Interactions With Reconfigurable Modular Robots Enhance Spatial Reasoning Performance

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***Abstract*—Reconfigurable modular robots (RMRobots) can change their shape and functionality (e.g., locomotion styles) to fit different environments, and have been widely investigated in applications, such as exploration and inspection. In this paper, we present a new application of RMRobots for improving human spatial ability which plays a significant role in developing an individual's performance and achievement in science, technology, engineering, and mathematics (STEM). Two user studies are conducted, and the results show that: 1) the task performance of interacting with RMRobots has a significant positive relationship with mental rotation, a widely used measure of spatial ability; and 2) interacting with RMRobots can effectively improve the performance on a task related to spatial reasoning skills according to behavioral data and electroencephalograph (EEG) indices. Our presented study broadens RMRobot research in the area of human–robot interaction.**

***Index Terms*—Electroencephalograph (EEG), human–robot interaction, mental rotation, reconfigurable modular robots (RMRobots), spatial ability.**

I. Introduction

SPATIAL ability refers to human reasoning skills regarding how to understand, retain, retrieve, and generate the spatial relations among objects, which is built on human's basic memory of shape and position [1]. To measure the spatial ability, two widely used metrics are mental rotation and mental folding [2]. In this paper, we focus on mental rotation, which measures the speed and accuracy of rotating the mental representation of 2-D or 3-D objects, given that the objects' spatial relations remains unchanged in physical space [3].

Spatial ability strongly affects developments in science, technology, engineering, and mathematics (STEM) disciplines [4], [5]. For example, a large, 50-year study showed that spatial ability can effectively predict achievement and attainment in STEM [4]. Therefore, the study of spatial ability and how to improve it is of both theoretical and practical importance. In academia and industry, efforts to improve STEM achievement by improving spatial ability are continuous [6]. The basic hypothesis is that spatial ability is sufficiently malleable such that effective training can successfully improve spatial ability [7].

An elegant study was presented in [8] that compared the difference in spatial ability among nine-month-old infants. It was found that the infants who spent more time touching and manipulating physical objects possessed superior mental rotation abilities. This finding indicates that the capacity is present; however, it requires effort to exploit. Other studies (e.g., [7]) have also demonstrated that elaborately designed training can effectively improve spatial ability.

In this paper, by making use of a tangible interaction with a reconfiguration modular robot (RMRobot)—referred to as EasySRRobot [9] (Fig. 1)—which consists of edge-hinged modules (EHModules), we present a new, economically feasible training and testing scheme for improving human spatial ability. We study EHModules because they provided sufficient rotational degrees-of-freedom (DOFs). The EasySRRobot can provide even more rotational DOFs when multiple EHModules are connected. When providing with multiple rotational DOFs, in this paper we show that the EasySRRobot is a good physical prototype that can be used as an effective training tool for mental rotation tests. Two user studies were conducted in which we collected and analyzed participants' electroencephalograph (EEG) and behavioral data. The comprehensive study presented in this paper improves our preliminary conference work [9], [10] in two aspects and makes the following contributions.

1) We present a comprehensive summary of related work, showing how this paper relates to and differs from traditional interactive technologies, tangible user interfaces (TUIs), and neural mechanism studies.
2) The experimental results in this paper indicate that: a) the task performance of interacting with the EasySRRobot has a significant positive relationship with

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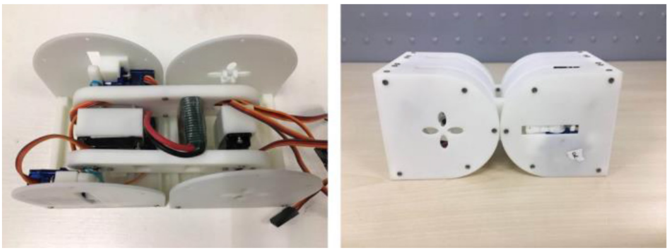

Fig. 1. Physical prototype of the EasySRRobot. The interior structure (left) and the outmost shape (right) of the module.

mental rotation; b) for a transformation task related to spatial ability, human performance can be significantly improved by our training scheme, i.e., tangible interactions with the EasySRRobot; and c) after training using tangible interactions with the EasySRRobot, the EEG alpha power is significantly suppressed while the participants are engaged in these tasks, which are consistent with the results from previous research [11] that shows the level of suppression of the alpha activity is positively related to the cognitive resources invested in the mental rotation task.

The subsequent sections of this paper are organized as follows. We present a comprehensive summary of the related work in Section II. The interaction with the EasySRRobot that is necessary for use in spatial ability training is presented in Section III. The first user study that explores the relationship between interacting with the EasySRRobot and the mental rotation performance is described in Section IV. The transformation task and its performance in the second user study, which shows interactions with the EasySRRobot can effectively improve spatial ability are presented in Section V. Finally, Section VI discusses the major findings and Section VII summarizes our concluding remarks.

