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REVIEW

Understanding spatial transformations: similarities and differences between mental rotation and mental folding

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Abstract Mental rotation and mental folding, two widely used measures of spatial ability, both require the dynamic spatial transformation of objects with respect to their internal spatial structure. Traditionally, however, these two skills have been considered quite distinct, based primarily on factor analyses of psychometric data. This paper reviews the similarities and differences between mental rotation and mental folding from a variety of perspectives, including their definitions, component cognitive processes, neurological bases, developmental trajectories, malleability, predictive validity, and psychometric properties. We conclude that mental rotation and mental folding are similar in many respects. However, the tasks differ in whether they require rigid or non-rigid transformations of objects. In addition, mental rotation shows robust sex-related differences whereas mental folding does not. We also identify specific questions for which research is lacking.

Keywords Mental rotation · Mental folding · Cognitive science

The ability to represent and mentally transform the shapes of objects is an impressive human skill, allowing us to infer how our actions might change objects in the future and what past events might have led to current appearances. In a series of seminal studies, Roger Shepard and his colleagues showed many decades ago that people can form a mental image of a two-dimensional shape or a three-dimensional object and that they can transform such images in various ways, as for instance by rotating, bending, or folding them (see the collection of papers in Shepard and Cooper 1982). Their work led to hundreds of subsequent papers in cognitive psychology, cognitive neuroscience, and cognitive development, mostly focusing on mental rotation.

Mental rotation and mental folding are similar to each other, as Shepard argued, in that both operations change the *intrinsic* spatial properties of shapes or objects, rather than *extrinsic* spatial relations between objects. Chatterjee (2008) discusses the intrinsic versus extrinsic contrast as a key dimension in a typology of spatial thinking. To understand the difference between intrinsic and extrinsic spatial relations, consider a cardboard coffee cup with a handle. It can be rotated, the handle can be folded, or the cup can fall off a table. As the cup rotates, its internal structure is maintained (i.e., its round elongated concave shape, with a handle attached), but its orientation is altered. Orientation can be considered an intrinsic property because it is not defined with respect to another object, but rather with respect to the observer, a privileged relation. If the handle is folded, the intrinsic structure is altered, but in a self-contained and internally specifiable way. When the cup falls off the table, the change from “on the table” to “on the floor under the table” is a transformation of its extrinsic spatial relations.

Despite the formal and definitional similarities between mental rotation and folding, however, psychometric research has often suggested that mental rotation and mental folding fall into separate factors (Lohman 1979). This literature creates doubts about the conclusion that

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mental rotation and paper folding are both instances of a natural kind, namely mental transformations of intrinsic spatial properties of shapes or mental images. The purpose of this paper is to consider this tension between a formal analysis and the psychometric tradition.

Creating a typology of spatial transformations is fraught with difficulty (see Hegarty and Waller 2005 for a summary of work on this topic and a critique). Consider the cautionary tale of mental rotation and perspective taking. There are formal senses in which these two processes are highly similar (and even computationally equivalent); mental rotation requires imagining motion of an object on its own axis while the observer remains in place, whereas perspective taking requires imagining moving around an object while it remains in place. Physically, both actions would provide the same visual information, suggesting that they should not be distinct. However, there is now a critical mass of findings showing definitively that mental rotation and perspective taking are different in many ways (Hegarty and Waller 2004; Huttenlocher and Presson 1973, 1979; Lohman 1979). In retrospect, the distinctions between mental rotation and perspective taking may be obvious: mental rotation applies to the intrinsic shapes of objects and perspective taking to extrinsically defined spatial relations among objects. But it took some time for the importance of this distinction to become apparent.

Keeping this cautionary tale in mind, the present paper considers whether grouping mental rotation with mental folding based on the intrinsic–extrinsic dichotomy is justified. We compare mental rotation and mental folding in terms of six kinds of criteria: cognitive processes, neurological bases, developmental change, malleability, predictive validity, and psychometric properties. We hope that the present comparison can provide a template for further theoretical work aimed at delineating the natural kinds of spatial cognition.

