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Review Article

Finding the missing piece: Blocks, puzzles, and shapes fuel school readiness☆

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ABSTRACT

Experiences with spatial toys such as blocks, puzzles, and shape games, and the spatial words and gestures they evoke from adults, have a significant influence on the early development of spatial skills. Spatial skills are important for success in science, technology, engineering, and mathematics (STEM) fields [77] (e.g., Wai, Lubinski, Benbow and Steiger, 2010), and are related to early mathematics performance [48] (Mix and Cheng, 2012), as early as age 3 [73] (Verdine, Golinkoff et al., in press). This paper focuses on the effects of early spatial experiences and their impacts on school readiness, discusses factors that influence the amount and quality of spatial play, and suggests methods for providing a “spatial education” prior to school entry.

Contents

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1. Early experiences with blocks, puzzles, and shapes play an important role in school readiness

Spatial skills, or the ability to mentally manipulate information about objects in the environment and the spaces we inhabit (see [70]), are essential for everyday functioning. However, the teaching of these skills is largely ignored in formal school settings [13] and, perhaps as a result, many people seem to believe that spatial skills are not "teachable." To the contrary, research indicates that spatial skills are quite malleable (e.g., [70]). This paper focuses on why it is so important to provide a "spatial education" to young children, discusses materials and methods for delivering that education, and makes recommendations about how to deliver spatial training to improve school readiness for science, technology, engineering, and mathematics (STEM) subjects.

2. Why do spatial skills matter?

Experiences such as efficiently packing a car trunk, using a mall map to find a store, and cutting equal slices of pizza for a group of children all require spatial ability. These activities are mostly innocuous, low-stakes endeavors (except maybe dividing the pizza evenly!). However, a number of vitally important careers require strong spatial skills (e.g., air traffic control) and errors could be disastrous in many common spatial challenges, for example, inaccurately following a diagram to install a child's car seat. Many spatial skills are also key in preparing students for the STEM disciplines [53]. Studies have shown that spatial competence in grade school has significant consequences for student trajectories in STEM fields through high school and adulthood (e.g., [38,76,77]). For example, Fig. 1 is adapted from [76] and shows the average spatial skills of individuals in grades 9–12 with their reported career fields 11 years later. As can be seen, the high school spatial abilities for those in STEM careers are, on average, much higher than students with careers in other fields.

This relation between STEM success and spatial skills is due, at least in part, to the reliance of the STEM disciplines on spatial representations such as diagrams, maps, blueprints, and timelines. These representations help illustrate complex, multi-step biological processes (e.g., DNA replication and cell division), complicated systems (e.g., gravity interactions between the earth, the moon, and a spacecraft), and timelines occurring on unfamiliar timescales (e.g., geologic time). Being able to generate, interpret, and visualize changes to these representations helps master complex concepts and generate new ideas.

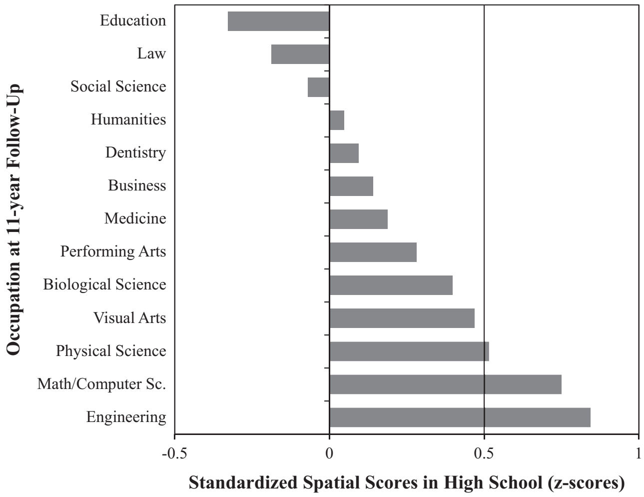

Fig. 1. Spatial Scores in 9th–12th Grade and Reported Occupations 11 Years Later.

2.1. Links between spatial skills and mathematics performance

Another reason that spatial skills may be vitally important for success in scientific disciplines is their relationship to mathematical skills (e.g., [48]). Links between spatial and mathematical skills have been firmly established in school-age children and adults (e.g., [2,11,33,37,62]). Clements and Sarama [13] posit that, at its core, mathematics involves spatial thinking and Mix and Cheng [48] concluded that, "The relation between spatial ability and mathematics is so well established that it no longer makes sense to ask whether they are related." (p. 206).

