Fiber Arts Require Spatial Skills: How A Stereotypically Feminine Practice Can Help Us Understand Spatial Skills and Improve Spatial Learning

In press, *Sex Roles*

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Abstract

In this review, we propose that fiber arts – a wide array of practices that use string, yarn, and fabric to create functional and fine art textiles – present a novel avenue to both explore basic science questions about spatial skills and to design interventions that help children learn spatial skills. First, we outline how fiber arts are applicable to existing theoretical frameworks that aim to organize our understanding of spatial skills, and highlight how fiber arts may be particularly relevant for understanding critically understudied non-rigid spatial skills. Next, we review the environmental factors that influence spatial skill development. In the third section of the paper, we review the literature on gender differences in spatial skill performance, as well as intervention approaches that have been taken to close gender gaps. Fourth, we outline how motivational features of fiber arts, specifically the roles of individual choice in goal-setting and growth-mindset-consistent messages in fiber arts contexts, could contribute to spatial learning. Finally, we suggest several avenues for future research, including leveraging fiber arts materials and techniques to investigate non-rigid mental transformation skills, and designing gender-inclusive fiber-arts-based spatial skills interventions that maintain the motivationally-relevant features of fiber arts practices and contexts.

Keywords: Spatial skills, STEM achievement, math-gender stereotypes, fiber arts, academic motivation

Fiber Arts Require Spatial Skills: How A Feminine-Stereotyped Practice Can Help Us Understand and Improve Spatial Learning

There is a clear yet often overlooked conceptual link between science, technology, engineering, and math (STEM) fields and *fiber arts* - a wide range of practices that use cloth, yarn, and fiber to create works of art and functional or culturally-relevant items. Fiber arts have been practiced across time periods and cultures (for example: Bauberger, 2016 on Yukon First Nations practices; Belfer, 1992 on fabric dying practices from ancient China, India, Peru, and Greece; Fowler, 2014 on Moroccan fiber traditions and how they connect to North American fine art; Kalbfleisch, 2015 on Aboriginal Canadian traditions; Parker, 1984 on European traditions) and serve different purposes (for example: Hickey, 2015 on fiber arts for pay, leisure, and fine art display; MacDonald, 2015; Moore & Prain, 2019 on fiber crafts as a site for community building, organizing, and political action). Although many may not consider mathematics and computer science when thinking of fiber arts, there is a distinct conceptual connection. The punch-cards of the Jacquard loom served as an important precursor for computers, creating a binary "code" that, when fed into an industrial loom, produced different patterns of cloth (Fernaeus et al., 2012). Further, many mathematicians have explored theoretical connections between complex math problems and fiber arts practices. For example, knots can serve as an important tool for visualizing deformable objects (Mcleay & Piggins, 1996), crochet allows visualization of mathematical concepts like the hyperbolic plane (Henderson & Taimioa, 2001), and weaving can be used to solve geometric proofs (Zelinka, 1984). Beyond upper-level mathematics, knitting, crochet, needlepoint, and weaving can be important teaching tools for even basic math skills (Belcastro & Yackel, 2007, 2011). As these examples illustrate, rich conceptual connections exist between fiber arts practices and STEM fields.

Beyond conceptual links to STEM fields broadly, fiber arts offer a striking opportunity to practice and understand basic spatial skills, such as rotation, transformation, folding, scaling, translating between 2-dimensional (2-D) and 3-dimensional (3-D) representations of objects, and proportional reasoning. Spatial skills are crucial to STEM learning: a recent meta-analysis confirmed that training students' spatial skills leads to significant transfer to math skills, with a medium effect size (Hawes et al., 2022). Despite the strong links between spatial skills and math performance, research is ongoing to understand exactly why this connection exists (Mix, 2019). At a neural level, spatial and math skills seem to rely on overlapping brain areas (Hawes, Sokolowski et al., 2019). At a behavioral level, several reasons for the connection have been proposed, including that understanding spatial relationships is required for understanding symbolic number representations (for example, the difference between 35 and 53 relies on the spatial relation between the number symbols; Mix, 2019), that we often represent quantity in a spatial manner, such as on a number line (e.g., Gunderson et al., 2012), and that effective mathematical problem-solving strategies often involve visuospatial representations (e.g., Seron et al., 1992). Given that math performance in early childhood is highly predictive of later math performance (Watts et al., 2014), improving spatial skills may be an important avenue for fostering strong math skills in both the short- and long-term. Indeed, students with higher spatial skills in high school were more likely to pursue higher levels of coursework in STEM fields (Wai et al., 2009). Fortunately, spatial skills are malleable (Uttal et al., 2013), and early exposure to spatial concepts, play, and talk shapes children's spatial and math learning in a way that persists over development (e.g., Casasola et al., 2020; Jirout & Newcombe, 2015; Levine et al., 2012; Pruden et al., 2011).

Further, fiber arts are distinct because they are primarily non-rigid, in contrast to more well-studied spatial skills and activities like mental rotation and block play, which involve rigid transformations. Thus, fiber arts provide a context for practicing mental transformations of deformable structures, which have been distinctly understudied despite their relevance for STEM fields that study physical phenomena – like the earth, ocean, atmosphere, and human tissue - that are not rigid (e.g., geoscience, atmospheric, and ocean science, Atit et al., 2013; McNeal & Petcovic, 2020; surgery in medicine, Tendick et al., 2000). In addition to the cognitive affordances of fiber arts, the actual and perceived over-representation of women as fiber arts practitioners, as well as the opportunities for choice and growth-mindset-consistent messages present in fiber arts contexts, make it a particularly useful context for spatial learning interventions.

In this review, we first briefly define spatial skills and make the case for how fiber arts connect to existing spatial skills frameworks in psychology. Next, we review the role environmental factors play in the development of spatial skills. We move on to consider the literature on gender differences in spatial skills, STEM pursuit, and interventions that have aimed to close gender gaps in both. We then discuss motivational features of fiber arts tasks and contexts. Finally, we outline future directions for basic and applied research on spatial skills and fiber arts. We propose that fiber arts could serve to advance basic research on spatial skills by allowing us to understand non-rigid mental transformations, which hold theoretical importance for conceptualizing the full breadth of spatial skills and how they support STEM achievement and pursuit. Further, the physical and conceptual affordances of fiber arts could make them a powerful tool for teaching and practicing spatial skills in early childhood through high school, which could in turn promote children’s success in and pursuit of STEM fields. Finally, the gender composition and motivational features of fiber arts communities may make them a new and potentially effective pathway to increase participation for groups that have been historically under-represented in math-heavy STEM fields.

