Comprehensive Assessment of Spatial Ability in Children: A Computerized Tasks Battery

Solmaz Soluki[1], Samira Yazdani[2], Ali Akbar Arjmandnia[2], Jalil Fathabadi[3], Saeid Hassanzadeh[2], and Vahid Nejati[3]

[1] Institute for Cognitive and Brain Sciences, Shahid Beheshti University, Tehran, Iran.

[2] Department of Psychology, University of Tehran, Tehran, Iran.

[3] Department of Psychology, Shahid Beheshti University, Tehran, Iran.

ABSTRACT

Spatial ability is known to have an important role in learning different skills in childhood and achieving success in specific professions. A vast majority of the studies on this topic have focused on adults, and few on in children. In this study, eight tasks were selected to assess eight factors of spatial ability and were modified to be suitable for children. Computerized versions of the tasks were designed and their reliability was measured. One-hundred and ten Iranian children aged 9 to 12 years old participated in the study. In order to assess the test-retest reliability, half of the participants were tested twice. Internal consistency reliability was calculated for some of the tasks. Intraclass correlation coefficients were obtained by test-retest reliability analysis for all tasks ranging from 0.689 to 0.997. The range of Cronbach's α coefficient was found to be between 0.335 and 0.784. The range of the ω coefficient was from 0.428 to 0.798. Each modified task had adequate reliability for assessing the respective spatial ability factors. This battery can help to identify the level of spatial performance in children.

KEYWORDS

spatial ability
factors of spatial ability
internal consistency
test-retest reliability
school-age children

INTRODUCTION

Spatial ability is defined as the ability to represent, transform, generate, and recall symbolic and nonlinguistic information (Linn & Petersen, 1985). Despite the importance of spatial ability in children, the majority of the studies in this field have been conducted on adults. Moreover, given the variety of factors in spatial ability, a lack of a comprehensive battery to measure this construct as a whole is another issue that should be taken into account.

Spatial ability plays a crucial role in different domains of children's life, especially in elementary school years, such as musical ability, motor skills, and academic competencies. In a meta-analysis, Hetland (2001) found a strong relationship between spatial relation (i.e., tasks requiring mental manipulation of shapes) and spatial temporal (i.e., mentally flipping and turning objects in the absence of a physical model) abilities with plying music instruction in children aged 3 to12. Spatial ability plays a crucial role in motor performance. An interventional study found that a motor training program improves spatial performance (mental rotation) in school aged children (Wiedenbauer & Jansen-Osmann, 2006). Also, several academic skills, such as mathematics and reading, are related to spatial ability. In a review study, Mix and Cheng (2012) found the relationship between mathematical abilities and three factors of spatial ability including spatial visualization, spatial orientation, and flexibility of closure. Additionally, spatial ability is known to be involved in representing conceptual knowledge such as number magnitudes, and also imagining and manipulating mathematical material that is able to form a spatial structure, such as the mental number line (Zorzi et al., 2002). In the same way, reading ability is correlated with spatial visualization and spatial relation factors in elementary school children (Boonen et al., 2014).

Previous studies have strongly supported the construct of spatial ability to include several separate and unified factors (Hegarty & Waller, 2009). Different kinds of spatial ability factors have been proposed based on factor analysis studies. For example, Carroll (1993) conducting a factor analysis study on more than 140 datasets, found five major factors including visualization (VIS), spatial relation (SR), closure speed (CS), flexibility of closure (FC), and perceptual speed (PS). This classification has been criticized by other investigators since

Corresponding author: Vahid Nejati, Department of Psychology, Shahid Beheshti University, Tehran. E-mail: nejati@sbu.ac.ir

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Carroll had ignored the spatial orientation (SO) factor, spatial temporal (ST) ability, and wayfinding (WF), which are considered as important components of spatial ability (Hegarty & Waller, 2005; Yilmaz, 2009). The five factors distinguished by Carroll, along with the latter three factors, appear to fully cover the nature of the spatial structure (Yilmaz, 2009). Therefore, these eight factors can be considered as the description of a spatial construct based on previous factor analysis and systematic review studies. Since there is a wide variety of definitions for the abovementioned factors in the literature, the most authoritative descriptions of them are listed in Table 1.

Uttal et al. (2013) presented a theoretical framework for spatial ability processes. They suggested that spatial tasks could be divided into two dimensions (i.e., intrinsic–extrinsic and static–dynamic). Based on these two dimensions, a 2 × 2 classification of spatial skills was developed: intrinsic-static, intrinsic-dynamic, extrinsic-static, and extrinsic-dynamic. The different spatial processes, including the abovementioned eight factors, fall within each of these four cells (Uttal et al., 2013). Three factors of CS, FC, and PS fall in the intrinsic-static cell which refer to perceiving objects, paths, or spatial configurations amid distracting background information. In contrast, two factors of VIS and SR fall in the intrinsic-dynamic cell since this cell involves piecing objects together into more complex configurations, visualizing, mentally transforming, and rotating objects, often from 2D to 3D or vice versa. The extrinsic-static cell refers to the coding of spatial position in relation to another object, or with respect to gravity. Therefore, the SO factor falls in the extrinsic-static cell. Finally, ST and WF fall in the extrinsic-dynamic cell, since visualizing an environment as a whole from different perspectives is related to the extrinsic-dynamic information (Uttal et al., 2013).