II. Related Work

A. Traditional Spatial Skill Training Methods

The training program for spatial skills has been divided into three mutually exclusive categories [7]. The first category trains an individual on spatial tasks by means of specific practice, rehearsal, or reading an instruction document, and is often performed in a laboratory setting. The experimental group is provided with repeated exposure to the stimulated materials in a specific spatial test. The training time in this category is typically brief.

The second category trains an individual by offering courses that focus on spatial skills' development, and the training time may vary, ranging from weeks to a year. Usually, the courses taken in the second category last for one or two semesters (e.g., the courses of engineering graphics, computer graphics, geology, astronomy, etc.) By enrolling in these courses, the participants are trained to develop critical spatial thinking and reasoning capacity.

Investigators have argued that the two traditional training programs mentioned above may only lead to marginal improvement of spatial skills, because the measures in the test phase are very similar to the training task [12]. It has been suggested that these two traditional spatial training programs may not cover all aspects of spatial skills that are used when humans work in 3-D physical space [13]. Moreover, the U.S. National Research Council (NRC) raised an issue about the generality of training effects and pointed out that an effective training should have the ability to transfer the improved spatial ability to untrained skills. The development of trainings with this generalizable goal is much more challenging and has not been fully exploited [1]. Accordingly, a third, better training category that makes use of active exploration of the real physical world (through an elaborate and flexible physical embodiment) is strongly desired [14].

B. Interactive Technologies

Because of the recent development of human–computer interactive technologies [e.g., video, augmented reality (AR), and modular robots], the last category of the training programs is focused on using these interactive technologies to administer trainings [15], [16].

Video game training involves playing action video games which require practiced spatial and visual skills [17], [18]. In these studies, four experiments were presented to compare experienced video-game players with nonvideo game players, and changes in different aspects of visual attention have been observed. A fifth experiment showed that when comparing with their pretraining abilities, players trained on an action video game achieved a notable improvement. Furthermore, Green and Bavelier [19] found that action-video game playing can effectively improve a wide range of visual skills.

Emerging technologies, such as AR and virtual reality (VR), provide more tools and new methods to study spatial skills [13], [14], [20]. Research in this new direction can be broadly classified into two classes. The first class focuses on investigating how general spatial ability can be improved by using these new technologies (e.g., [14]). The second class is the study of specific characteristics of spatial ability for which AR/VR is desired for efficient training (e.g., [21]). In particular, Dünser *et al.* [14] summarized studies that apply AR/VR technologies to explore different characteristics inherent in spatial ability. It was concluded that AR/VR is useful for developing effective tools for training spatial ability directly in 3-D space.

C. Tangible User Interface

In addition to virtual interfaces, such as video games and AR/VR, a TUI is an alternative for promoting spatial skills. The core idea is to represent data with physical objects and enable users to manipulate the data by manipulating the objects directly [21]. Preliminary work with empirical studies has been conducted to explore the effect of TUIs on a human's spatial cognition. It was found that interacting with TUIs could effectively compensate for a user's low spatial cognition while learning the operation of an anesthesia machine [22]. Kim and Maher [23] revealed that TUIs could improve the spatial cognition of designers that were associated with creative design processes.

Block building is one TUI. In particular, block building provides an interesting route for investigating and training spatial skills. Generally, blocks can be played in two ways. The first way is free play, in which individuals can build any model of blocks they would like to build [24]. The second way is structured block play, in which individuals are instructed to complete a particular design by following a given model [25]. Both methods of playing with blocks can evoke distinct cognitive processes: the first method invokes an individual's imagination and creativity to develop comprehensive relations without any hints, while the second method calls on the ability to understand and remember a given spatial relation for building a predefined model. Furthermore, structured block play can be used to develop spatial skills in many aspects, such as the part-whole relationship, symmetry, balance, transformation, measurement, etc. [27]. It has been demonstrated that training in block playing enhances both behavioral performance and spatial-processing-related brain activation as measured by functional magnetic resonance imaging (fMRI) [26].

D. Human–Robot Interaction

Another way of utilizing a TUI is through a human–robot interaction, which has recently raised substantial concerns [27]. Human–robot interaction opens up new possibilities for spatial understanding and reasoning. Compared with static building blocks, robots can be reconfigurable or move autonomously. This ability allows humans to interact with robots dynamically in new extrinsic spatial arrangements, while with building blocks, human can only distinguish between different intrinsic characteristics of static spatial relations.