How Fiber Arts Use Spatial Skills

Defining Spatial Skills

Decades of research have focused on defining the multi-faceted mental processes and behavioral tasks that tap into “spatial thinking”. Newcombe and Shipley (2015) defined spatial thinking as mentally representing “shapes, locations, paths, relations among entities and relations between entities and frames of reference” (p. 2). Spatial skills may be rooted in evolutionarily important sensorimotor brain systems that govern our ability to interact with our physical environment, including landscapes, objects, and tools (Hawes et al., 2019). Spatial skills in a modern context also support our reasoning about magnitudes, use of number systems, understanding diagrams, and visualizing both small- and large-scale concepts and scientific processes, and, consequently, are crucial for STEM learning (Mix & Cheng, 2012).

Spatial skills are multidimensional, with many component parts. One of the most well-studied spatial skills is mental transformation, or the ability to represent and rotate, flip, or scale 2-D and 3-D objects mentally (e.g., Nazareth et al., 2013). A number of other spatial skills have been identified, including mental folding (mentally representing what an object would look like if manipulated and folded), disembedding (recognizing 2-D and 3-D shapes within a larger visual display), penetrative thinking (visualizing the relationships among internal components of an object), visuospatial short term and working memory (holding in mind spatial relationships and mentally manipulating them), visual perspective taking (identifying 2-D images that match different perspectives of a 3-D scene), spatial scaling (relating distance in one space to distance in another space of a different size, such as in map reading), proportional reasoning (matching or comparing visual representations of proportions), spatial analogy (recognizing analogous relationships between objects) (e.g., Harris et al., 2013; Mix et al., 2018; Pruden et al., 201; Mohring, Frick & Newcombe, 2018), and sequential spatial thinking (visualizing how a series of spatial transformations leads to a final product) (Newcombe & Shipley, 2015). Finally, larger scale spatial skills and strategies, such as navigation, involve the ability to move through and orient within real-world or virtual environments (Nazareth et al., 2019; Schinazi et al., 2013).

Recent Theoretical Framework for Organizing Spatial Skills

Despite extensive research and agreement that spatial skills are important for a range of human endeavors (e.g., Wai et al., 2009), even recent work continues to debate the exact conceptual structure of spatial skills and how to arrange component skills into a cohesive theoretical framework. We highlight a two-dimensional framework proposed by Newcombe and Shipley (2015) which categorizes spatial skills by 1) whether they involve intrinsic (within-object) or extrinsic (between-object) relationships, and 2) whether the objects involved are static (non-moving) or dynamic (moving). For example, identifying relationships within a single, non-moving object to appropriately categorize that object (e.g., as a pear versus an orange) is an example of intrinsic, static spatial thinking, whereas thinking about the shapes created when you cut up an orange is an example of intrinsic, dynamic spatial thinking. Understanding 2-D physical representations of space, such as maps, is an example of static, extrinsic spatial thinking, whereas actually moving one’s body while navigating through an environment is an example of dynamic, extrinsic thought.

How Fiber Arts Map Onto the Two-Dimensional Theoretical Framework of Spatial Skills

Fiber arts make up a wide range of practices, including crochet, knitting, needlepoint, embroidery, weaving, lacework, spinning, sewing, quilting, rug hooking, felting, braiding, macrame, and fabric dying (Belfer, 1992). Mapping fiber arts practices onto the extrinsic-intrinsic and static-dynamic dimensions of Newcombe and Shipley's (2015) framework (Figure 1) illustrates both the wide range of spatial skills employed in fiber arts and provides a road map for investigating fiber arts as a site for spatial skill development.

The involvement of spatial skills in fiber arts practices is particularly strong for intrinsic spatial skills (Figure 1 and Table 1). First, the intrinsic, static spatial skills of disembedding and categorization are used when isolating specific stitches in order to differentiate how an object was made – for example, determining whether a hat was knitted or crocheted (Allen et al., 2020, Book 2, Chapter 2 versus Allen et al., 2020, Book 3, Chapter 1). Another intrinsic, static spatial skill, penetrative thinking, is required for understanding, for example, how the internal structure of an individual crochet stitch differs depending on its type (single, double, treble) (Allen et al., 2020, Book 3, Chapter 1).

Intrinsic, dynamic spatial skills are frequently used within fiber arts contexts as well (Figure 1 and Table 1). First, mentally rotating or otherwise transforming continuous pieces of yarn or thread into 3-D objects that can be flat (e.g., a scarf) or tubular (e.g., a hat or sock) are key to practices like knitting, crocheting, and weaving. Sequential spatial thinking – mentally visualizing the outcome of many transformations together – is relevant for almost all fiber arts practices, for example, resist dying techniques, where one makes a series of folds or applies layers of wax to fabric before completing multiple bouts of dying to achieve patterns (Belfer, 1992). Finally, many fiber arts practices use charted patterns, which require visualizing what a 3-D item will look like from 2-D representations of spatial relationships (for example, using a grid planning sheet in weaving, Peppler, et al., 2020). Intriguingly, there may be variation between different fiber arts practices in the extent to which 2-D to 3-D (and 3-D to 2-D) reasoning is required. Sewing, for example, may rely heavily on this type of reasoning: deconstructing existing 3-D pieces of clothing, creating 2-D paper templates for a new piece, and then constructing the new 3-D clothing, all require transformations in both directions and often require thinking inside out (for example, to make seams, Makes, 2017).

Extrinsic spatial thinking is also involved in specific fiber arts practices (see Figure 1). Spatial scaling is a static, extrinsic spatial skill that comes into play in fiber arts like crochet and knitting when practitioners determine the gauge (i.e., stitches per inch) used in a final project by first creating swatches – small, usually square, samples of crocheted or knitted fabric using the yarn weight (i.e., thickness) and the size of crochet hooks or knitting needles specified by the pattern (Gresalfi & Chapman, 2017; Allen et al., 2020). Another extrinsic, static spatial skill is proportional reasoning, which is required, for example, when mixing the appropriate amount of dye to liquid to achieve particular shades when dying fabric. Dynamic, extrinsic spatial thinking is involved when fiber practitioners stitch or otherwise join multiple pieces of fabric together to create a larger object, such as sewn quilts or clothing (e.g., Belcastro & Yackel, 2011, Chapter 9). As these non-exhaustive examples illustrate, fiber arts incorporate a wide variety of spatial skills that are of interest to psychologists seeking to support spatial and math learning.