We still need to know more about causal relations between these skills and the direction of the effects. However, there is growing evidence that the relationship between spatial and mathematical abilities emerges quite early. Verdine et al. [73] found relations between spatial and mathematical skills at age 3, when children first begin to count and do simple addition and subtraction. Indeed, Verdine et al. [74] were able to predict over 70% of the variability in mathematics performance at age 4 using only measures of spatial skill at age 3 and 4 with executive function measures at age 4. Spatial skill uniquely predicted 27% of the variability in mathematics even after accounting for executive function. This line of research is also yielding evidence that spatial assembly skills at age 3 continue to predict mathematical skills at age 5 [21]. Other research investigating the connection between spatial and mathematical skills in older children and adults (e.g., [78,4]) show that the relationship appears to grow in strength with additional time. Although not conclusive evidence of causality, increasingly high correlations are consistent with spatial skills providing a foundation for mathematics learning.

These early links between spatial and mathematical skills are intriguing; in later written mathematics and when problem solving can be assisted by diagramming, spatial skills have a more intuitive role in supporting mathematics. How can we explain earlier links between spatial and mathematical skills? One potential mechanism is that mental models of number may be grounded in spatial representations. Research shows that the number line appears to be invoked to solve approximate calculation and estimation problems (e.g., [5]). To apprehend that numbers farther down the number line are bigger than those at the beginning, children have to spatially represent the ordering (see Fig. 2). Gunderson et al. [33], in the first of two longitudinal datasets, found that children's spatial skill at the start of 1st and 2nd grade predicted number line improvement during the school year. In the second dataset, 5-year-olds' spatial skill predicted their approximate symbolic calculation skills at age 8, mediated by their linear number line knowledge at age 6. Ramani et al. [61] also indicates a role for spatial skills in mathematical domains by showing that a board game based on the linear number line can improve number line estimation, magnitude comparison, numeral identification, and counting among lower-income children. Children who develop better spatial representations of number earlier may be able to build on this knowledge base to learn other numerical concepts (e.g., place value; [49]). Further evidence of a spatial and mathematical link comes from neuroscientific evidence that suggests that similar areas in the brain, specifically the intraparietal sulcus [1] and the neighboring angular gyrus [29], respond to

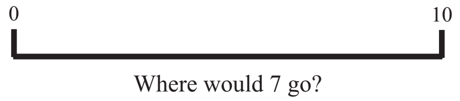

Fig. 2. A typical number line estimation task consists of trials asking participants to locate a number on a line (e.g., 7) with other numbers anchoring each end of the line (e.g., 0 and 10) and no marks in between.

various spatial and mathematical problems involving magnitude estimation, the mental number line, and mathematical calculation.

Whatever the mechanisms, many now believe that spatial training is an important and often overlooked resource for improving performance in STEM-related subjects (e.g., [11,33]). A large body of evidence shows that most spatial skills are highly malleable and that training is effective, durable, and transferrable [70] even at relatively young ages (e.g., [32]). There is also evidence that relational language regarding space (i.e., using words like on, in, and under) can help solve spatial problems (e.g., [46]) and that exposure to spatial language is related to spatial cognition [58]. Therefore, current evidence strongly suggests that spatial training and additional spatial language exposure will work to improve spatial cognition and have ancillary benefits for mathematical achievement.

However, current spatial instruction in the U.S. falls far short (e.g., [27]; National Council of Teachers of Mathematics (NCTM) [52]) and student scores on international tests bear that out [54]. A number of organizations have noted these shortcomings [51,16,55] and current guidelines suggest young children learn to do things like make pictures and designs by combining two- and three-dimensional shapes (NCTM); recognize, compare, and name common shapes, their parts and attributes; and understand directionality, order, and position of objects, such as up, down, in front, and behind (Head Start). But how do we achieve these goals? What should an early "spatial education" look like and what factors influence the potential quality of that education?