Cognitive processes

The typical test of mental rotation involves distinguishing a shape or an object that has been rotated from a similar, rotated shape or object, often a mirror image. Reaction time data demonstrate that mental rotation is the direct mental analog of the physical process of rotation; the further the stimulus has been rotated, the longer one takes to imagine rotating it (Cooper 1976; Shepard and Metzler 1971). Both 2D and 3D mental rotation tasks demonstrate a linear increase in response time as a function of the angle of rotation (Cooper 1975; Shepard and Metzler 1971). The 2D and 3D versions of the task seem to rely on substantially the same mental processes, despite increased response times for 3D figures, a difference that has been attributed to longer encoding times (Shepard and Metzler 1988). It has been argued that tests with 2D figures are more susceptible to non-rotation strategies (e.g., piecemeal transformations or comparisons), resulting in a curvilinear component of the response time function (Kung and Hamm 2010). However, there are individual differences in this effect and it seems to be a matter of strategy preference (Searle and Hamm 2012).

Like mental rotation tests, mental folding tests come in both 2D and 3D versions. Of course, folding an object, even if it is presented in 2D, always requires imagining a three-dimensional motion, but in 2D tests both the stimuli and the answer choices are 2D, while in 3D tests, at least one is represented in 3D. Two-dimensional tests are typically called *paper folding*. The stimuli in paper folding tests usually consist of multiple images of a piece of paper being folded, followed by an image of a portion being removed, such as having a hole punched. Answer choices represent potential images of the unfolded paper. Three-dimensional tests have been referred to as “paper folding,” “surface development,” or “cube folding.” These terms are potentially misleading (e.g., not every folded object is a cube), so in this article we use the term *volumetric folding* to refer to 3D folding tests. This term leverages the physical difference between 2D and 3D objects, referencing the volume created as a 3D structure is created via folding. These tasks typically involve transforming a 2D unfolded shape into a 3D folded shape, or the reverse. Judgments about relations between edges and corners once the object has been folded are typically required as the key component of the test. It is currently unclear whether dimensionality strongly affects the processes involved in solving mental folding problems.

Mental rotation and mental folding appear to share many underlying cognitive processes. First and foremost, as argued above, they are both dynamic spatial transformations of intrinsic shape. Second, as with the angle of rotation for mental rotation tasks, Shepard and Feng (1972) demonstrated that response times increased as a function of the number of squares that must be mentally lifted and moved through space during the folding process, which they called “squares carried” (Shepard and Feng 1972). Participants were provided with diagrams that showed an unfolded cube with an arrow on two of the faces. The goal was to indicate whether or not the arrows would touch when the cube is folded. The base of the cube was indicated to constrain mental folding so that number of squares being mentally carried through the folds would be consistent across participants. Linear increases in response time have been replicated repeatedly and with different ages for rotation (Carter et al. 1983; Childs and Polich 1979; Kail et al. 1978; Marmor 1975, 1977), but for folding these results have only been replicated in adults and only with volumetric folding (Milivojevic et al. 2003; Pellegrino et al. 1984; Wright et al. 2008).

Mental rotation and mental folding also differ, however, in a few ways. First, mental rotation is a rigid transformation and mental folding is not; the distances between points in the object are not changed by rotation but are changed by folding. Second, it has been suggested that mental rotation and mental folding tests may differ based on the greater susceptibility of folding tests to solution by an analytic rather than a spatial strategy (Lohman 1979). There are two basic strategies for solving spatial problems. One is to solve the problem as intended (e.g., to mentally rotate or mentally fold an image holistically). Another is to solve the problem through a predominately verbal-analytic approach, usually accompanied by attending to individual parts separately. Lohman argues that mental folding tests are more amenable to such a verbal-analytic solution, because tests of mental folding typically require multiple folding transformations, while mental rotation tests usually show a single rotation. Additional steps create more opportunity for using analytic strategies and may make them more effective (Lohman 1979). Some researchers have gone so far as to suggest that mental folding solutions always include an analytic component and that mental rotation tests never elicit this strategy (Linn and Petersen 1985). However, while mental folding tasks are sometimes solved via an analytic rather than a spatial strategy, this is not always or even often the case (Kyllonen et al. 1984; Snow 1978, 1980). Similarly, while mental rotation problems are often solved spatially, rather than analytically, there are individual differences in strategy for mental rotation tests as well (Bethell-Fox and Shepard 1988; Cooper 1980; Kail et al. 1979; Kung and Hamm 2010; Searle and Hamm 2012). In fact, there is a class of people referred to as “non-rotators” who do not appear to ever solve mental rotation problems via mentally rotating the object as a whole (Geiser et al. 2006). Thus, both types of problems can be solved through both strategies; mental folding tasks may be more vulnerable to a mixed or purely non-spatial approach, but this idea has never been rigorously evaluated.