Non-Rigid Mental Transformations: An Understudied Spatial Skill Relevant to Fiber Arts

In addition to the clear connections between fiber arts and these well-studied spatial skills, fiber arts practices routinely utilize a distinctly understudied aspect of spatial skills: non-rigid mental transformations. Most research on spatial skills has focused on rigid spatial transformations, such as mental rotation, where the distance between two points within an object *remains the same* when the object moves. Non-rigid transformations, by contrast, are ones in which the distance between two points within an object *changes* when the object is transformed (e.g., bending, breaking, and folding, Atit et al., 2013). Non-rigid mental transformations can be further categorized as brittle (a hard object breaks into different pieces and pieces move discontinuously) and ductile (continuous change in the distance between points within an object, like a string bending) (Resnick & Shipley, 2013). Notably, almost all prior work on non-rigid mental transformations has been on brittle change (Resnick & Shipley, 2013). Despite the relative lack of attention to non-rigid mental transformations within the cognitive psychology literature, these skills are important to consider because they may be separable from rigid mental transformations (Atit et al., 2013) and relevant for particular STEM fields, such as geology, atmospheric science and oceanography (McNeal & Petcovic, 2020; Resnick & Shipley, 2013). Fiber arts offer an opportunity to measure ductile, non-rigid mental transformations, and to more fully map out the relationships between non-rigid spatial skills and STEM performance.

Improving Spatial Skills through Fiber Arts

Fiber Arts Experience as an Environmental Influence on Spatial Thinking

Spatial skills are malleable throughout development (Uttal et al., 2013), but given the role that early spatial and math skills play in later educational and career outcomes, much work has focused on the early environmental factors that shape spatial thinking. In both correlational and experimental contexts, preschool-aged children who hear more spatially-relevant talk, such as terms describing the shapes, sizes, or features of objects, perform better on spatial transformation, spatial analogies, block design, and mental rotation tasks (Casasola et al., 2020; Pruden et al., 2011). In addition to spatial talk, greater engagement with toys and games that allow spatial skill practice (e.g., puzzles, blocks, board games) early in development is correlated with children's spatial skills (Jirout & Newcombe, 2015; Levine et al., 2012). Further, the role of spatial activities in spatial skill development continues through adolescence. For example, adolescents' self-reported frequency of engagement in spatial activities (e.g., drawing in 3-D perspective, carpentry, crochet, ballet, football) is positively correlated with concurrent performance on a mental folding task, even when controlling for childhood spatial activity engagement, suggesting that continued engagement in spatial activities after childhood influences spatial skill (Peterson et al., 2020). In sum, from early childhood through adolescence, engagement with spatial activities along with appropriate scaffolding by adult caregivers helps improve spatial skills.

Despite the theoretical overlaps between the affordances of fiber arts and key spatial skills, there is surprisingly little work in psychology examining fiber arts practices in early and middle childhood as an environmental input that fosters spatial skills. An early study by Newcombe and colleagues (1983) asked undergraduates to rate a list of over 200 activities as being either "spatial" or "non-spatial" and further asked them to identify each activity as "male-stereotyped", "female-stereotyped", or "neutral". Seventy-five percent of the participants thought that embroidery (no pattern), crochet (with seams), knitting (with seams), knitting (multicolor), quilting, and tailoring were female-stereotyped and required spatial skill. In a separate sample of college students, women who reported more frequently engaging in embroidery, tailoring, crochet, and knitting with seams, and men who reported more frequently engaging in knitting with seams and knitting multicolored projects, had significantly higher scores on a measure of 2-D to 3-D mental folding (Newcombe et al., 1983). Similarly, adolescents' scores on the Spatial Activities Questionnaire, which includes crochet (pieces needing seams), embroidery/needlepoint (no pattern), knitting (multicolored), patchwork quilting, and sketching clothing designs, among other spatial activities, are associated with their performance on a mental paper folding task (Peterson et al., 2020; Signorella & Jamison, 1986). Thus, some evidence for a relationship between fiber arts practices and spatial skills exists for adolescents and adults. However, an open question is whether fiber arts can be used to improve children's and adolescents' spatial skills.

Unlike psychology, researchers in education have designed intervention studies using fiber arts as a site for STEM learning (Gresalfi & Chapman, 2017; Peppler et al., 2020). Two recent observational studies used a case study approach to highlight how fiber arts interventions might improve proportional reasoning, rate calculation, measurement, algebraic reasoning, and computer science skills. Gresalfi and Chapman (2017) asked a group of 9- to 16-year-old girls to design a swatch and then a larger rectangular knitting project in order to practice spatial scaling, as well as the mathematical concepts of rate and ratio. (Although counting stitches was not a challenging task for the 9-16-year-olds in this study, the authors noted that counting might be useful learning objective while knitting for younger children.) In another descriptive report about an intervention design, Peppler et al. (2020) outlined how algebraic reasoning and parallel processing of patterns can be practiced with hand looms, while sewing offers an opportunity to learn about loops and functions, which are key concepts in computer science. Both research groups provide descriptive evidence that fiber arts such as knitting, weaving, and sewing have striking affordances for learning math and computer science skills. Although spatial skills were not the primary focus of these studies, their designs can inform future research on the affordances of fiber arts for spatial learning specifically.

Developmental Trajectories of Spatial Skills and Fiber Arts Practices

In order to effectively leverage fiber arts practices to design developmentally appropriate interventions that improve children's spatial skills, we must first understand which spatial skills develop by what ages. Most children can accurately complete static mental rotation tasks by five years (Frick et al., 2013). Four and five-year-olds can use scaled representations (i.e., maps) to find hidden items (Newcombe et al., 2015). Around age six, children are able to match diagrammatic representations of physical objects to both actual 3-D objects and pictures of those objects (Frick & Newcombe, 2015). By the early school years, therefore, children can mentally rotate objects, use cultural artifacts to represent the location of items in their physical environment, and translate from 2-D diagrams to 3-D objects (Frick & Newcombe, 2015; Newcombe, Levine & Mix, 2015).

At the same time, there are large individual differences and substantial room for improvement in young children's spatial skills. For example, training studies have successfully improved five to eight-year-olds' representations of continuous magnitude, spatial scaling, and mental rotation at immediate post-test with medium to large effect sizes (Cohen's $d = .87$ for mental rotation after a one-week computerized intervention, Cheung et al., 2020; $d = .58$ for mental rotation after a 5 minute mental rotation intervention and $d = .45$ for spatial scaling after a 5 minute spatial scaling intervention, Gilligan et al., 2020; $d = .42$-.73 for spatial visualization and form perception after a 3-4 week intervention, Mix et al., 2021). Indeed, a recent meta-analysis of 29 spatial training studies, most of which were conducted with children, found that the average effect size was Hedge's g = .49, and, importantly for the consideration of fiber-arts-based interventions, found that interventions using physical manipulatives were more effective than other interventions (Hawes et al., 2022). Another meta-analysis found no difference in effect sizes for spatial training studies that used an immediate post-test, a post-test a week or less after the intervention, or a post-test a month or less after the intervention, indicating that the effects of spatial training are durable for at least several weeks (Uttal et al., 2013). We are therefore well-positioned to consider how fiber-arts-based interventions could support the further spatial skill development that occurs during early and middle childhood.