3. What materials can help provide a preschool spatial education?

3.1. Blocks

Relatively few training studies have been aimed at young children [70]. However, indications are that spatial construction tasks such as block building are effective in spatial training. Casey et al. [8] found that a block building intervention improved spatial skills and that a narrative context helped to increase the effectiveness of the intervention for children in kindergarten. Likewise, a recent randomized controlled trial study by Grissmer et al. [32] provided experience to kindergarten and first grade children with sets of visuo-spatial toys (e.g., Legos®, Wikki Stix®, pattern blocks, etc.). They found that these activities, a mixed bag of spatial assembly tasks, improved spatial and mathematics skills. Thus, this study demonstrates many of the proposed causal links that correlational designs cannot.

Although not a training study, [73] investigated spatial assembly skills using Mega Bloks® and found relations to children's mathematical skills. Recent data collected from longitudinal aspects of that study indicate that these early block building skills are predictive of spatial and mathematical skills into kindergarten [21]. Errors made in replicating block constructions from Farmer et al. also indicated that 3-year-olds struggle to use units in recreating block models. Understanding part/whole relationships and that larger objects can be segmented into smaller units underlies mathematics. Additionally, creating designs which are symmetric around an axis requires counting or measurement to ensure the respective parts match. Measurement is a main function of geometry and is important in almost all scientific fields. The practice a child gets while counting and measuring with blocks may be one mechanism by which spatial experience influences early mathematics skills.

Research also indicates that children are likely to benefit more from block building when parents and children play with blocks together toward a common goal. For example, Ferrara et al. [22] observed 3- to 4.5-year-old children playing with blocks for 10 minutes with their parents. Participants either experienced a free play situation with instructions to build whatever they wanted, a guided play situation in which the parent helped the child build a pre-determined structure, or a preassembled play situation in which the structure was already built. Parents in the guided play condition used more spatial language during the play session. Therefore, goal-oriented play with blocks appears to have two advantages for spatial instruction: (1) It elicits more spatial language than when the play is open-ended [22]; and (2) it focuses both the adult and the child on solving specific problems that require spatial thinking (similar to [8,9]).

3.2. Puzzles

A number of studies establish puzzles as a potential activity for providing a "spatial education" to toddlers and preschoolers. For example, a cross-sectional study of puzzle skills by Verdine et al. [75] found high correlations between puzzle performance and a range of spatial skills in elementary school-aged children. Performance on a standard jigsaw puzzle was related to mental rotation (.45), spatial perception (.52), and spatial visualization (.58). Longitudinal studies have also established a direct relationship between puzzle *experience* and spatial skills. Levine et al. [44] found that children observed playing with more puzzles during 6×90 min in-home sessions that occurred between the ages of 2 and 4 years, had better spatial transformation ability at 4.5-years-old. This relation held despite controls for parent education, income, and parent language. Among those children who did play with puzzles, the frequency of play predicted spatial transformation skill and average puzzle difficulty was correlated with more spatial language exposure (r=.68) and parent engagement (r=.44). These results suggest that children's spatial skills benefit from puzzle play. They also suggest that groups of lower-performing children who are challenged with more difficult puzzles and who receive more spatial language and parent engagement may tend to benefit the most.

A longitudinal study [21,72], using the Test of Spatial Assembly which required 3-year-olds to copy a design using 2-D geometric shapes (similar to tangrams) and 3-D blocks, found correlations between that test and scores on standardized tests like the Wechsler Preschool and Primary Scale of Intelligence Block Design subtest given one year later and the Woodcock-Johnson III Spatial Relations subtest given one and two years later (r's $\geq$.35). TOSA scores at age 3 were also correlated with scores on the Early Mathematics Assessment System [28] given one year later and the Wechsler Individual Achievement Test Math Problem Solving subtest given one and two years later (r's$\geq$.38). In addition to providing evidence that spatial skills are likely influenced by puzzle building, this study further establishes the link between spatial and mathematical skills.

3.3. Shapes

Inserting shapes into shape sorters, categorizing them, and practicing shape naming with adults are among the first experiences that help build geometric-spatial skills. Early shape play also likely provides important experience in the mental manipulation of spatial information [17]. Indeed many toddlers are given shape sorting toys and many toys, even for infants, include basic geometric shapes in their designs. Therefore, it is not surprising that by 2.5 years, middle-class children receptively know the names of many common geometric forms [14,10]. If these toys are common and children learn their shapes at a young age, why use shapes to improve a "spatial education"?