The development of spatial abilities through the lifespan is still a topic of debate. Piaget and Inhelder (1956) suggested that children's spatial ability does not reach an adult level before the age of twelve, but several other studies revealed contrary results. For example, Huttenlocher et al. (1999) showed that spatial understanding develops earlier than was proposed by Piaget. Based on this finding, they suggested stages for spatial ability development. According to Huttenlocher et al. (1999), children continue to develop spatial understanding and complete their mental development in spatial learning by the age of nine or ten. However, there is no more detailed information about the age of the acquisition of each spatial factor, which can be due to the lack of comprehensive assessment tasks of spatial ability designed especially for children (Ekstrom et al.,1976; Killgore, 2006; Kozhevnikov & Hegarty, 2001; Sanchez & Wiley, 2014). According to the above studies, it can be inferred that spatial ability factors may fully develop until the age of nine to twelve. Thus, measurement of spatial factors in this age range seems crucial.

Problems in spatial ability factors are usually associated with neurodevelopmental disorders. These problems are common in children with autism spectrum disorder (ASD; Kurtz, 2006), specific learning disorder (SLD; McDonough et al., 2017), developmental coordination disorder (DCD; Prunty et al., 2016; Wilson et al., 2017), and attention deficit-hyperactivity disorder (ADHD; Kurtz, 2006). These children may have problems in understanding the symbols that are used in subjects involving diagrams, maps, charts, or graphs, or in reading maps, finding paths from home to school, and playing games which require eye-hand coordination (Riddoch & Humphreys, 1993; Kurtz, 2006). This evidence points to spatial ability as a strong contributor to both learning processes and outcomes (Nejati, 2021).

The importance of spatial ability during development makes the evaluation of all eight factors crucial in order to reduce the probable consequences of any deficits in these factors which can affect the quality of life in children and youth. During the past 20 years, some batteries have been developed to examine the typical development of spatial functions in children. For example, the Test of Visual Perceptual Skills (TVPS; Gardner, 1996) and the Developmental Test of Visual Perception (DTVP; Brown & Murdolo, 2015) are suitable for the assessment of three of the eight mentioned factors of spatial ability including FC, CS, and PS in children aged 4 to 16 years old. In addition, the Visual Object and Space Perception test (VOSP; Weber et al., 2004), the L94 visual perceptual battery (Stiers et al., 1999), and the Basic Visual Spatial Processing tests (BEVPS; Schmetz et al., 2018) are developed to assess FC, CS, PS , and VIS. Similarly, Pisella et al. (2013) developed a battery with six tasks inspired by the Birmingham object recognition battery (BORB; Riddoch & Humphreys, 1993) and VOSP subtests, and tested a group of children aged 4 to 12 years old. These tests covered only FC, CS, PS, and VIS. The NEPSY-II (Korkman et al., 2007), a multidomain neuropsychological battery, is designed for assessing neurocognitive abilities in children aged from 3 to 16.11

TABLE 1.
Definitions of the Spatial Ability Factors

Factor	Definition
Flexibility of Closure (FC)	The apprehension and identification of a visual pattern, especially if the pattern is disguised or obscured (Carroll, 1993).
Closure Speed (CS)	The apprehension and identification of a disguised or obscured visual pattern, without knowing its identity (Carroll, 1993).
Perceptual Speed (PS)	The finding of a known visual pattern or accurately comparing one or more patterns in a visual field in which the patterns are not disguised or obscured (Carroll, 1993).
Visualization (VIS)	The manipulation or transformation of spatial patterns into other arrangements (Ekstrom et al.,1976).
Spatial Relation (SR)	The manipulation of relatively simple visual patterns through mental rotation, transformation, or otherwise, Carroll, 1993)
Spatial Orientation (SO)	The imagination of the appearance of an object from different perspectives (Yilmaz, 2009).
Spatial Temporal (ST)	The judgment of speed of an object respecting a moving stimulus (Halpern, 2013).
Wayfinding (WF)	The integration of spatial information about natural and artificial objects and surfaces in the surroundings environment (Allen, 1999; Bell & Saucier, 2004).

years old. The NEPSY-II is divided into six domains of cognitive functioning. Visuospatial processing is one of the domains which consists of Arrows, Block Construction, Design Copying, Geometric Puzzles, Picture Puzzles, and Route Finding subtests. Most of the subtests are designed to assess visual motor construction. Finally, La Femina et al. (2009) developed a spatial ability test battery for children aged from 4 to 11 years old. This battery targets the visual motor construction and basic visual process such as visual attention. In sum, none of the batteries mentioned above provide a systematic assessment for all spatial ability factors. With respect to the classifications of spatial ability by Yilmaz (2009) and Uttal et al. (2013), factors such as SR, SO, ST, and WF are not included in the available spatial ability batteries. Thus, a comprehensive battery of behavioral tasks is required to assess all factors of spatial ability as a unified construct and to provide a profile of spatial ability in children. Also, the use of such spatial tasks can be necessary in order to adopt them in clinical settings, for example, to assess the efficacy of rehabilitation interventions.