Overall, a comparison of cognitive processes indicates that mental rotation and mental folding are quite similar. However, the transformations do differ in rigidity. More research is required to determine the impact of rigidity and to examine the extent of analytic strategies in mental folding assessments (Table 1).

Neurological bases

Imaging and electroencephalogram (EEG) techniques have the potential to identify the neural activity correlates of mental rotation and folding. Such studies may be useful in exploring strategies as different approaches might rely on different areas of the brain. In examining mental rotation and mental folding, neuroscience research has focused on two issues: confirming that these mental transformations are accomplished as analogs to physical manipulation and exploring the role of simulated action in mental rotation.

The distinctively spatial component of mental rotation appears to be correlated with activation in the parietal lobe (Alivisatos and Petrides 1997; Cohen et al. 1996; Harris et al. 2000; Jordan et al. 2001; Kosslyn et al. 1998; Richter et al. 2000). More specifically, a meta-analysis by Zacks (2008) suggests that activity in the parietal lobe is focused on the intraparietal sulcus (IPS), extending outward to neighboring regions. In terms of the analogy between physical and mental processes, level of activation of this area is linked to angle of rotation (Zacks 2008). There has been some debate on whether or not activation is lateralized, and the results are mixed. Zacks (2008) notes that parietal activation has often been observed as right lateralized, but this is not always the case, with some studies detecting bilateral or even left lateralized activity.

Mental folding has also been found to be associated with activation in the parietal lobe (Jaušovec and Jaušovec 2012; Milivojevic et al. 2003; Unterrainer et al. 2000). Milivojevic et al. (2003) used the timing and amplitude of event-related potentials (ERPs) during mental folding (as well as mental rotation) to determine whether ERPs, like response times, might be related to the physical constraints of transforming an object. For mental rotation, they found an amplitude decrease and delay of onset of the key 400–600 ms peak, as a function of angle of rotation. This amplitude modulation during mental rotation has been specifically related to mentally rotating the object, as opposed to other processes that might be involved in solving a mental rotation task, such as initially encoding the object (see Heil 2002 for a review). For mental folding, the results were not as clear. An amplitude decrease for the related peak was reported beyond the baseline of one “square carried” (i.e., if more than a single squared needed to be moved through space to arrive at the answer), but not as a function of additional squares carried beyond this baseline. There was also no change in timing of the ERP peak for folding. However, reaction time did increase for both mental rotation and mental folding, as a function of angle of rotation and squares carried, respectively. Thus, the behavioral and neurological data are not in complete alignment for mental folding. The lack of a relation between amplitude modulation during mental folding and squares carried is unexpected, particularly given the presence of a relation between squares carried and response time in the same subjects.

Another area of investigation has explored the role of motor processes in spatial transformations. The data for mental rotation suggest that motor processes are often

Table 1 Cognitive processes comparison

	Mental rotation	Mental folding
Intrinsic transformation	✔	✔
Geometrically rigid transformation	✔	×
Physical analog (as measured by linearly increasing response time)	✔	✔ (only tested in 3D with adults)
Strategy		
Spatial	✔	✔
Analytic	Less susceptible?	More susceptible?
Dimensionality differences	×	Not tested

involved (Richter et al. 2000; Tagaris et al. 1997; Vingerhoets et al. 2001; Zacks 2008), implying that people may be literally simulating turning the stimuli, at least to some degree. Kosslyn et al. (2001) demonstrated that activation of motor areas is indicative of such a strategy. Subjects either were shown a Shepard-Metzler style cube being rotated by a motor or were asked to rotate it themselves. They were then instructed to perform the mental rotation task as they had just witnessed the rotation. Responses were delivered via a foot pedal and participants were told not to move their hands. Activity in the motor cortex was recorded for those instructed to imagine rotating the cube by hand, but not for the other participants. However, unfortunately, motor activity has apparently not been investigated for mental folding.