What is surprising about early shape knowledge is that it takes many additional years for children to discover the properties that actually define shapes (e.g., [66]). Children will recognize an equilateral triangle resting on a side as a triangle well before they will categorize an isosceles triangle with one short side as another member of the category. If children do not understand that what defines a triangle is having three sides and three angles, do they really know what a triangle is? Early mathematics curricula have started to call for more aggressive teaching of shapes. Although increasing the quantity of instructional time should have positive impacts, to really shorten the extended timeframe it takes to learn the defining features of shapes, we have to address how and what we teach.

Sarama and Clements [65] claim that the minimal time teachers spend on geometry is not effective because they typically ask for shape identification and confirm a correct response without raising awareness of the defining properties. For example, saying "That's right!" when a child successfully names a triangle rather than, "That's right! Triangles have 3 sides." Other work (e.g., [23]) indicates that definition-focused shape categories can be developed at ages 4 and 5 with varied exemplars and when guided play allows discovery of those defining features. Other work shows guided comparison of exemplars from an object category moves children from using perceptual similarities to relational and functional properties (e.g., [50]) and that interventions using shapes and focusing children on their properties and part-whole relationships can help children solve other spatial problems [9].

When used with an adult, the insertion of shapes into a shape sorter provides a shared goal that likely elicits shape words *and* spatial relation language (e.g., "no, the *triangle* goes in the slot *on top of* the *square*"). However, shape sorters and their digital counterparts in touchscreen apps tend to incorporate only a single, equilateral instance of each shape category [18]. When these shape toys do include many shapes, they are typically quasi-geometric shapes (e.g., stars, hearts, crescents, etc.) rather than varied instances of traditional shapes. All of the above mentioned studies, and indeed studies on the development of concept formation in general (e.g., [6,60]), suggest that designing toys with varied, non-canonical instances in each shape category would improve the ability to learn their defining features. Including multiple varied instances per category would also invite adults to highlight shared properties within shape categories, likely increasing spatial language about relative length and size and providing more practice with mathematics (e.g., counting sides). It is alarming that shape sets with these properties are not readily accessible to parents and that may be a proximal cause of children entering school without definition-focused concepts for most geometric shapes.

3.4. *Other materials*

Although to this point our focus has been on blocks, puzzles, and shapes because they are more commonly available and apparently effective in delivering a spatial education, a number of other materials and skill areas are being investigated with young children. For example, dynamic spatial transformations form an important aspect of spatial skills and Harris et al. [35] recently developed a mental paper folding test suitable for young children. Tzuriel and Egozi [69] used a "Spatial Sense" intervention program with 1st-graders designed to improve their ability to represent and transform spatial information, which was effective in improving scores on spatial relations and mental rotation tasks. Further, this intervention reduced or eliminated pre-test gender differences in spatial skills. Ratliff, McGinnis, and Levine [63] developed a test of children's ability to envision what the cross-section of an object will look like (i.e., penetrative thinking). This skill is important in a range of STEM fields, for example, understanding anatomical cross-sections in biology and neuroscience. Frick et al. [24] also recently developed a computerized test of mental rotation skills for young children and included instructional conditions that showed promise in improving those skills. Although work is needed to develop and test interventions for all of these skill areas, these tests can help provide a blueprint for making those interventions accessible to younger age groups, a significant hurdle in delivering a spatial education for preschoolers. Activities that are likely to improve some of these skill areas also already exist, like Origami or building paper airplanes for practice with dynamic spatial transformations.

4. How can we improve the effectiveness of spatial instruction?

4.1. *Spatial language*

We produce spatial language around children without thinking about it. Words that describe spatial properties of objects and events like, big, near, and curved, may help children attend to, retain, and recall spatial information. Indeed exposure to spatial language appears to have important influences on the development of spatial cognition and mathematical skills. A longitudinal study by Pruden et al. [58] found that children hearing more spatial language from 14- to 46-months performed better on spatial tests at 54 months. Spatial language input predicted how much children produced, and those producing more spatial language performed better on later spatial problem solving tasks. Other research by Loewenstein and Gentner [46,26], found that 3-year-olds could solve a spatial analogy task if they heard relational language to help them encode where a prize was to be found. In the baseline condition the researcher said "I'm putting this winner right here" as they placed the target on one set of shelves and children had to infer the location of that target on another set of shelves. In the language condition, they hid the "winner" the same way except they said "I'm putting the winner [in, on, or under] the box." These spatial relation words improved performance in the language condition, likely because they help children encode and recall important spatial information.