Moreover, the majority of developed spatial tests (e.g., the TVPS, the DTV; Brown & Murdolo, 2015; Gardner, 1996; Harris et al., 2013) are paper-and-pencil. These kinds of tests have some limitations. First, it is not possible to add moving elements to the tests. Although it is possible to determine how many items a person can pass in a specified time, it is not possible to examine the time that a person spends on an individual item, or the time spent on various subtests of the spatial problem posed by a test item. Reaction time and accuracy in solving parts of a problem may originate from different psychological skills (Mumaw et al., 1982). Generally, people may trade between RT and accuracy of performance in different ways, so measuring both RT and accuracy may be needed to sufficiently assess the spatial skill (Hunt & Pellegrino, 1985). It can be assumed that computer-administered testing can resolve both of the mentioned problems.

The goal of this study was to collect and modify eight tasks for eight factors of spatial ability, including FC, CS, PS, VIS, SR, SO, ST, and WF in order to obtain a comprehensive assessment of spatial ability for school-age children and evaluate its reliability.

MATERIALS AND METHODS

Participants

Participants were Iranian children who were selected from two elementary schools in Tehran. Multistage sampling was carried out in the spring of 2019. The participants were selected was as follows: a letter was sent to more than 50 schools to recruit the required number of participants. After the initial contact, some schools agreed to participate, out of which two schools were selected randomly. The schools received a formal letter, an informed consent form, demographic information questionnaire, and the Conners' Parent Rating Scale (short form; Conners et al., 1998) and sent them to parents. Finally, researchers selected the samples randomly from among children whose parents volunteered and filled in all of the forms. Researchers examined the information available at the schools (children's records) in order to ensure they did not suffer from any significant psychological or physical deficits; 12 children were excluded at this stage. Also, 16 children whose scores in the Conners scale were above the cutoff point were excluded from the study. Finally, out of 243 children aged 9 to 12 years old who volunteered from two schools, 110 children were selected (62 males, 48 females; M_{age} = 10.01 ± 1.05).

A pilot study was executed prior to our main study. The aims of the pilot study were to investigate the feasibility of the modified spatial tasks, and to estimate the required time for each task to be done later in the main study. The sample size was chosen based on the literature (Lee et al., 2014). Twelve children (9-12 years old) were selected through convenience sampling. They were assessed through all the tasks in a youth cultural centre. The results revealed that some tasks should be modified compared to the original tasks (the details of each task are mentioned in the Instruments section). It was also found out that in order to perform all the tasks, children would need two sessions of 45 minutes each.

The study was approved by the ethical committee of the Shahid Beheshti University (ethical code: IR.SBU.ICBS.97/1022).

CONNER'S PARENT RATING SCALE-48

This is a 48-item questionnaire which includes six hyperactivity factors including attention deficit, behavioral disorder, impulse disorder, hyperactivity, psychosomatic disorders, and anxiety disorders. In a study by Khoushabi (2002), Cronbach' α validity of this questionnaire was estimated to be 93% among the Iranian population.

SPATIAL TASKS

The eight spatial ability tasks that were selected for computer implementation had to meet a set of criteria. First, the task had to be well defined, which means that it must be clear which construct each task is evaluating and how the evaluation must be done. Second, the task and its derived processing measures had to have some history of use in the study of individual differences in spatial ability. Finally, each task had to only measure one of the spatial factors (e.g., CS, SR, and VIS).

The following modifications were applied to six tasks of FC, CS, PS, VIS, SR, and SO:

1. Items of the tasks were transformed into a computer program to examine RT for each item.

2. Two practice items were included before the test and feedback appeared after each item to show if the practice test was done correctly or not.

3. Response time to each item was restricted to 10 s for CS, FC, PS, and SR tasks and there was no time limit for SO and VIS tasks. Speed component has a crucial role in performance of participants in FC, CS, PS, and SR tasks (Carroll, 1993). According to the TVPS-R manual, 10 s was considered as an internal stimulus. In contrast, tasks that measure SO and VIS factors do not have time restriction for response (Ekstrom et al., 1976), so items remain on screen until the participants respond.

4. Scoring criteria were revised. The number of correct responses was considered as participant accuracy (ACC) and the seconds that the participant consumed for giving correct responses was considered as RT. The subtests of the TVPS-R were stopped after three consecutive wrong answers. Since we wanted to calculate RTs of correct responses in each task, the participants had to answer all of the items to the end. Moreover, in contrast to the original versions of the tasks, we recorded RTs of the ACC.

Tasks of FC, CS, and PS were adapted from the three subtests of the TVPS-R. The TVPS-R was initially developed to determine the visual-perceptual strengths and weaknesses among 4 to 13 year-old-children (Gardner, 1996) with a test reliability of 74-85%. The validity of this test has been confirmed by numerous studies (Davis et al., 2005; Gardner, 1996; Tsai et al., 2008). This nonverbal and nonmotor test is composed of seven subtests including visual memory, visual spatial relationships, visual form constancy, visual sequential memory, visual figure ground, visual closure, and visual discrimination. Each subtest includes 16 items.

