loaded heavily on one factor and the dorsal stream tasks loaded heavily on the other factor. For the ventral tasks, the mean loading on the first factor was 0.843 (all loadings of the ventral tasks on the first factor > 0.720) whereas the mean loading on the other factor was only 0.222. The opposite pattern was observed for the dorsal tasks: The mean loading

Table 3
Factor loadings from principal component analysis and factor analysis of young adults’ reaction times

<table>
<thead>
<tr>
<th>Visual and spatial tasks</th>
<th>Principal components</th>
<th>Rotated factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>General</td>
<td>Ventral/dorsal</td>
</tr>
<tr>
<td>Unnameable shapes</td>
<td>0.587</td>
<td>0.698</td>
</tr>
<tr>
<td>Puzzle pieces</td>
<td>0.778</td>
<td>0.519</td>
</tr>
<tr>
<td>Abstract matching</td>
<td>0.754</td>
<td>0.328</td>
</tr>
<tr>
<td>Dot location</td>
<td>0.775</td>
<td>-0.379</td>
</tr>
<tr>
<td>Curve tracing</td>
<td>0.728</td>
<td>-0.461</td>
</tr>
<tr>
<td>2-D mental rotation</td>
<td>0.783</td>
<td>-0.390</td>
</tr>
<tr>
<td>3-D mental rotation</td>
<td>0.851</td>
<td>-0.148</td>
</tr>
</tbody>
</table>
on first factor was only 0.229 whereas the mean loading on second factor was 0.828 (all loadings of the dorsal tasks on the second factor > 0.750).

4. Discussion

The present results reveal that there is a high degree of covariation in speed of performance on tasks that emphasize perceptual functions performed by the same neural processing stream (i.e., ventral or dorsal), whereas the covariation is much lower between speed of performance on tasks that emphasize functions performed by different processing streams. Factor analysis revealed that each of the ventral tasks loaded heavily on one factor and each of the dorsal tasks loaded heavily on another factor. These results suggest that, despite the extensive cross-talk between neural structures [30], human visuospatial abilities can be classified using categories based on the functional specializations of the ventral and dorsal processing streams [18].

Importantly, the high correlations and pattern of factor loadings in the present study cannot be attributed to common task requirements or to a surface similarity among the stimuli. The functions assessed by the ventral stream tasks were diverse, including both shape comparison, as in the puzzle pieces task, and the integration of multiple features processed by ventral structures, as in the abstract matching task. The functions assessed by the dorsal stream tasks were even more diverse, including distance discrimination, mental rotation, and shifting of spatial attention. Thus, the high correlations between tasks emphasizing a particular stream appear to be due to an underlying neurobiologically based similarity rather than a similarity in stimuli and task requirements.

The present findings may be contrasted with the results of previous studies that factor analyzed data from speeded tasks. Such studies often report that only one significant factor underlies speeded performance on diverse tasks [10,19]. This may be because most visuospatial laboratory tasks (and indeed most real-world tasks as well) rely on both ventral and dorsal processes. If neither type of process predominates in any task, then separate factors will not emerge. Although a single principal component accounts for the majority of the variance in the present study, distinct ventral and dorsal factors were also observed, presumably because the tasks were constructed on the basis of knowledge about their neural substrates.

The finding of a ventral and a dorsal factor indicates that an individual who is good at one ventral task is likely to be good at another ventral task, and an individual who is good at one dorsal task is likely to be good at another dorsal task. Why should strength in one task be associated with strength in another task that emphasizes the same processing stream? As with other kinds of abilities, individual differences in visuospatial ability must arise from some combination of differences in heredity and differences in environment. Although it is well established that experience plays important roles in the development of the visual system [13], it seems unlikely that experiential differences could be responsible for the ability differences observed in the present study. The tasks in the present study tap fundamental processes (e.g., shape discrimination, feature integration, spatial attention, distance judgment) that are used every day by sighted individuals. The development of these processes likely requires appropriate experience. However, we suspect that most sighted individuals will not differ greatly in the amount of experience that they have had with these processes, and thus, it seems unlikely that experiential differences are a major determinant of the abilities assessed in the present study.

Instead, we tend to prefer an explanation of the present findings that emphasizes genetic rather than experiential differences. Recent research on individuals with Williams syndrome has tentatively identified a particular gene may be responsible for the impairments in visuospatial abilities associated with this developmental disorder [7]. Importantly for the present argument, the deficits associated with this syndrome are most pronounced with respect to dorsal rather than ventral stream functions. Affected children are selectively impaired at drawing, line orientation judgments, and spatial construction and spatial transformation tasks, whereas form and face perception (as well as linguistic abilities) are selectively preserved [2]. Although multiple genes probably affect the development of each of the processing streams, nevertheless the findings with respect to Williams syndrome suggest that genes may have stream-specific effects and thus could play a role in the selective determination of ventral or dorsal visuospatial abilities.

The present findings are consistent with theoretical claims made by F. J. Gall more than 150 years ago. Gall made two claims: first, that different neural structures perform different psychological functions, and second, that variation in these structures is the cause of psychological and behavioral differences between individual humans [8]. The first claim launched the functional localization research program [14,31] and the second claim has been important in human neuropsychology [3] where the psychological and behavioral differences involved are typically the result of brain injury.

Over the years, however, Gall’s focus on differences between normal individuals has been overshadowed by his methodological inadequacies, stemming in part from his emphasis on variations in the size of different brain structures. Alternatively, individual differences
could result from variations in the efficiency of specific neural structures [15]. Such variations in efficiency would still be in the spirit of Gall’s claim that differences between structures associated with specific functions underlie differences between individuals. Regardless of whether the relevant neural variable is size or efficiency, behavioral measurements that assess the function(s) of a particular neural structure or system should exhibit higher correlations than behavioral measurements that assess the functions of different structures or systems. Thus, factor analysis should reveal separate factors associated with the functions of different neural systems. The present study represents a novel test of the implications of the functional localization hypothesis for individual differences, and the results are consistent with the predictions of this hypothesis.

The present factor analytic approach to brain-based abilities has a variety of possible applications, several of which we have begun to explore. One possibility is that the present set of tasks (or a set of tasks like them) could be used to provide a preliminary assessment of the involvement of the ventral and the dorsal streams in novel tasks for which the underlying processes are unknown. That is, the involvement of the ventral and dorsal streams could be assessed by examining whether a novel task loads on the same factor as the current group of ventral tasks, on the same factor as the current group of dorsal tasks, neither, or both.

Another possibility would be to use the present set of tasks to assess ventral and dorsal stream processes in individuals or groups whose strengths and weaknesses are unknown. For example, based on neuroimaging studies, Grady and colleagues [9] have suggested that older adults show less functional separation of the ventral and dorsal pathways than young adults. Such age-related dedifferentiation could be assessed by examining whether distinct ventral and dorsal factors are observed in older adults. Finally, neuroimaging research is needed that examines the activation of ventral and dorsal stream structures by the present set of tasks. Such research is needed not only to confirm the assumed reliance of the present tasks on specific structures, but also to examine whether individuals with strengths in a particular factor analytically defined ability show more activation or less activation (i.e., more efficient usage) of the corresponding processing stream.

In summary, the present results suggest that the specialization for related functions seen within the ventral stream and within the dorsal stream have direct behavioral manifestations in normal individuals. More specifically, our findings demonstrate that at least two brain-based ability factors, corresponding to the functions of the two processing streams, underlie individual differences in visuospatial information processing.

These findings provide converging evidence for the functional integrity of the ventral and dorsal processing streams, and indicate that this integrity is apparent at the level of individual behavior.

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