Overall, as with the cognitive comparison, neuroscience findings indicate that mental rotation and mental folding may be similar, but more research on mental folding is needed. For both tasks, processing appears to occur in the parietal cortex, particularly the IPS. Amplitude modulation in mental rotation has been shown to relate to angle of rotation, much like reaction time. However, the situation is unclear for mental folding; the EEG data did not relate to squares carried, but the reaction time data did. Additionally, the role of motor functioning has thus far only been evaluated for mental rotation. Future work should more thoroughly investigate mental folding (Table 2).

Table 2 Neural bases comparison

	Mental rotation	Mental folding
Parietal cortex/physical analog	✔	? (more work needed)
Motor processes	✔ (but not always)	?

Developmental change

Some precursors to mental rotation may appear as early as 4 months of age (Hespos and Rochat 1997; Moore and Johnson 2008; Quinn and Liben 2008; Rochat and Hespos 1996). However, on tasks that more directly mirror adult versions, children do not succeed until at least 4 years of age (Marmor 1975, 1977) with some studies not reporting adult-like performance until as late as 7 years (Dean and Harvey 1979; Piaget and Inhelder 1966/1971). Criteria for mental rotation include not only performing above chance, but also showing a linear response time pattern (Dean and Harvey 1979; Frick et al., in press; Marmor 1975, 1977). Children's mental rotation abilities continue to increase in speed through later childhood (Kail et al. 1978), although a tradeoff of speed for accuracy may still impact children's response times differently (Carter et al. 1983; Childs and Polich 1979).

There is no research on precursors to mental folding in infants and, until recently, there were not any studies of mental folding in early childhood either. However, Harris et al. (in press) and Levine et al. (2012) have begun such investigation. Harris et al. (in press) reported that children began to perform above chance beginning at 5.5 years old on their measure, while Levine et al. (2012) found that children were above chance by 3 years old on their task. However, early group level indications of success in Levine et al. may be due to a small subset of precocious folders, who may be more properly thought of as a different population, whose higher scores push group performance above chance. Thus, at least some evidence suggests that both mental rotation and paper folding may be present at roughly the same age. More work is needed to better understand mental folding in early development, as well as to explore the psychometric properties of these two tests in childhood (Table 3).

Malleability

A recent meta-analysis by Uttal et al. (2012) demonstrated that, across a wide age range, spatial thinking skills are malleable. The relative effect size of training compared to a control was quite large, about half a standard deviation. When mental rotation and mental folding were considered separately, similar effect sizes were found, across three

Table 3 Developmental comparison

	Mental rotation	Mental folding
From 0 and 5 years	Possibly	Possibly
At 6 years and later	✔	✔

methodologies: similar effects of repeated testing ($g_{\text{rotation}} = .43$ and $g_{\text{folding}} = .46$), pre-test/post-test treatment-only gains ($g_{\text{rotation}} = .56$ and $g_{\text{folding}} = .60$), and treatment over control gains ($g_{\text{rotation}} = .49$ and $g_{\text{folding}} = .53$). Treatment-only studies are those without a control group, where only within-subject change is considered. The treatment-only effects were determined to be homogenous for both mental rotation and mental folding (i.e., the effects in all studies were similar). Effects for both mental rotation and mental folding held for all three age groups defined in the meta-analysis (under 13, 13–18, and over 18). Training for both tasks was found to be durable, lasting over multiple months.