In robotic research, RMRobots represent a special type of robot that can change their shape through the changing of module arrangements [28]. This type of robot consists of modules, each of which independently encapsulates a simple function and can communicate with each other. The shape of an RMRobot is determined by the positions and orientations of all of its modules. Complex tasks can be completed through the collaboration of connected modules. Compared to other fixed-body and monolithic robots, RMRobots can change their shape and functionality in response to a change in the environment or task; thus, reconfigurable modular robots have received substantial attention in recent years from both academia and industry because of their versatility and flexibility [29].

Many types of RMRobots exist, e.g., edge-hinged and central-point-hinged. In this paper, we focused on the edge-hinged RMRobot, in which each module consists of two edge-linked semi-cylindrical cubes. In an EHModule, the link that connects the two cubes is realized by a double-hinge with two axes of rotation [30]. With this hinge, one semi-cylindrical cube can rotate in a range of $[0, \pi]$ with respect to the other semi-cylindrical cube. By connecting multiple modules via mechanical or magnetic connectors, RMRobot can provide more rotational DOFs.

E. Neural Mechanism

The neural mechanisms that underlie the task of spatial ability tests have been investigated. fMRI studies [31], [32] indicated that when performing mental rotation, there was significant activation in the parietal cortex and premotor and supplementary motor areas of the brain.

EEG studies found that mental rotation resulted in: 1) brain activation over the left premotor area [33] and 2) a marked negative event-related potential (ERP) component over the right frontocentral area [34].

A comparison of the enhanced synchronization pattern and the resting conditions during mental rotation were performed in [35], in which several noteworthy EEG features in the frequency domain were identified: 1) phase synchrony was increased among the frontal areas (F3, Fz, F4), parietal areas (P3, Pz, P4), and posterior temporal areas (T5, T6); 2) the posterior temporal areas (T5, T6) showed strong synchrony with the midline electrodes (Cz, Fz); and (3) the connections from frontopolar (Fp1, Fp2) to frontobasal (F7, F8) were enhanced.

Another EEG study showed that: 1) the right frontal lobe mediated the encoding, comparison and decision processes and 2) the left parietal and temporal regions were involved in generating images and mentally rotating these images [36]. Moreover, the alpha power (8–12 Hz) was recorded over the frontal, occipital, parietal, and temporal lobes of both the left and right cerebral hemispheres, when participants matched 3-D shapes to a prespecified target by mental rotation. The results indicated that: 1) when the participants were engaged in the tasks related to mental rotation, the alpha power was suppressed and 2) the duration of suppression increased with the task difficulty of the mental rotation [37]. Therefore, the level of suppression on the alpha activity can indicate the amount of cognitive resources invested in a mental rotation task [38]. This paper shows that after training by interaction with RMRobots, lower alpha activity in the left frontal area was identified. Our EEG results consistently showed that spatial ability, such as understanding and reasoning among complex spatial relations can be effectively improved by tangible interaction with RMRobots.

F. Current Study

In conclusion, robots have the same advantages and types of play as blocks. Compared with blocks, robots can transform themselves automatically. Furthermore, the shape change of robots is more efficient and quicker than manually building and dismantling blocks. As a result, the use of robots will lead to a fluent interactive experience for users. However, to the best of our knowledge, no research has been reported to explore the role of robots on improving users' spatial ability measured by mental rotation. Therefore, in this paper, we choose the RMRobot as a training tool to study spatial ability. To the best of our knowledge, this is the first time that RMRobots are used to enhance human spatial ability through tangible interactions.

To test the validity of using the RMRobot as a training tool to improve spatial ability, we chose a representative traditional training method (i.e., reading instructional materials) from the first category as the baseline and propose a novel