Verdine et al. [73] found correlations between spatial language and scores on block building and mathematics tests. These correlations held even after accounting for vocabulary scores from the PPVT, making it unlikely that general language exposure or ability could explain the relationship. Further, the correlations were primarily evident for words explicating the relationship between objects (between, below, above, and near) rather than size (e.g., big or short), suggesting that this type of language may help children spatially encode information. As Gentner [25] concluded, language is a cognitive tool that "augments the ability to hold and manipulate concepts" (p. 219), and spatial language appears to be no exception.

4.2. *Gesture*

The literature on the importance of gesture in learning goes back to papers by Goldin-Meadow and her collaborators (see [31] for review) who showed that teachers profit from gesture because they can interpret them (often unknowingly) to discern what their pupils understand [30]. And students profit because gestures can convey meaning, complementing what is offered through language. Gesture is inherently spatial and continuous, helping "to ground words in the world" ([31]; p. 239). Gesture may even be more helpful when the words are not forthcoming – as when children do not have words for left or under or do not know shape names.

Ehrlich et al. [19] reported that 4–5-year-old children who spontaneously gestured more in a mental transformation task where they needed to fit two shapes together [43] performed significantly better than children who did not. In this case, gesture occurred when children mimed moving the two pieces together with their hands. In one condition of a subsequent study by Ping et al. [57], they taught 4-year-olds to gesture how they would align animals on a screen. In another condition, they had the children manipulate a joystick to align the animals. Results indicated that only the children who practiced using gestures improved significantly on the mental transformation post-test.

Another paper demonstrating the importance of gesture in spatial training observed parent-child interaction during ordinary activities [7]. Children who saw their parents gesture more when they used spatial words (like pointing to a corner when saying *corner*) had more spatial language at 42 months than children whose parents gestured less. As Cartmill et al. [7] conclude, "… gesture is well suited to capturing the continuous information in the spatial world" and "…has the potential to play a powerful role in teaching children about space" (p. 7). Used alone or combined with spatial language, gestures may help children grasp the meaning of spatial terms as they enact their meaning (as when a parent spreads her hands when she uses the word big). Therefore, attention to spatial gestures in early spatial instruction is likely to increase the efficacy of that training.

5. What role should digital technology play in spatial learning?

Preschoolers and toddlers seem captivated by electronic toys and digital devices as anyone can observe in an airport, restaurant, or doctor's office [42,47]. Recently, Sesame Workshop [67] did a study that found that over 80% of apps in the Education category of iTunes were purchased for children. In 2012, the number of apps targeted to preschool and elementary school children jumped to 72% from 47% in 2009. Clearly, options for digitally teaching children are proliferating, but what influence will a shift to digital and electronic materials have for preschoolers and how will it affect spatial instruction?

The excitement about electronic technology is understandable and some studies have shown remarkably good results. For example, a study conducted by PBS suggested that children's vocabularies can be increased by as much as 31% in two weeks from an app called Martha Speaks developed by PBS Kids [12]. Such findings are tempered, however, by the fact that preschoolers experienced less learning (11% and 17% for 3- and 4-year-olds, respectively) and other studies show bigger advantages of traditional materials. For example, Parish-Morris et al. [56] examined 3- and 5-year-olds' interactions with traditional books and electronic console books (e-books). Overall parent-child engagement was higher and parents asked more content questions with traditional books compared to e-books that "read aloud." Three-year-olds that used e-books also did poorly on text comprehension questions, failing to get the point of the stories. There is also evidence from electronic and traditional shape sorters that electronic sorters do not elicit as much spatial talk from parents [80].

In general electronic toys tend to cut interactions with adults out of the equation, which may have ramifications for learning beyond language. Even as early as 8 months of age, babies treat humans as the best cues for learning (e.g., [79,20,41]). Furthermore, from around the age of 18 months, babies begin to "size up" adults for who is a reliable source of information and who is not (e.g., [40]). People are powerful for young children and their actual physical presence and involvement seems to promote children's learning, possibly because of their contingent responses to children [64,68].