FLEXIBILITY OF CLOSURE (FC) TASK

The figure ground discrimination subtest of the TVPS-R was modified for measuring FC. A shape is displayed on the top of the screen and four patterns with complicated and conglomerated background are presented on the bottom. Participants are asked to find the shape in one of the four patterns and press the number of the correct response on the keyboard. There are 16 items in this task (see Figure 1).

CLOSURE SPEED (CS) TASK

The visual closure subtest of the TVPS-R was modified for measuring CS. In addition to the mentioned modifications, one more change was applied. An incomplete shape is presented on the top of the screen and four complete shapes are presented on the bottom of screen for each item (this manner of stimulus presenting is the reverse of the original subtest). Participants imagine the completed shape, match it with one of the shapes on the bottom of screen, and press the number of correct responses on the keyboard. There are 16 items in this task (see Figure 2).

PERCEPTUAL SPEED (PS) TASK

The visual discrimination subtest of the TVPS-R was modified for measuring PS. A shape is displayed on the top of the screen and the participants determine which of the five shapes on the bottom is exactly the same as the shape on the top, and press the number of the correct response on the keyboard. There are 16 items in this task (see Figure 3).

VISUALIZATION (VIS) TASK

Researchers commonly use the paper folding task for measuring VIS. Harris et al. (2013) devised a version of the paper folding task for children aged 5 to 7 years old. This was designed to be the simplest test of mental folding. It requires participants to imagine folds applied to a piece of paper, without any representation of the folding action itself. The paper is colored differently on each side to make the sides distinct. The task consists of 12 items and the picture of the unfolded paper is shown in each item. Each of the 12 items represented a different paper shape. Orientation of folding is specified by an arrow and location of folding is marked by dotted lines. Participants are asked to visualize the folded paper accordingly and select the matching picture from among the four pictures. The test has an acceptable level of internal reliability (α = .81). This task was designed for preschool children and it would be too simple for children aged 9 to 12 years old based on our pilot study, so in the current study, four new items were added considering the complexity rule:

1. The number of folds was increased.
2. Some of the folds overlapped each other.
3. The number of paper angles was increased.
4. There were holes in the paper.

There are 16 items in this task (see Figure 4).

SPATIAL RELATION (SR) TASK

The mental rotation task was used to assess SR. This task was developed by Wiedenbauer and Jansen-Osmann (2006). Children decide whether two presented animal stimuli are identical or mirror images of each other. The experimental stimuli consist of figures of six different animals. Within a given item, an animal is presented twice: An upright standing standard figure is presented on the left side, a comparison figure that was rotated in the picture plane and is either identical (same items) or, in half of the items, mirror-reversed (different items), is presented on the right side. Half of the standard figures are presented facing to the left, the other half facing to the right. The angular disparity between the two figures is 22.5 °, 67.5 °, 112.5 °, or 157.5 ° clockwise and counter-clockwise (i.e., 202.5 °, 247.5 °, 292.5 °, or 337.5 °). In each of the eight angular disparities, each pair of drawings is presented twice (once in a same and once in a different item). The total number of items is 96.

In the pilot study, this task was found to be too long and tiring for children. Thus, we only used figures of three animals (elephant, leopard, and horse) which resulted in a total of 48 items.

Each item starts with a 500 ms presentation of a grey 5 mm fixation square followed by two stimuli, prompting the children to answer by pressing the 1 key for same and 2 for different (see Figure 5).

SPATIAL ORIENTATION (SO) TASK

The picture task was applied for the purpose of measuring SO. This task was developed by Zoest (2015) based on Hegarty and Waller (2004). In each item, a picture is shown with one photographer standing in a scene with numerous objects. The photographer in the picture is taking a photo of what he can see from his perspective. Next to the picture, three photos are shown. For each item, the participants have to detect the matched photo based on the perspective of the photographer. Reliability was reported .73 based on Cronbach's α.

This task was designed for eight to ten-year-old children and based on our pilot study, it was too simple for children aged 9 to 12 years old. Thus, in the current study, four new items were added considering the complexity rule:

1. The number of objects in the scene was increased.
2. The perspective of the photographer was more challenging. For instance, some of the objects were placed behind the photographer.
3. The distance between objects was changed.
4. The distance between objects and photographer was changed.

There are 16 items in this task (see Figure 6).

SPATIAL TEMPORAL (ST) TASK

The interception task was selected for assessing ST. The task was developed by Hunt et al. (1988) for the first time and Sanchez and Wiley (2014) presented a new version. This task is designed to measure the ability to combine speed and path extrapolation. The updated intercept task consists of a game-like interface in which a small circular target moves horizontally across the top of the screen at one of three preset speeds (175, 100, and 75 px/s). In this task, the participants' goal is to hit this moving circular target with a missile that is launched from the lower right corner of the screen by pressing the spacebar. The missile moves straight up at a constant velocity of 175 px/s, to the point of intersection that is exactly 350 px away. It takes 2 s for the missile to reach the intersection point with a constant velocity. This is consistent across all trials. Thus, to successfully hit the target, the participant must release the missile when any point of the circle (e.g., target) crosses within the point of intersection. To make the task more difficult, waiting time (and thus the initial starting point) for each circular target is also manipulated by adding either 750, 1000, or 1250 ms to each of the three preset speeds, which results in nine different trial types overall. Participants complete each of these nine trials seven times, resulting in 63 trials overall. Prior to the actual trials, participants are given five random practice trials of varying speeds and waiting times to familiarize themselves with the interface.