Importantly, children in early and middle childhood are able to engage in a variety of fiber arts practices. Many educators include fiber arts in their curricula, starting in the preschool years with Waldorf and Montessori-style schooling (Belcastro & Yackel, 2006). One curriculum for kindergarten to second grade includes opportunities for children to practice sewing, cross-stitching, and embroidery, while also learning about how wool is processed (Drillick, 2010). In their book on the ways fiber arts can be used to explicitly teach mathematics concepts, Belcastro and Yackel (2011) explain that fiber projects can be calibrated to children's knowledge level – for example, knitting or crocheting in the round can be used to teach kindergarten to third graders about geometric shapes, or can be used by college students to understand calculus. Although fiber arts are certainly practiced with young children, they are also taught to elementary school, middle, and high-school students as well (e.g., Gresalfi & Chapman, 2017; Peppler et al., 2020). Thus, fiber-arts-based interventions that build on these existing teaching practices offer a promising approach to enhance spatial skills from preschool to high school.

Role of Gender in Spatial Thinking

Gender Differences in Spatial Skills

In addition to individual differences in spatial skill development, decades of research have examined the existence, extent, and causes of sex and gender differences in spatial skills. One of the most consistent findings is a male advantage for 3-D mental rotation, which emerges with a small effect size by age 6 and grows stronger with development, reaching a medium effect size by age 14 (see recent meta-analysis by Lauer et al., 2019). Interestingly, factors like the format of stimulus presentation (presenting 2-D rather than 3-D figures) and reducing time pressure to complete tasks sometimes result in a smaller gender difference in mental rotation performance, although Lauer and colleagues' (2019) meta-analysis found a significant gender difference even after accounting for these factors. However, a male advantage has not been shown on other, quite similar spatial skills, such as mental folding with children (Harris et al., 2013), and mental bending with adults (Atit et al., 2013; Resnick & Shipley, 2013). Some gender differences favoring males are found on navigation tasks, though these differences are smaller than those found on mental rotation tasks, emerge later in development (after 13 years), and tend to be smaller in industrialized countries with formal schooling, suggesting that environment shapes navigation skill (Newcombe, 2020).

Many explanations have been proposed for sex and gender differences in performance on tests of spatial skill. Explanations based on biological sex include that prenatal androgen exposure – which is higher at particular points during gestation for males – may drive an early-emerging male advantage in mental rotation (Ceci et al., 2014). Note, however, that this narrative is complicated by studies of females with increased prenatal androgen exposure (female/male twins, congenital adrenal hyperplasia) that do not consistently show a link between increased androgen exposure and increased mental rotation performance (e.g., Hines et al., 2003; Vuoksimaa et al., 2010). Hormonal factors later in life may also contribute to performance on spatial tasks (e.g., Peragine et al., 2022). For example, cisgender women given a small dose of testosterone show improved mental rotation performance relative to women given a placebo, but do not show differences in spatial navigation tasks (Pintzka et al., 2016). In addition, a meta-analysis found that across ten studies, transgender men showed a significant improvement in mental rotation skills after receiving gender-affirming hormone therapy (Karalexi et al., 2020). Furthermore, decreases in progesterone and estradiol levels during the menstrual cycle result in increases in mental rotation performance for both cisgender women and transgender men (Peragine et al., 2022). In brief, existing evidence suggests that sex hormones may serve an activation role to acutely influence performance on spatial tasks. However, the relationship between sex hormones and spatial task performance is both complex and may not generalize to all spatial skills.

Beyond biological explanations lies a gender-based, environmental one: perhaps girls and boys are exposed to different amounts of spatial talk, types of toys, and quality of spatial play early in life, and these early experiences lead to different spatial skill outcomes. Indeed, in one study of parent-child interactions around physical toys and shapes on an app, parents talked about shape names more with their 3-year-old sons than their daughters (Verdine et al., 2019). Similarly, when asked to play with an engineering toy and associated book that emphasized spatial relationships, mothers spent more time building with their sons and more time reading the book with their daughters (Coyle & Liben, 2020). Finally, a related sociocultural and motivational argument can be made: girls and boys may receive different implicit or explicit messages about what skills are “for” boys and men or girls and women. As just one example, first- and second-grade girls - but not boys - whose teachers reported greater math anxiety at the beginning of the school year demonstrated lower math skill at the end of the school year, even controlling for initial math skill and working memory capacity (Beilock et al., 2010). Beilock and colleagues (2010) proposed that one reason that only girls’ math skills were impacted by their teachers’ math anxiety was that girls saw their teachers as same-gender role models and therefore internalized teachers’ anxiety. In summary, although biological processes may influence the developmental trajectory of some spatial skills, environmental differences informed by societal ideas about gender seem to emerge early, persist over development, and exert considerable influence over children's spatial skills as well.

A limitation within the literature on gender differences in spatial skills is a relative lack of attention to transgender children and adults, including people who do not identify within the gender binary. One exception is recent work exploring the role that gender-affirming hormone therapy plays in adults' performance on mental rotation tasks, noted above (e.g., Karalexi et al., 2020; Peragine et al., 2022). More research is needed to understand how gender-affirming hormone therapy impacts spatial skills among adolescents, and how these processes may be similar or different for people identifying outside of the gender binary. Further, to our knowledge, the impact of environmental factors - like exposure to spatial talk, spatial activities, same-gender role models, and societal stereotypes about spatial skills and STEM achievement - on transgender children's spatial skill development have not been studied. Investigating gender-typed environmental influences on spatial skill development among transgender youth may be particularly important to support their spatial learning, given that they experience shifts over time in the extent to which their externally-recognized gender identity aligns with their gender. Given the interplay among biological and environmental factors on spatial skills development, future work can build on existing research to explore spatial skill development among transgender children and adolescents.