Does training on mental rotation transfer to mental folding and vice versa? Mental rotation training has been shown to result in improvements on both mental rotation and volumetric folding scores (Duesbury and O'Neil 1996; Sanz de Acedo Lizarraga and García Ganuza 2003) and on paper folding scores (Lohman and Nichols 1990). Training on folding origami was shown to transfer to mental rotation (Boakes 2009). Despite the apparent similarity between physically folding origami and mentally folding during a test, origami training did not result in improved scores for either the paper folding or volumetric folding measure, though this may have been due to the amount of training. Boakes' (2009) participants only received an average of 5 h of training during a 1-month period, but in another study, in which participants received approximately 18 h across 3 months, an improvement in paper folding scores was found (Jaušovec and Jaušovec 2012).

Transfer between mental rotation and mental folding has been demonstrated in the same study, allowing for direct comparisons in effects to be made. Wright et al. (2008) trained one group on mental rotation and another on volumetric folding. Both groups showed improved performance on both their trained and not trained test, for both items seen during pre-test and novel items.

The results of training studies strongly suggest that mental rotation and mental folding are tapping a common skill that can be trained. While this common skill may be a high-level ability to perform dynamic spatial transformation, it is also possible that another shared component is being trained, such as interpreting, coding, and retaining the input that defines the intrinsic shape. For example, Göksun et al. (in press) reported that people's gestures reveal important differences in how they encode objects on a mental rotation test and that these differences are related to performance. People who perform well on a mental rotation task appear to attend more closely the internal structure of the target objects, an important component to solving these tasks, as they think and communicate about them. The data on malleability indicate that mental rotation and mental folding have common components (Table 4).

Predictive validity

Many studies relating spatial transformation ability to achievement in science, technology, engineering, and mathematics (STEM) use a composite score, comprised of mental rotation and mental folding scores, which does not allow for a comparison between the two. Such studies generally find that a spatial composite score is related to STEM learning. For example, spatial skills help explain individual differences in ability to learn from a diagram (Höffler 2010). Spatial skills are also important for graph comprehension with a rotation-folding composite score related to inhibiting a natural inclination (Clement 1985) to interpret graphs as literal depictions of some event (Kozhevnikov et al. 2007; Kozhevnikov and Thorton 2006). Problem solving is also supported through spatial thinking, though these studies have predominately only measured mental rotation and not mental folding. Spatial thinking appears to help new learners isolate the important components of the problem (Bodner and McMillen 1986). This relation is particularly evident when students are able or encouraged to draw. Students who drew before or during problem solving performed better, and high-spatial students were more likely to draw (Pribyl and Bodner 1987). In addition, students with lower spatial skills were more likely to draw incorrect diagrams (Pribyl and Bodner 1987), often offering a literal depiction of objects in the problem rather than the problem itself (Van Garderen 2006).

The relation of dynamic spatial transformations to early success has led some researchers to suggest that difficulty with spatial thinking is a barrier to STEM entry (Uttal and Cohen, in press). As would be expected, high-spatial ability is predictive of entry into the STEM disciplines. Some of the most well-known and extensive findings on this relation come from Project TALENT. Project TALENT was a large-scale, longitudinal study that followed 400,000 high-school students for 11 years and measured spatial skill through a composite score (Wai et al. 2009). Research on this dataset revealed that high scores on spatial thinking measures are predictive of college major and job choice in one of the STEM disciplines (Humphreys et al. 1993; Wai et al. 2009).

Similar results have also been found with more focused studies. Baker and Talley (1972) reported that mental

Table 4 Malleability comparison

	Mental rotation	Mental folding
Malleable	✔	✔
Durable	✔	✔
Transfers from other skill	✔	✔

folding was a strong predictor of senior versus freshman status in chemistry majors. This suggests that students with better spatial skills are more likely to continue in a STEM major. Science majors have higher mental folding scores than non-science majors for both sexes, but only female science majors outperform their non-science major counterparts on mental rotation (Lord 1987). Education majors with a math or science focus have higher spatial skills, measured by a composite score, than those with a focus on humanities, business, social science, and special education (Lord and Rupert 1995). Similar to the Project TALENT data, education majors with a mechanical/art and physical education focus also received high composite scores and were not statistically different from those in math/science (Lord and Holland 1997). Siemankowski and MacKnight (1971) examined the mental folding scores of students from a variety of majors and found that science, math, and arts majors outperformed non-science majors, such as education and liberal arts. Mental folding, but not mental rotation, has been related to the number of geoscience classes taken, though both predicted geoscience conceptual understanding (Black 2005). However, Cherney and Collaer (2005) reported a relation between math courses and mental rotation; mental folding was not assessed.