Since this task was developed for assessing adults, some modifications were done to fit this task for measuring spatial temporal ability in children based on our pilot study:

1. Target preset speeds were changed to 175 px/s, 200 px/s, and 250 px/s.
2. 575 ms were added to preset speeds as waiting time so three different trials were created. Each trial repeated seven times (21 trials overall).

Accuracy scores are considered as variables in analysis (see Figure 7).

WAYFINDING (WF) TASK

A task from Mengue-Topio et al. (2011) was adapted for assessing wayfinding. This task consists of three phases which include Memory for Landmarks (ML), Learning the Path (LP), and Shortcut Distance (SD). The virtual space comprises a 4 × 4 regular grid of streets lined with high brick walls. It is surrounded by distant landscapes providing no distinctive cues. Three buildings and 17 landmarks are located in different places of the space. The buildings are a railway station (A), a store (B), and an apartment building (C). The virtual environment is projected onto a 1.20 × 1.50 m screen. The distance between the screen and the participant is 2 m. The participants explore the virtual town using a keyboard and a mouse. Pressing the backspace key effects forward movement and moving the mouse to the right or left controlled rotational movements. Participants navigate from a first-person viewpoint, at a constant velocity. The sum of landmarks that are recognized correctly are considered as a score of the ML phase (ACC). The number of trials until the participants reach the criterion of walking the route forward and back twice without any errors are summed and considered as the score of the LP phase. For the SD phase, in which the participants are asked to find the shortest route between A and B (or the reverse) and back again, the distance between two buildings are calculated to identify the shortest path. The virtual environment is designed based on Iranian cities (see Figure 8).

Procedure

In the first stage of the current study, the required modifications to the eight spatial tasks were applied and then their computerized versions were designed. The Unity software was used to program and run the experiments. A pilot study was done in the second stage. In the third stage, after checking the inclusion criteria, participants were individually tested in a quiet room in the school for two sessions of 45 minutes each, within one week. Each task was preceded by a practice phase, and before starting the test phase, all children were asked to repeat the task instructions to ensure that they have understood them. All tasks were presented in the same order for all participants on a 15 in. PC screen. In the fourth stage, half of the participants were tested again by all the tasks after one month in order to assess the test-retest reliability.

Statistical Analysis

BM SPSS version 22 (SPSS Inc., Chicago, IL, USA) and R version 4.0.1 (R Core Team, 2020) with the psych package (Revelle, 2020) were used for analysis. The gathered data were summarized using means and SDs with 95% Cis for continuous data. Test-retest reliability was evaluated using the intraclass correlation coefficient (ICC) on 55 randomly selected participants who were reassessed with all spatial tasks about a month after the first evaluation. Because of time and accessibility limitations, only half of the participants were chosen for retests from among the 110 participants.

Internal consistency is typically a measure based on the correlations between different items on the same test. It measures whether several items that are proposed to measure the same general construct produce similar scores (Cho & Kim, 2015). Internal consistency was examined based on Cronbach´s αand McDonald's ω (McDonald, 1999) for all tasks except the ST and WF tasks (these two tasks do not have items due to their gaming nature). Since four items were added for visualization and spatial orientation tasks, we used scale reliability. This way, we were able to examine effect of adding four items to internal consistency reliability of the mentioned tasks.

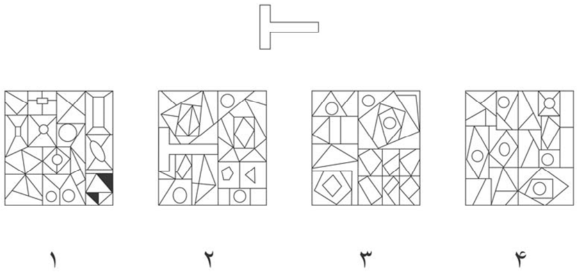

FIGURE 1.

Example of items in the Flexibility of Closure task. Participants had to find the shape on the top of the screen in one of the four patterns (i.e., 2 is the correct answer).

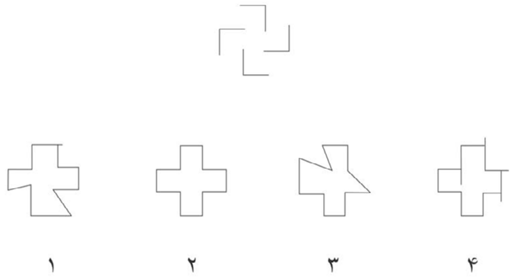

FIGURE 2.