From Gender Differences in Spatial Skills to Gender Differences in STEM Pursuit

Women are persistently under-represented in some STEM fields at the baccalaureate and doctoral levels, as well as in the workforce (see Ceci et al., 2014 for a review). In particular, Ceci and colleagues (2014) showed that women are under-represented in many math-intensive fields like geosciences, economics, engineering, math, computer science, chemistry, and physics, while they are either equally or over-represented in fields such as biology, psychology, and the social sciences. The gender difference in the pursuit of STEM degrees and jobs is striking given that school-aged girls' and boys' science and math performance on state standardized tests in the United States and on internationally-used assessments are not reliably different (Else-Quest et al., 2010; Hyde et al., 2008; Reilly et al., 2019). There are many proposed explanations for why this educational and occupational gender gap exists for some STEM fields despite similarities in math and science achievement. One major contributor is the emergence of gendered attitudes and expectations about STEM ability and interest in the early school years, which further solidify in high school (Ceci et al., 2014; Master, 2021). Gender differences in spatial skill, which widen over middle childhood and early adolescence, could also contribute to differences in STEM pursuit (Lauer et al, 2019).

Interventions to Close the Gender Gap in Spatial Skills and STEM Pursuit

To promote equal educational opportunities, and to increase participation in the STEM workforce, many researchers have tried to intervene on girls' and women's spatial skills and beliefs about STEM fields. Liben and Coyle (2014) provide a useful framework for summarizing these intervention approaches: 1) interventions that attempt to improve girls' and women's skills, 2) interventions that target the stereotype that STEM fields are not of interest to or appropriate for girls and women, and 3) interventions that try to address girls' and women's perception that they do not already possess the skills required for success in STEM fields. An intervention that gives young girls practice using engineering toys, or gives college students supplementary modules on spatial thinking, would be examples of the first variety (Coyle & Liben, 2020; Miller & Halpern, 2014). An intervention that focuses on making STEM seem "girl-friendly" by packaging stereotypically masculine toys in pink would be an example of the second intervention approach (e.g., Coyle & Liben, 2020). Finally, an intervention that emphasizes that STEM fields allow girls or women to meet a stereotypically feminine goal (e.g., helping others) might be an example of the third intervention strategy (Weisgram & Bigler, 2006).

Each of these intervention strategies have seen some success, but Liben and Coyle (2014) point out that altering existing games and toys that have spatial features to be more “stereotypically feminine” may backfire by altering the basic goals and affordances of those activities. Furthermore, interventions on gender stereotypes about STEM may ultimately be ineffective if they fail to make girls and women believe that STEM topics and careers are *more* interesting than alternative pursuits. Finally, it is worth noting that interventions that focus on women’s and girls’ beliefs and skills may fail if there are other, structural reasons that prevent them from pursuing STEM degrees and careers (e.g., hostile work environments, lack of flexibility around childbirth in the pipeline from PhD to tenure-track faculty; Ceci et al., 2014). Using fiber arts as an intervention tool could bridge these strategies by leveraging a set of activities that are already feminine-stereotyped and are inherently spatial – and highlight non-rigid transformations, unlike more frequently-studied, masculine-stereotyped activities like blocks and Legos. Furthermore, the robust participation of women in fiber arts means that structural barriers to their participation may be lower in these spaces, and provides evidence that women participate in high numbers in a set of practices that use spatial skills – some of the same skills that previous psychological research recognizes as foundational to educational and career success in STEM fields.

Motivational Features of Fiber Arts Practices and Contexts

Motivational Features of Fiber Arts Practices

In addition to the cognitive and gender-related features that make fiber arts an ideal site for spatial interventions, fiber arts practices and the contexts in which they occur have motivational properties that could magnify their intervention potential. Within the fields of psychology and education, intrinsic motivation, or the motivation to complete tasks for their own sake rather than any external rewards, has been linked to increased learning and enjoyment (Sheldon, 2007). Choice is crucial to intrinsic motivation, and many studies have linked increased choice to increased task persistence and learning (Grolnick & Ryan, 1987; Zuckerman et al., 1978). In particular, allowing people to make choices about what goals to pursue, rather than dictating their goals, increases interest, learning, and performance (Reeve et al., 2003). Fiber arts tasks often offer practitioners an opportunity to choose among many existing patterns (for example, to make a hat versus a scarf versus a dress, or even create their own pattern) and materials (for example, different colors of fabric or types of yarn). When designing spatial skills interventions based on fiber arts practices, it will be important to retain these elements of creative control and choice in order to further support motivation for spatial learning.

Motivational Affordances of the Contexts in Which Fiber Arts are Practiced

In addition to the benefits of individual choice for intrinsic motivation, motivational features existing in the crafting community may make fiber arts an especially inclusive environment in which to situate interventions aimed at teaching spatial skills. Recent work by Gresalfi and Chapman (2017) explored features of the social context in which fiber arts are pursued (e.g., traditional knitting or quilting groups, maker culture), and identified the collaborative atmosphere of crafting spaces and acknowledgement that mistakes are both inevitable and necessary for learning as key for “attract[ing] and maintain[ing] women’s participation” (Gresalfi & Chapman, 2017, p. 1). The normalization of failure as part of the learning process is strikingly similar to growth mindset messages that have been explored in psychology (Dweck, 2006). A growth mindset refers to the belief that people can change and improve their abilities through practice, as opposed to holding a fixed mindset, which is the belief that people cannot change their level of ability (Haimovitz & Dweck, 2017).

Many researchers have tried to induce growth mindsets in children and adolescents through classroom and online interventions that explicitly communicate the idea that children can change their academic achievement through effort. Some studies have demonstrated that growth mindset interventions have positive effects on high-schoolers' academic achievement (Yeager et al., 2016 effect size $d = .10$, equivalent to a GPA increase of .13 points for those who were 1 SD below the mean on prior performance), and recent work suggests that these interventions are particularly effective for lower-achieving students (Yeager et al., 2019, standardized mean difference effect size = .11). Yeager and colleagues (2019) explicitly address whether such effect sizes represent a meaningful improvement, suggesting that if the most effective educational interventions have an effect size of .20 standard deviations, the .11 effect size they found was small but important. A recent meta-analysis of growth mindset interventions found a meta-analytic effect size of $d = .08$, but noted that only 5 of the 43 effect sizes were significantly greater than zero (Sisk et al., 2018). Mixed findings in the mindset literature, as well as a lack of successful interventions with younger children, suggest that understanding when, why, and for whom mindset interventions work is crucial for moving this field forward (e.g., Yeager & Dweck, 2020).