A mental rotation-folding composite score has also been related to STEM course experience, consistent with the idea that the use of spatial skills in STEM courses offers opportunities for practice and improvement. This relation has been shown in physics for both a business-as-usual course (Pallrand and Seeber 1984) and one designed around microcomputer-based laboratory instruction (Kozhevnikov and Thorton 2006). It was also shown for mental folding in a chemistry class designed around concrete models (Talley 1973) and for mental rotation in a geometry course (Battista et al. 1982). Interestingly, Wittig et al. (1984) reported on an 11-month, post-baccalaureate engineering training program for women in which participants' volumetric folding, but not mental rotation, was improved.

It seems to be clear that both mental rotation and mental folding scores are likely useful in predicting both STEM entry and success. However, the frequent use of composite scores prevents a definitive answer from being drawn as to whether these two types of tasks have a different relation to STEM (Table 5).

Psychometric properties

Thus far, our review appears to indicate that mental rotation and mental folding are similar in many respects. We must now examine why the psychometric literature has indicated that they are different. Specifically, we consider whether this conclusion may be due to how the tests were designed, rather than how the target skills function.

The search for a spatial factor, or set of spatial factors, that could be differentiated from *g* (general intelligence) began almost a century ago (Eliot 2000). Factor analyses support disaggregating dynamic spatial transformations into multiple factors (Lohman 1979). The most commonly suggested factors are spatial visualization (Vz), and spatial relations (SR), and, occasionally, spatial orientation (SO) (Lohman 1979). The Vz factor is a class of complex mental transformations, including mental folding and figural synthesis (combining disparate pieces into a single target object through translations and rotations of the pieces), SR is synonymous with mental rotation, and SO is akin to perspective taking. In contrast to the cognitive and neural evidence, the psychometric data suggest that mental folding and mental rotation are not similar since they load onto different factors (Lohman 1979).

One of the first major factor analysis projects to include mental rotation and mental folding was Thurstone's PMA (primary mental abilities) study (Thurstone 1938). Thurstone later explained Vz as "the ability to imagine the movement or internal displacement among the parts of a configuration that one is thinking about" (Thurstone 1951). For Thurstone, spatial skills are best divided into two constructs: rigid and non-rigid transformations. This division supports the idea, discussed earlier, that mental rotation and mental folding may be different in terms of the rigidity of the transformation.

The distinction between SR and Vz was also found in Guilford and colleague's work with the Army Air Forces (AAF) data (Guilford et al. 1952; Guilford and Lacey

Table 5 STEM relation comparison

	Mental rotation	Mental folding	Composite
Success in			
Engineering		✔	✔
Biology			✔
Physics			✔
Math	✔		✔
Chemistry	✔	✔	
Geoscience		✔	
Trained by			
Physics			✔
Chemistry		✔	
Math	✔		
Engineering	× (one study)	✔	
Entry		✔	✔
Geoscience	× (one study)	✔	
Math	✔		

1947) and by Zimmerman (1953) and Holzinger and Harman (1938). The replication across different samples with different tests supported the validity of these factors.

However, understanding the factor-analytic work requires attention to the way mental rotation and mental folding were measured and to the other spatial tests used. First, both the PMA and AAF data relied on multiple tests of mental rotation, but only included one test of paper folding and one of volumetric folding. Factors represent shared variance, which can come from many sources. Using multiple mental rotation tasks may create enough shared methods variance to suggest a distinct factor.