Example of items in the Closure Speed task. Participants had to imagine the completed shape on the top and match it with one of the shapes on the bottom (i.e., 2 is the correct answer).

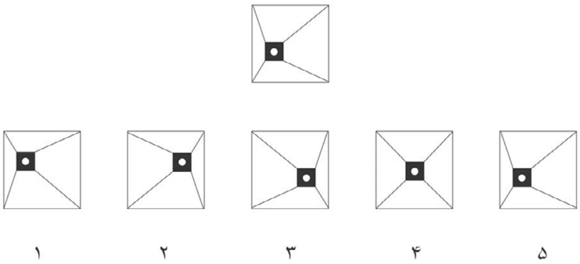

FIGURE 3.

Example of items in the Perceptual Speed task. Participants had to determine which of the five shapes on the bottom is exactly the same as the shape on the top (i.e., 5 is the correct answer).

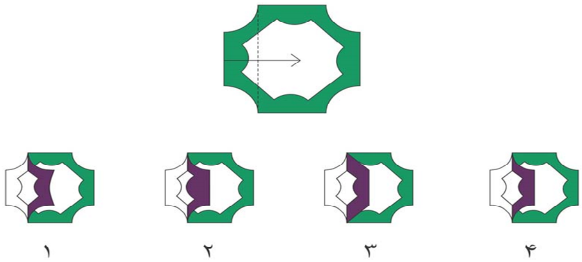

FIGURE 4.

Example of items in the Visualization task. Participants had to mentally visualize that folds applied to a piece of paper and select the matching picture among the four pictures on the bottom (i.e., 4 is the correct answer).

FIGURE 5.

Example of items in the Spatial Relation task. Participants had to decide whether the wo presented animal stimuli are identical or mirror images of each other (i.e., 2 is the correct answer).

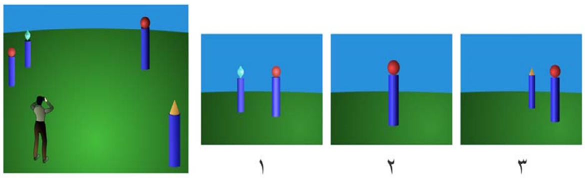

FIGURE 6.

Example of items in the Spatial Orientation task. A photographer in the picture is taking a photo of what he can see from his perspective, participants had to detect the matched photo based on the perspective of the photographer (i.e., 2 is the correct answer).

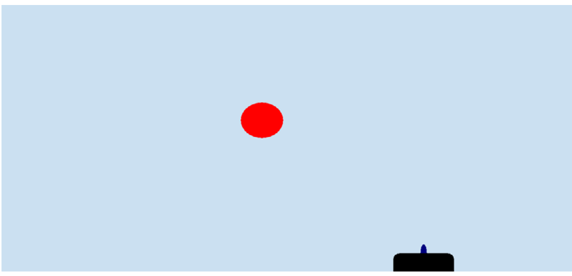

FIGURE 7.

Example of items in the Spatial Temporal task. A red circular target moves horizontally across the top of the screen. This moving circular target should be hit a 'blue missile' by participants with pressing the spacebar. The missile launches from the lower right corner of the screen.

FIGURE 8.

Example of items in the Wayfinding task. This task consists of three phases including memory for Land Marks (ML), Learning the Path (LP) and Shortcut Distance (SD).

RESULTS

Descriptive statistics are illustrated in Table 2.

Test-Retest Reliability

Descriptive data of the modified spatial ability tasks for test and retest with the corresponding correlation values for main variables are shown in Table 3. The ICC of the 12 variables demonstrated a very high reliability: ICC = 0.975 for the RT of the FC task, ICC = 0.996 for the RT of the CS task, ICC = 0.966 for the RT of the PS task, ICC = 0.968 for the ACC of the VIS task, ICC = 0.997 for the RT of the VIS task, ICC = 0.992 for the ACC of the SR task, ICC = 0.963 for the RT of the SR task, ICC = 0.968 for the ACC of the SR task, ICC = 0.997 for the RT of the SO task, ICC = 0.942 for the ACC of the ST task, ICC = 0.912 for the ACC of the ML and ICC = 0.981 for the meters of the SD task. The remaining variables demonstrated high and marginal reliability: ICC = 0.886 for the ACC of the FC task, ICC = 0.888 for the ACC of the CS task, ICC = 0.881 for the ACC of the PS task, and ICC = 0.689 for the number of trails of the LP task. All coefficients were statistically significant at p = .001 (see Table 3).

Internal Consistency Reliability

Internal consistency was calculated for the six aforementioned modified tasks.

Results based on Cronbach's α are: the FC task: 16 items, α = .548; the CS task: 16 items, α = .391; the PS task: 16 items, α = .355; the VIS task: 16 items, α = .659; the SR task: 48 items, α = .645; and the SO task: 16 items, α = .784.

Results based on McDonald's ω are: the FC task: 16 items, ω_t = .598; the CS task: 16 items, ω_t = .496; the PS task: 16 items, ω_t = .428; the VIS task: 16 items, ω_t = .739; the SR task: 48 items, ω_t = .757; and the SO task: 16 items, ω_t = .798.