In addition to growth mindset interventions aimed at d high-schoolers, both experimental and correlational studies document that adults' praise emphasizing the role of malleable effort in success (rather than fixed aspects of a person's ability) increases and preschool and elementary-school children's persistence on, enjoyment, and choice of challenging tasks (e.g., Cimpian et al., 2007; Gunderson, Gripshover, et al., 2013; Mueller & Dweck, 1998; but see Li & Bates, 2019). Furthermore, parents' messages about failure may be even more important than messages about success in shaping children's beliefs about the role of effort and fixed ability. Parents who espoused the belief that failure is "enhancing" (rather than "debilitating") were more likely to have children who believed that malleable effort is responsible for outcomes, even after controlling for the extent to which parents held growth mindsets (Haimovitz & Dweck, 2016). Although gaps remain in the research on growth mindset interventions and how socializers communicate about the roles of effort and failure in learning, it remains worthwhile to understand how these kinds of messages are used in fiber arts communities, and whether the inclusion of these messages is important for the effectiveness of fiber-arts-based interventions.

Future Directions

Opportunity to Further Understand and Measure Non-Rigid Mental Transformation Skills

Considering fiber arts in the context of spatial skill development leads to a number of avenues for future research. The first avenue for research is to leverage fiber arts to help answer basic research questions about a wide range of non-rigid mental transformation skills, which are currently exceptionally under-studied and, from limited research, seem separable from rigid transformation skills (Atit et al., 2013; Harris et al., 2013).

From the available prior research, several non-rigid mental transformations have been identified and assessed, specifically, mental bending, paper folding, and brittle transformation (Atit et al., 2013; Harris et al., 2013). However, most of these involve *brittle* non-rigid transformations: only an assessment of mental bending, in which a flat plastic sheet is bent to different extents, involves *ductile* non-rigid transformation skills. In ductile transformations, which are highly relevant to fiber arts, the overall size of an object does not change, but there is continuous change in the distance between two points within an object – this would be the case when knitting, crocheting, or weaving from one or more pieces of thread or yarn (Resnick & Shipley, 2013). Notably, there may be significant variation across (and even within) fiber arts categories in the kinds of non-rigid transformations that are required, and some practices could offer unique affordances for different spatial skills. For example, reasoning about ductile transformations may be highly relevant for knitting, crocheting, and weaving, whereas understanding brittle changes may be more relevant in sewing or quilting. A key part of investigating the relationship between specific fiber arts skills and specific STEM outcomes will be to develop and test assessments of ductile, non-rigid transformation skills based on fiber arts practices. For example, a ductile non-rigid task similar to existing 2-D or 3-D mental rotation tasks could be developed that involves recognizing or even re-creating different knot constructions. Building on this, future research could examine the interrelations among multiple ductile non-rigid skills (e.g., mental bending, knot construction), brittle non-rigid skills (e.g., mental folding, brittle transformation), and rigid skills (e.g., mental rotation, mental transformation), to determine whether these form distinct clusters of spatial skills.

Opportunity to Intervene on and Improve Non-Rigid Spatial Skills

In addition to examining theoretically-driven distinctions among non-rigid spatial skills, an important next step is to determine whether non-rigid spatial skills are predictive of STEM learning and achievement. Non-rigid transformations may support different kinds of STEM skills and outcomes than the more heavily studied rigid transformations. Only one study, to our knowledge, has explored the relationship between STEM occupations, brittle non-rigid mental transformation skill, and rigid mental transformation skill (mental rotation) (Resnick & Shipley, 2013). This study found that geologists and chemists performed similarly on a mental rotation task, but that geologists were better at the brittle transformation task than chemists. The authors suggest that experts in both disciplines must be able to comfortably rotate items (rock formations and molecules, respectively) but that only geologists have to reason about items breaking into many different pieces. This study provides suggestive evidence that non-rigid mental transformation may be more relevant for some STEM fields than others, and that there could be interesting heterogeneity between fields.

In their recent review, McNeal and Petcovic (2020) suggest that non-rigid spatial skills might be vital for STEM fields that require thinking about non-rigid or fluid phenomena, like atmospheric science or oceanography. If the distinction between non-rigid and rigid transformation is important both theoretically and practically, in that it is predictive of later STEM achievement, then it is vital to fully map the landscape of non-rigid skills and develop reliable methods to measure them. We must also further explore *which* rigid and non-rigid spatial skills are important for *which* STEM fields – for example, non-rigid spatial skills could be particularly important for fields where it is necessary to visualize deformable structures, such as surgery or neuroscience. For example, mental folding performance, a brittle non-rigid spatial skill, is positively correlated with trainees' laparoscopic surgical performance (Keehner et al., 2004). It would also be useful to use longitudinal methods to see if ductile, non-rigid spatial skills predict math or science achievement during childhood or predict STEM pursuit later in life.

Training studies could be developed to empirically test whether training ductile and brittle non-rigid spatial skills using fiber arts results in close transfer to rigid spatial skills, slightly farther transfer to math skills, and much farther transfer to STEM achievement later in development. For example, an intervention using sewing could introduce 4- and 5-year-olds to large embroidery needles, and have them align and sew along pre-cut, square pieces of fabric to make a pillow, while 8- to 10-year-olds might use regular sewing needles and be more actively involved in drawing and cutting out complex fabric shapes to join. We might expect that a sewing intervention would improve children's performance on existing measures of mental folding and bending, and possibly also breaking. Another intervention might use large knitting needles, crochet hooks, or cardboard tapestry looms and bulky yarn with 4- and 5-year-olds to create a square cloth, while 8- to 10-year-olds might use smaller needles and hooks or a floor loom to create a cloth that increases or decreases in width. We might expect that these yarn-based interventions would improve children's performance on to-be-developed measures of ductile non-rigid mental transformation. Either a sewing or yarn-based intervention, depending on how explicitly measurement was included, could also be expected to improve children's understanding of continuous magnitude and the number line, which could boost a host of other math skills. Importantly, all of these interventions would ideally include pre- and post-tests of existing rigid transformation measures, to see if these skills were also improved by non-rigid skill interventions. All of these methods – retrospective and longitudinal correlational work, as well as training studies - would also shed further light on the developmental course of non-rigid mental transformation skills, and offer an opportunity to engage in cross-disciplinary partnerships with fiber arts educators and practitioners.

Exploring Motivational Components of Fiber Arts Tasks and Contexts

Importantly, when designing spatial skills interventions using fiber arts practices, it will be crucial to attend to the task and contextual features of fiber arts practices that are expected to promote engagement, success, and persistence. First, fiber arts may have motivationally-relevant task affordances. As Peppler et al. (2020) pointed out, creating a woven pillowcase cover or knitted hat may be intrinsically rewarding and promote persistence. Studying the motivationally-relevant task affordances of fiber arts, and comparing the efficacy of spatial skill interventions using “traditional” materials like blocks and puzzles to interventions using fiber arts, could allow better insight into best practices for spatial interventions. In particular, given research on the importance of choice for increasing intrinsic motivation, experimentally manipulating the level of task choice given to students – for example, allowing students to design and then execute their own pattern, versus choosing from a large or small number of existing patterns – and measuring its effect on students’ learning could be a fruitful avenue to pursue.