Second, a difference in difficulty of the tests may have played a role in the emergence of multiple factors. Lohman (1979) built on Holzinger and Harman's analysis, using their results to calculate the residual correlations between spatial items after controlling for *g*. Lohman's analysis indicated that spatial thinking could be described by a bipolar SR-Vz factor, with mental rotation and mental folding on opposite ends of the spectrum. Lohman suggests that this bipolar factor represents a speed-power distinction, with SR representing speed and Vz representing power. He claims this distinction is relevant across multiple domains of intelligence. Tests of speeded skills are fairly simple and can be solved successfully by the majority of test-takers, given sufficient time. Tests of power are complex and difficult for most people. This distinction, based on the construction of the tests, may not reflect a difference in the skills, if assessed differently. For example, the mental rotation tests required only a single rotation, while multiple folds were used in the mental folding tests. This need not be the case; a single fold could be tested or multiple rotations through multiple planes could be required. There were also differences in response format, with the Vz tests typically requiring free response, leaving more room for error (Lohman 1979).

Differences in relation to *g* also suggest that difficulty may be playing a role. There is a close relation between Vz and *g*. If Vz tests are indeed more difficult tests, then they would be expected to relate closely to this higher-order construct. Guilford et al. (1952) noted that the solutions for difficult Vz problems seem to involve more reasoning, including verbal reasoning. As mentioned, mental folding tests may be more susceptible to the use of analytic strategies, again suggesting an issue of test design. The involvement of non-spatial reasoning would support the idea that mental folding tests, in their current form, are psychometrically different from mental rotation tests, because they are a less pure measure of dynamic spatial transformations.

The psychometric literature appears to strongly support a distinction between mental rotation and mental folding; tests of each type load onto separate spatial factors. However, the design of these studies and the tasks used leaves the results open to other interpretations. Future research should equate number of tests and difficulty, in order to more accurately examine the structure of spatial skills (Table 6).

Sex differences

This review has argued thus far that mental rotation and mental folding are likely to be closely related cognitive processes, despite previous psychometric work. However, there is one glaring difference between the two skills, namely that mental rotation shows a strong sex difference while mental folding shows none at all (Linn and Petersen 1985; Voyer et al. 1995). If these two skills are in fact nothing more than two instantiations of a broader cognitive skill, what is the source of this difference in whether or not we see sex differences?

One possible explanation might involve the fact that mental rotation is rigid, while mental folding is not. Rigid transformations are limited to translation, rotation, and mirroring (where for 2D objects a mirror reflection is equivalent to an 180° rotation through the picture plane). There is some evidence that rigid transformations other than rotation (i.e., mirroring and translation) may also consistently show a sex difference. The ability to mentally mirror was tested by Kerns and Berenbaum's (1991) "Mirror Image Test" and sex differences, in favor of males, were reported. This test was designed as a complement to mental rotation tasks and similarly requires subjects to identify a transformed version of the target stimuli. No rotation is involved for either the correct answer or foils, so this test is not simply a mental rotation task where the incorrect, mirror image answers are now correct. Translation has also been tested, in children, as part of Levine et al. (1999) Children's Mental Transformation Task. In this task, children are shown a 2D object that has been bisected, with the pieces either translated, rotated, or both. Children are asked to identify the original object from among four answer choices. Sex differences were reported for all types of items and there was no type by sex interaction. Further research is required on mentally mirroring and translating visual stimuli. However, it is important to acknowledge that focusing on rigidity only shifts the question of why there are sex differences for

Table 6 Psychometric comparison

	Mental rotation	Mental folding
Factors	Spatial relations	Spatial visualizations

Table 7 Comparison summary

Section	Comparison	Mental rotation	Mental folding	Composite
Cognitive	Intrinsic transformation	✔	✔	
	Geometrically rigid transformation	✔	×	
	Physical analog (as measured by linearly increasing response time)	✔	✔ (only tested in 3D with adults)	
	Strategy			
	Spatial	✔	✔	
	Analytic	Less susceptible?	More susceptible?	
	Dimensionality differences	×	Not tested	
Neural	Parietal cortex/physical analog	✔	? (more work needed)	
	Motor processes	✔ (but not always)	?	
Developmental	From 0 and 5 years	Possibly	Possibly	
	At 6 years and later	✔	✔	
Malleability	Malleable	✔	✔	
	Durable	✔	✔	
	Transfers from other skill	✔	✔	
STEM	Success in			
	Engineering		✔	✔
	Biology			✔
	Physics			✔
	Math	✔		✔
	Chemistry	✔	✔	
	Geoscience		✔	
	Trained by			
	Physics			✔
	Chemistry		✔	
	Math	✔		
	Engineering	× (one study)	✔	
	Entry		✔	✔
	Geoscience	× (one study)	✔	
	Math	✔		
Psychometric	Factors	Spatial relations	Spatial visualizations	