Internal consistency for the 16 items of the VIS task was α = .659. The internal consistency of the task was α = .224 when the four last items were excluded and when Items 13, 14, 15, and 16 were omitted individually, Cronbach's αwas .588, .604, .616, and .535. respectively. Internal consistency for the 16 items of the SO task was α = .784. The internal consistency of the task was α = .690 when the four last items were excluded and when Items 13, 14, 15, and 16 were omitted individually, Cronbach's α was .771, .760, .758, and .761, respectively (see Table 4).

DISCUSSION

The aim of this study was to present and describe some of the psychometric properties of a comprehensive computerized battery of spatial ability tasks. This battery can overcome the limitations of a comprehensive test to evaluate all of the eight factors of spatial ability construct in children. With respect to the results, all tasks have good test-retest reliability. These findings are in line with our expectations that internal consistency for the modified tasks would be acceptable to low. This was predictable, since the difficulty of the items was increasing during performing the tasks.

Generally, in spatial ability tasks, the accuracy of responses is considered as task performance. Notably, RT is a decisive factor in task performance. In line with this idea, Hunt and Pellegrino (1985) pointed out that RT is an influential factor in performing spatial tasks.
Current computerized battery tasks make it possible to distinguish between RT and accuracy of responses on an item-by-item basis. Moreover, spatial ability is highly consistent with both the hierarchical models (e.g., Carroll, 1993) and the nonhierarchical Radex models (e.g., Marshalek et al., 1983) of human intelligence. In these models, the more complex a task is, the more strongly it tends to be correlated with general intelligence (g) and the higher it is placed in the hierarchy (in the hierarchical models), or the closer it is placed to the center of the configuration

TABLE 2.
Descriptive Statistics for All Variables

Factor		ACC (raw score)	ACC (%)		RT(s)	
		M (*SD*)	*M* (*SD*)	Max	*M* (*SD*)	Max
FC		11.69 (2.36)	73.07 (14.75)	100	63.76 (18.74)	116.60
CS		13.02 (1.91)	81.36 (11.94)	93.75	76.65 (17.94)	118.63
PS		12.84 (1.74)	80.23 (10.89)	100	66.08 (19.08)	117.06
VIS		10.83 (2.80)	60.15 (15.58)	88.89	80.10 (27.94)	163.84
SR		34.32 (9.93)	71.50 (20.69)	100	60.13 (24.02)	114.80
SO		9.82 (3.59)	54.54 (19.94)	94.44	76.79 (35.73)	166.22
ST		13.55 (2.94)	64.64 (14.03)	90.00	-	-
WF	ML	12.74 (2.09)	79.60 (13.08)	56.25	-	-
	LP (NT)	4.64 (0.75)	46.36 (7.51)	80	-	-
	SD (meters)	32.85 (7.99)	-	47.66	-	-

Note. N = 110. FC = flexibility of closure; CS = closure speed; PS = perceptual speed; VIS = visualization; SR = spatial relation; SO = spatial orientation; ST = spatial temporal; ML = memory for landmarks; P = learning the path; SD = shortcut distance ACC= accuracy score, ST and WF tasks do not have RT as a variable.

TABLE 3.

Descriptive Data and Correlation Values for the Test-Retest Scores of Spatial Ability Tasks

Variable		Test (n = 55)	Retest (n = 55)	ICC	Reliability			
					95% CI		F test with true value	Rating
		M (SD)	*M (SD)*		Lower bound	Upper bound	Value	
FC	ACC (%)	73.07 (14.82)	76.93 (15.77)	0.886	0.804	0.933	8.74*	high
	RT (s)	63.90 (19.29)	60.86 (17.84)	0.975	0.957	0.985	39.48*	very high
CS	ACC (%)	81.36 (11.00)	82.27 (11.52)	0.888	0.809	0.935	8.96*	high
	RT (s)	77.42 (17.54)	74.26 (17.13)	0.996	0.993	0.998	234.03*	very high
PS	ACC (%)	80.23 (10.94)	82.50 (8.95)	0.881	0.796	0.931	8.41*	high
	RT (s)	66.08 (19.47)	60.10 (19.73)	0.966	0.941	0.980	29.27*	very high
VIS	ACC (%)	60.10 (15.72)	63.94 (13.18)	0.968	0.945	0.981	31.17*	very high
	RT (s)	79.93 (29.62)	73.66 (29.25)	0.997	0.994	0.998	291.88*	very high
SR	ACC (%)	71.06 (21.22)	72.92 (21.52)	0.992	0.987	0.995	128.65*	very high
	RT (s)	57.28 (24.60)	51.52 (22.06)	0.963	0.937	0.979	27.22*	very high
SO	ACC (%)	54.55 (20.03)	59.49 (17.72)	0.968	0.945	0.981	31.36*	very high
	RT (s)	77.35 (36.47)	77.52 (37.05)	0.997	0.995	0.998	327.74*	very high
ST	ACC (%)	64.74 (14.77)	66.55 (14.41)	0.942	0.900	0.966	17.14*	very high
ML	ACC (%)	79.77 (13.92)	85 (9.52)	0.912	0.849	0.949	11.38*	very high
LP	NT (%)	46.55 (7.75)	44.55 (5.38)	0.689	0.467	0.819	3.22*	marginal
SD	meters	32.52 (8.08)	31.89 (8.00)	0.981	0.967	0.989	52.15*	very high