In addition to task affordances of fiber arts, future research could also explore the motivational messages conveyed in the social contexts where fiber arts occurs. One avenue of research could involve observational work on existing fiber arts communities – community art classes, crafting guilds, or fiber arts classes at the university level –to more formally document the motivational messages present in these spaces. Motivational messages may align with existing and well-studied frameworks in social psychology, including growth mindsets and failure-as-enhancing mindsets. However, other messages might be conveyed within fiber arts spaces that are important to include in educational interventions, and could even inform broader research on motivational frameworks. In addition to observational research, fiber-arts-based spatial interventions could incorporate growth mindset messaging to promote student motivation and spatial skill learning. If observational work reveals that there are additional motivational messages being conveyed in fiber arts spaces, beyond those previously investigated in psychology, those other messages could be tested and included as well.

Designing Gender-Sensitive Spatial Skills Interventions

On a theoretical level, further documenting and understanding non-rigid spatial skills may shed new light on a puzzling contradiction within the literature on sex and gender differences in spatial skills. Specifically, mental folding – the most well-studied non-rigid spatial transformation task – is one of the spatial skills with the smallest gender gap in performance, in contrast to mental rotation tasks, which show the largest and most consistent male advantage in performance (Harris et al., 2013; Newcombe, 2020). As Newcombe (2020) noted, no one has managed to articulate a clear theoretical reason why performance on the two tasks should be so different. Perhaps examining a broader range of non-rigid mental transformation skills, beyond paper folding, will allow us to better understand sex and gender differences and similarities in spatial skill performance, including the environmental contributions to particular types of spatial skills.

In addition to the cognitive and motivational reasons fiber arts may be a useful context for training non-rigid spatial skills, fiber-arts-based interventions could serve as a useful tool for improving girls' spatial skills in particular. Unlike many existing spatial skill interventions, which involve masculine-stereotyped toys and games, or have tried to adapt masculine-stereotyped toys and games to be appealing to women and girls by changing their colors or packaging (e.g., Coyle & Liben, 2020), fiber arts are already feminine-stereotyped. There is no need to alter fiber arts tasks to increase their appeal to girls and women, and, therefore, the spatial affordances of fiber arts practices are not in danger of being altered unnecessarily. Furthermore, the motivational messages integral to the contexts in which fiber arts are practiced may also be particularly useful for encouraging girls' and women's participation. Correlational work suggests that fields where women are under-represented are those where there are strong beliefs that immutable "brilliance" is required for success (Cimpian & Leslie, 2017).

Experimental work with adults has found that women, relative to men, expressed less interest in pursuing educational or work positions that emphasized the role of brilliance (rather than hard work) in achieving success (Bian et al., 2018). We expect that fiber arts contexts incorporate messages promoting a growth mindset and the importance of struggle and failure for eventual success, which may help counteract these beliefs about “brilliance” and serve as a particularly conducive environment for women and girls to learn spatial skills. Although most research on gender differences in spatial skills, to our knowledge, does not focus on transgender people, there is strong queer representation within fiber arts (Auther & Speaks, 2015), which could suggest that fiber arts are already an inclusive learning context for transgender people as well. In assessing the efficacy of fiber-arts-based interventions, it will be important to explore whether and how the motivational messages and gendered features of fiber arts learning contexts affect the learning and motivation of transgender children and adults.

Challenges for Future Fiber Arts and Spatial Skills Research

Although there are many exciting avenues for research at the nexus of fiber arts and spatial learning, challenges exist to their pursuit. A central challenge for researchers planning to study the non-rigid mental transformation skills needed for STEM learning and fiber arts will be gathering the necessary domain-specific expertise across disciplines. This type of research will require content knowledge of STEM (sub)disciplines, specialized fiber arts practices, and cognitive and developmental psychology research methods. For example, it may be difficult to understand why ductile change is important for an atmospheric scientist or how fabric dying processes work for a psychology researcher who is trained as neither an atmospheric scientist nor a fiber artist who focuses on fabric dying. One way to address this concern is cross-disciplinary collaboration, which is not unprecedented: work by LaDue et al. (2021) and Wilson et al. (2020)

demonstrates how cognitive psychologists can work in tandem with geologists to advance learning in both fields.

A second challenge lies in the design and implementation of fiber-arts-based spatial skills interventions. In particular, it will be important to figure out how to titrate the difficulty, children's interest in, and the particular spatial skill(s) targeted by intervention materials. Existing observational work in the education literature (e.g., Peppler et al., 2020; Gresalfi & Chapman, 2017) and talking with fiber art educators will serve as important starting points for answering some of these questions. Another challenge with proposing fiber-arts-based interventions is that they are more time- and resource-intensive compared to some other spatial interventions (such as computerized training programs), and could require more hands-on time from a skilled instructor. However, we argue that fiber-arts-based spatial skill interventions are worth pursuing despite these costs, as they have potential to teach types of spatial skills that are not currently being addressed and to reach students who aren't currently being reached.

A final challenge is to find creative ways to document and measure the motivational features of fiber arts learning contexts that could make them particularly inclusive for girls, women, and non-binary people. Here, we argue that there are many different features – for example, the existence of same-gender role models, growth mindset messages, and learner interest – that could make fiber arts spaces uniquely beneficial environments for spatial learning. However, it will be important to carefully investigate each of these features and to replicate the most important features when designing fiber-arts-based interventions for the lab or classroom.

Conclusion

To conclude, we propose that fiber arts – a broad array of practices that involve manipulating string and fabric to create culturally relevant functional and art objects – present a two-fold opportunity: first, to answer basic science questions about the structure and STEM correlates of non-rigid spatial skills, and second, to develop new spatial learning opportunities for children starting in early childhood and spanning through high school. Fiber arts are an important site for spatial skills research because of their unique combination of attributes – their physical affordances as non-rigid, ductile media, their motivational affordances and messages conveyed in fiber arts contexts, and their gendered associations. By further cataloguing the landscape of non-rigid spatial skills, we can more fully understand the spatial skills that underlie STEM fields. Fiber arts can also serve as the basis for new interventions to improve children's spatial skills, while maintaining the motivational features of fiber arts that can support learning and persistence. Using fiber arts in spatial skills and STEM interventions will allow us to leverage – rather than work against – gendered associations when training spatial skills. By reaching across cognitive, developmental, and social psychology, studying fiber arts offers an opportunity to create an integrative research paradigm to answer pressing theoretical and applied questions about spatial learning.