mental rotation to a question of why there are sex differences for rigid transformations.

Conclusion

One prerequisite for research is careful delineation of constructs and definitions, and for the domain of spatial thinking, there has been no consensus on typology or nomenclature. One step, which took several decades, was establishing that mental rotation and perspective taking are distinct processes. However, it is daunting to consider proceeding with successive pairwise contrasts of this kind. A principled path forward in distinguishing or grouping spatial skills into natural kinds is offered by the proposal of a contrast between extrinsic and intrinsic spatial representations, crossed with whether such representations are dynamically transformed or simply represented in a static form (Chatterjee 2008). This paper has compared mental rotation to mental folding, in order to consider an implication of Chatterjee's proposal that the two skills should be very similar, a conclusion in contradiction to the traditional psychometric literature.

As summarized in Table 7, the evidence indicates that the two processes are in fact more overlapping than distinct, although they are different in some ways. Both operations focus on transforming internally specified representations of objects. Tests of both types are usually solved spatially, but are susceptible to non-spatial strategies as well. These findings have been largely supported by the available studies of neural correlates, as well as by behavioral data. Research on the early development of both of these skills appears to indicate that they reach near-adult levels around the age of 6, though more work is needed. Both skills can be trained and training effects are durable. Training for each has also been shown to transfer to the other. Mental rotation and mental folding are also both related to entry into and success in the STEM disciplines. Previous psychometric evaluations indicated that mental rotation and mental folding were different, but this research may have been confounded by the inclusion of a disproportionate amount of mental rotation tests and tests differing in the level of difficulty. However, this review found two major ways in which mental rotation and mental folding differ: mental rotation is a geometrically rigid transformation and mental folding is not, and mental rotation shows sex differences while mental folding does not.

Recent work suggests not only that rigidity is a crucial distinction, but that the type of non-rigid transformation may matter as well (Atit et al., in press; Resnick and Shipley, in press). Borrowing from material science terminology, these papers distinguish between brittle non-rigid transformations, in which the object does not remain whole and pieces are rigidly transformed independently, and ductile transformations, performed on objects holistically. Resnick and Shipley studied brittle transformations (as when objects break into pieces, or when pieces of objects are re-assembled). Atit et al. studied bending, which, like folding, is a ductile transformation, and found that mental folding shared variance with both mental rotation, as expected given this review, and with mental bending, as expected given the fact that both folding and bending are ductile non-rigid transformations. However, mental rotation did not share variance with bending, after controlling for the other tests. The difference between a bend and a fold may appear minor, but folding involves distinct areas within an object that are rigidly preserved, despite the non-rigid transformation of the object as a whole, while there are no such rigid areas in bending (Atit et al., in press).

Analyses similar to the one in this paper should be considered for other types of spatial thinking. Other skills investigated should include those that also focus on transforming objects and might be expected to be somewhat similar to those examined here (e.g., cross-sectioning), but also spatial skills that might be expected to be distinct (e.g., navigation and spatial perceptual skills). However, as indicated in this review, few skills have been as well studied as mental rotation. A great deal of additional research will be required on the nature of individual spatial thinking skills, including some aspects of mental folding, before the nature of their interrelation can be fully understood. Analyses following the one in this paper will help highlight task-specific, construct-irrelevant features of tests and test-taker strategies that may be confounding current research. These processes should also help us move beyond simply comparing constructs, exploring the shape of a broad cognitive ability, and instead begin to also consider how seemingly minor similarities and differences uncovered may be related to other outcomes, such as sex differences.

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