Note. ICC = intraclass correlation coefficient; FC = flexibility of closure; CS = closure speed; PS = perceptual speed; VIS = visualization; SR = spatial relation; SO = spatial orientation; ST = spatial temporal; ML = memory for landmarks; P = learning the path; SD = shortcut distance ACC= accuracy score.
* $p < .001$

(in the Radex models). This complexity range corresponds well to the degree of central executive involvement. Thus, more time will be required for more complex tasks including spatial ability tasks. It has been proposed that children who suffer from neurodevelopmental disorders such as ADHD, SLD, and ASD have slower processing in general than typically developing (TD) children (Alderson & Rapport, 2008; Geary et al., 2007; Kofler et al., 2013) , and it takes them longer to perform on more difficult tasks. Therefore, this is essential for assessing children's performance in the current eight tasks, especially for FC, CS, PS, and SR tasks, which have a speed-based nature (Carroll, 1993). Thus, this battery can be used to explore RT and power aspects of testing in a way that is not possible in a paper-pencil format.

Our findings indicate that the ICC range for all the variables was from very high to marginal. Most scores show a tendency toward improvement on the retest, especially in the LD phase of the WF task. This is not surprising for the mentioned variable, since participants should learn a specified path, so a practice effect was predictable. A previous report of the test-retest reliability for visual closure, figure ground discrimination, and visual discrimination subtests of the TVPS-R, which are the same as FC, CS, and PS tasks in current study, respectively, showed slightly lower internal consistency (McFall & Crowe, 1993). These contradictions in findings are probably because of the difference in the participants. Participants in McFall and Crowe were children with learning disorders. In this group of children, the effect of practice between test-retest is lower than in TD children due to learning problems.

Both the αand ω coefficient results indicated that internal consistency of the FC, CS, and PS tasks was low, questionable for theVIS and SR tasks, and acceptable for the SO task. Similar to our findings, internal consistency reported based on the half-split test for figure ground discrimination, visual closure, and visual discrimination subtests of the TVPS-R was ranged from moderate to low (Gardner, 1996). In general, the size of the reliability coefficient is based on both average correlations among items and the number of items (Nunnally, 1978). Thus, low levels of internal consistency of these three tasks were observed in the present study and in Gardner's original work, which might be related to the small number of items and the progressive difficulty of items in each task. Furthermore, in line with our study, Hegarty and Waller (2004) reported high internal consistency for the picture task in adults. In addition, internal consistency the for original paper folding task, which was developed for preschool children, was high (Harris et al., 2013). The difference in internal consistency between the original and our modified version is probably due to the increased difficulty of our version by adding four items.

In the present study, scale reliability analysis was performed in order to examine the effects of four new added items on the VIS and SO tasks. The analysis showed that the added items, individually or collectively,

TABLE 4.
Reliability scale coefficient if item deleted for two spatial tasks

Items deleted	Cronbach's α	
	Visualization task	Spatial orientation task
13	.588	.771
14	.604	.760
15	.616	.758
16	.535	.761
13 to 16	.224	.690

increased the reliability of both tasks. In sum, the four new items added to these tasks made it more appropriate to be used for evaluating VIS and SO in a broader age range (up to 12 years old, at least) compared to the original tasks (Harris et al., 2013).

From the theoretical point of view, this battery may allow for better investigations of the spatial construct, which consists of different factors (see Carroll, 1993; Uttal et al., 2013; Yilmaz, 2009). Moreover, the availability of a comprehensive spatial battery task could help clarify which of the eight factors of spatial ability is defective in different neurodevelopmental disorders, since until now, there are no clear explanations in the literature (Alpanda, 2015; Cheng & Mix, 2014; Garcia-Sanchez et al., 1997; Geary, et al., 2007; Murphy et al., 2007). From the clinical viewpoint, clarifying distinct spatial performance profiles for each child is essential for implementing individual-based intervention strategies.

Limitations and Future Directions

There have been some limitations in the present study. The sample size was small and we could not examine spatial performance in a wider age range. Thus, we were not able to compare spatial performance in different age groups of children.

We are going to compare all spatial factors in this battery among ADHD, SLD, and TD children in a future study. Also, one of our future aims is to examine the predictive effect of spatial ability factors on executive functions in ADHD, SLD, and TD children. Another future line of research can focus on the comparison of individual differences in spatial factors (girls vs. boys). Finally, this battery can be used for evaluations of spatial interventions that will be designed for enhancement of spatial ability in children.

Conclusion

The prepared tasks in the present study assess all factors of spatial ability in one unified battery. Reaction time was added to the task scores as a crucial indicator. Our findings showed that the battery tasks have suitable reliability for the assessment of all eight factors of spatial ability. Therefore, our battery may be a suitable tool for researchers who are interested in investigating the development of spatial ability.

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