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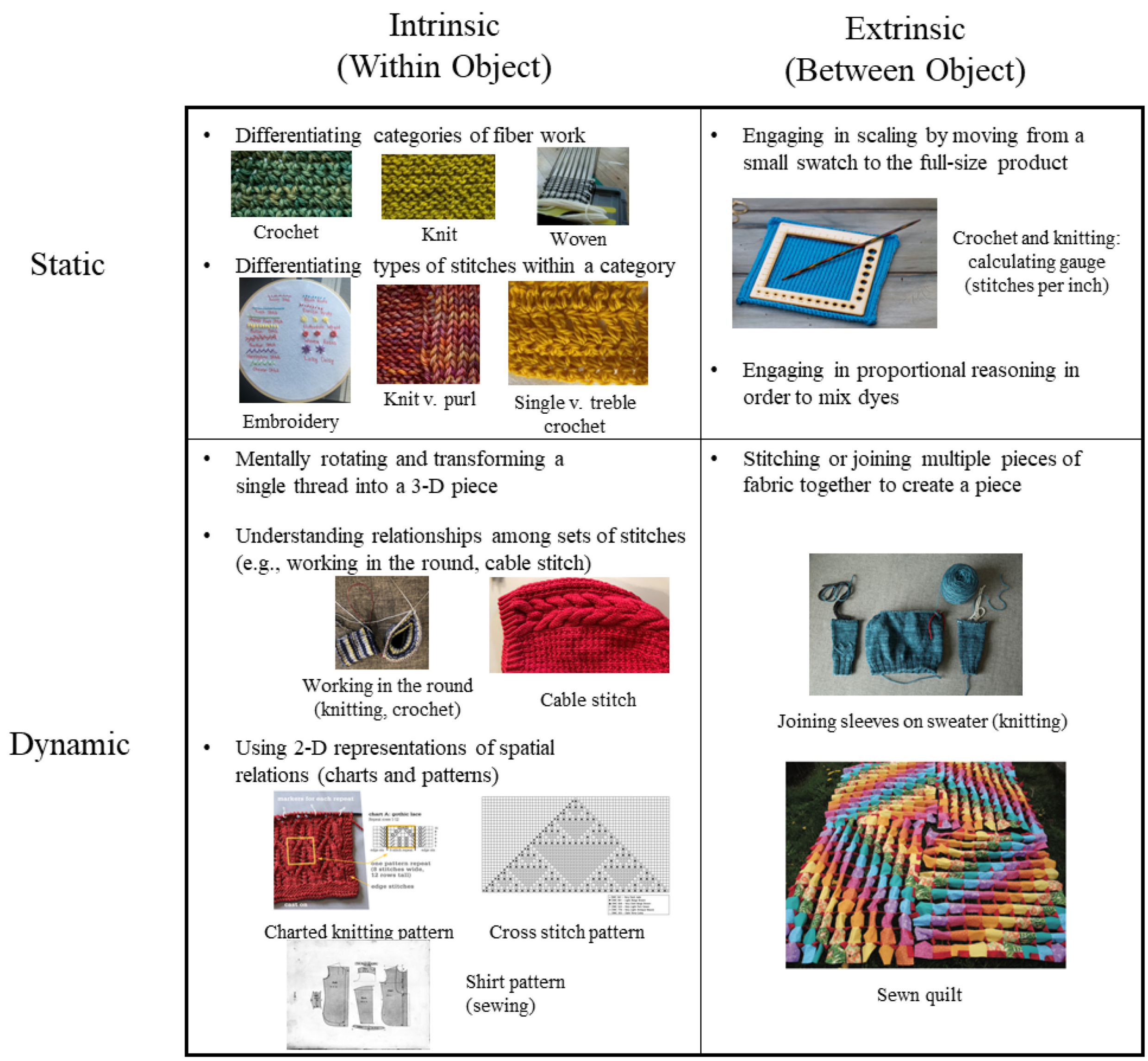
Figure 1

Examples of Fiber Arts Practices Categorized According to Newcombe and Shipley's (2015) Spatial Framework



Note. Images in top left quadrant: Crochet and Knit and Photographs by Grace Bennett-Pierre. Woven and Photograph by Clare Nicholls. Embroidered and Photographs by Emily D'Antonio.
Images in bottom left quadrant: Knit and Photographs by Hannah Ruebeck. From *Lace: Learn to Knit Lace with a Free Pattern* [Photograph], by Emily Wessel, 2010-2022, Tin Can Knits (https://blog.tincanknits.com/2014/06/06/lets-knit-lace/). By permission of author.
From *Crafting by concepts: Fiber arts and mathematics* (p. 83), by Belcastro, S.-M., & Yackel (Eds.), 2011, Natick, MA: Taylor and Francis. From *The Shirt System sewing pattern* [Photograph], by W.D.F. Vincent, 1898, Wikimedia Commons

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From *Crafting by concepts: Fiber arts and mathematics* (p. 209), by Belcastro, S.-M., & Yackel (Eds.), 2011, Natick, MA: Taylor and Francis.

Table 1

Within-Object (Intrinsic) Spatial Relations in the Context of Fiber Arts

Within-Object (Intrinsic) Spatial Relations	Static or Dynamic	Example Applications to Fiber Arts
1. Disembedding: Isolating and attending to one aspect of a complex display or scene. For children, this category includes recognition of basic 2-D and 3-D geometric shapes.	Static	Isolating a single stitch or sequence of stitches from a larger item.
2. Categorization: Learning categories based on spatial relations.	Static	Differentiating types of stitch work based on component parts (e.g., single crochet versus double crochet; knit stitch versus crochet stitch).
3. Penetrative thinking: Visualizing spatial relations inside an object.	Static	Visualizing how to create a stitch or knot, or how overlapping strings work within a woven piece.
4. Visualizing 3-D from 2-D: Understanding 3-D spatial relations presented in a 2-D image or drawing.	Dynamic	Using written and charted 2-D patterns to create 3-D pieces.
5. Mental transformations: Visualizing how an object will change when rigidly or non-rigidly transformed.	Dynamic	Rotating a piece (or pieces) and folding a piece (or pieces) to make knitted pieces in the round, or to make crocheted, knitted, woven, or sewn pieces with multiple parts.
6. Sequential spatial thinking: Visualizing the product of a series of transformations.	Dynamic	Using iterative, step-wise processes to create a fiber arts product (e.g., series of stitches, series of sets of stitches, multiple pieces put together).

Note. Within-Object (Intrinsic) Spatial Relations are reproduced from Table 3 in Newcombe & Shipley, 2015.