Technology does have advantages over concrete materials. Games can be very engaging and, when used in their free time, may provide "bonus" learning experiences. Properly programmed digital platforms can adjust the difficulty level of the task in response to the increasing skill level of a child, creating an individualized experience for the child that can increase engagement, reduce frustration, and optimize learning. For example, Kellman et al. [39] used perceptual learning in a computer-delivered intervention to help second-graders recognize the equivalence of mathematical expressions. In comparison to using concrete materials, the visual input from a screen can also be reset instantaneously, creating shorter down times and providing a greater ability to show repeated examples; these properties will allow children to accumulate more relevant task experience in less time and may be helpful considering their fleeting attention spans.

What seems to be of primary importance when considering the use of technology for teaching is an observation by Cohen et al. [15]: "Overall, children are enthusiastic about iPads…but the device alone does not guarantee engagement and learning" (p. 9). Many aspects of electronic and digital technology must be designed carefully for use with preschoolers. Besides providing age-appropriate content, the technology must respond to the learner's input contingently, adjust the level of instruction to scaffold the experience, and have an intuitive interface. Few toys and apps appear to have been constructed with these principles in mind. Further, with many companies claiming unsubstantiated educational benefits of technology, parents may not be getting the information needed to make the best choices.

5.1. *Pathways for providing a "spatial education"*

By the age of 3, lower-SES children are already at a disadvantage in spatial skills (e.g., [43,73]) and gender differences, largely favoring males, already exist (e.g., mental rotation; [59]; and mapping tasks; [71]) or will shortly [45,70]. Therefore, instinct would say that we should particularly target lower-SES children and females for early spatial interventions. However, almost all children have relatively paltry access to formal spatial instruction, making it likely that the spatial and mathematical skills of most children would improve dramatically with good access to a "spatial education" delivered via goal-oriented activities and with awareness of the importance of spatial language and gestures.

5.1.1. *Families*

Due to the amount of time that many young children spend with their parents, making parents aware of how important spatial skills are is paramount for increasing school readiness. Further, we need to make clear to parents that it is important that these activities not be merely distractions for their children while they do chores around the house; interacting with children during spatial activities to complete shared goals will increase what children learn. Parent's spatial language may well play a causal role in how children think about spatial relationships and even how they learn about the number system.

5.1.2. *Toy manufacturers*

Although parents can individually work to provide a spatial education, spatial toys can also be improved to encourage parental interaction and directed play, and electronic versions can be made to react more contingently and adapt to children's skill levels. Attempts can also be made to get manufacturers of spatial toys to include instructions for specific activities that can be implemented to increase parents' use of spatial language and scaffolding. Finally, as part of their social outreach activities, toy manufacturers should be encouraged to provide spatial toys to lower-income populations and preschools who cannot afford such materials.

5.1.3. Preschools

Formal preschool provides substantial opportunities to screen and proactively address shortcomings in spatial skills. Policy makers have more control over early school experiences, where blocks, puzzles, and shapes, along with improvements in spatial language and gesture and increased use of guided play can be inserted into the curricula. A number of agencies and organizations have become aware of the importance of spatial skills for success in a range of STEM subjects, but much research is still needed to determine the best methods for implementing a “spatial education” in preschools. Perhaps more importantly there is a need to train teachers about the best methods for teaching these skills and give them adequate support in doing so. Those in education fields, who do not tend to have exceptional spatial skills (see Fig. 1; [76]), are likely to have more anxiety about teaching the topic. Research has shown that spatial anxiety in teachers leads to lower spatial skill in students [34]. Improving access to a spatial education is as much about how we teach these skills as it is about how much we teach them.

Numerous studies have found that preschool intervention has surprising longevity and wide impact [3], making the utility of various investments in early intervention high [36]. And because of the link between spatial and mathematics skills, spatial instruction can be expected to have a “two-for-one” effect that yields benefits in mathematics and the spatial domain. Therefore, increasing access to a preschool “spatial education” constitutes a safe bet for fueling school readiness and igniting long-term performance gains in STEM-related fields.

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