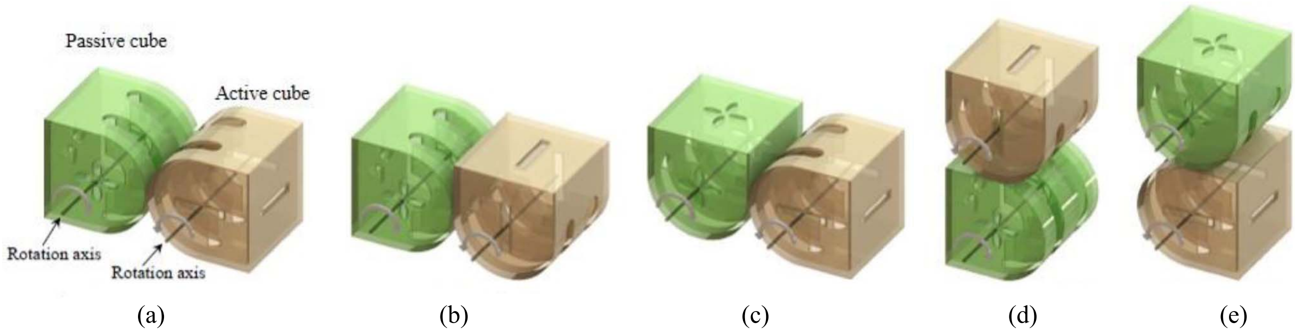

Fig. 2. Four possible rotations of an EHModule in the EasySRRobot. The figures are rendered in semi-transparency and rotation axes are drawn with dashed-dotted lines. We use different colors to render the active and passive cubes. (a) One EHModule consists of one active cube (yellow) and one passive cube (green). Each cube can independently rotate around its axis in the range of $\pm 90°$. (b) Active cube rotates around its own axis by 90°. (c) Passive cube rotates around its own axis by $-90°$. (d) Active cube rotates around the axis of the passive cube by 90°. (e) Passive cube rotates around the axis of the active cube by $-90°$. See accompanying video for more details.

training method from the last category (i.e., physical exploration and interaction with the RMRobots). Our user studies show that training through interactions with the RMRobots achieves significantly better performance, i.e., the same accuracy with less time to correctly complete a transformation task. We also find that interacting with the RMRobots could effectively improve the performance of a spatial reasoning task according to both behavioral data and the EEG indicators.

III. Tangible Interaction With EHModules

We chose EasySRRobot [9] as a physical prototype of the EHModules (Fig. 2). Each EHModule in EasySRRobot has two semi-cylindrical cubes connected by a link, and each cube can rotate independently, i.e., each cube can rotate around two axes: 1) its own axis and 2) the axis of the other cube. With the aid of mechanical connectors, multiple modules can be connected to provide more rotational DOFs. Refer to the accompanying demo video for more details.

To implement the self-reconfigurable function, each EHModule encapsulates the following onboard components: a battery (Li-Po7.4v, 500 mAh), two HX1218D servomotors (driving the rotations of two cubes), three SG90 servomotors (driving mechanical connectors), ATmega328P CPU (micro-processor), an nRF24L01transceiver IC, and an HC-05 Bluetooth module (intermodule communications).

We consider two settings in the interaction design: one setting is to use one EHModule and the other setting is to use two connected EHModules. Although it is possible to use more EHModules, we start with simple configurations such that the experimental tasks and results are controllable.

In the above two settings, the number of rotational DOFs can be computed as follows. For the first setting with one EHModule, each of its two cubes can rotate around two axes: 1) its own axis and 2) the axis of the other cube [Fig. 2(a)]. Therefore, this setting has $2 \times 2 = 4$ types of rotations [Fig. 2(b)–(d)].

Two EHModules can be connected via mechanical connectors, which differentiates the two cubes in a module [Fig. 2(a)].

1) *Active Cube:* From slits on the planar faces, hooks can extend to latch the passive cube in the other EHModule.
2) *Passive Cube:* Through the hook cavities on the planar faces, hooks from the active cube in another EHModule can latch into the faces.

In the second setting, there are three different ways to connect two EHModules, according to how the connection is established between faces (two side planes and one top plane) on the active/passive cubes. Since each EHModule has four rotation DOFs, a total of $3 \times 4 \times 4 = 48$ rotation DOFs can be provided by two EHModules (Fig. 3).

There are two ways for users to tangibly interact with EHModules.

1) Automatically transform EHModules between different configurations, using the touch screen in a mobile phone as a tangible interface for sending instructions to the modules through the HC-05 Bluetooth device.
2) Directly treat the cubes in the modules as a tangible interface and use hands to hold and rotate them. Each cube can be rotated independently in any angle between $[0, \pi]$. The two HX1218D servomotors assembled at the ends of the link can support cubes in a specified angle.

Compared with the traditional training method (i.e., reading instructional materials), the physical nature of tangible interactions with the EHModule has distinct advantages for spatial learning. First, the constant visual representation of the EHModule object in the automatic reconfiguration process provides immediate feedback regarding the transformation performed. Learners thus have an increased cognitive capacity to reason and understand the process of the transformation. Second, haptic feedback can also facilitate learners to recall and mentally reconstruct the transformation process. Both aspects are essential to promote an individual's spatial ability.

IV. User Study I

The first user study was performed to explore the relationship between performance of the interaction with the EHModules and the spatial ability. Several spatial ability tests exist, such as the 3-D mental rotation tests proposed by Vandenberg and Kuse [39] and the Purdue spatial visualization test [40]. In this paper, we chose a shorter version (20 items) of the Purdue visualization of rotations (ROT) test [40], [41]. The ROT test has been widely used to measure

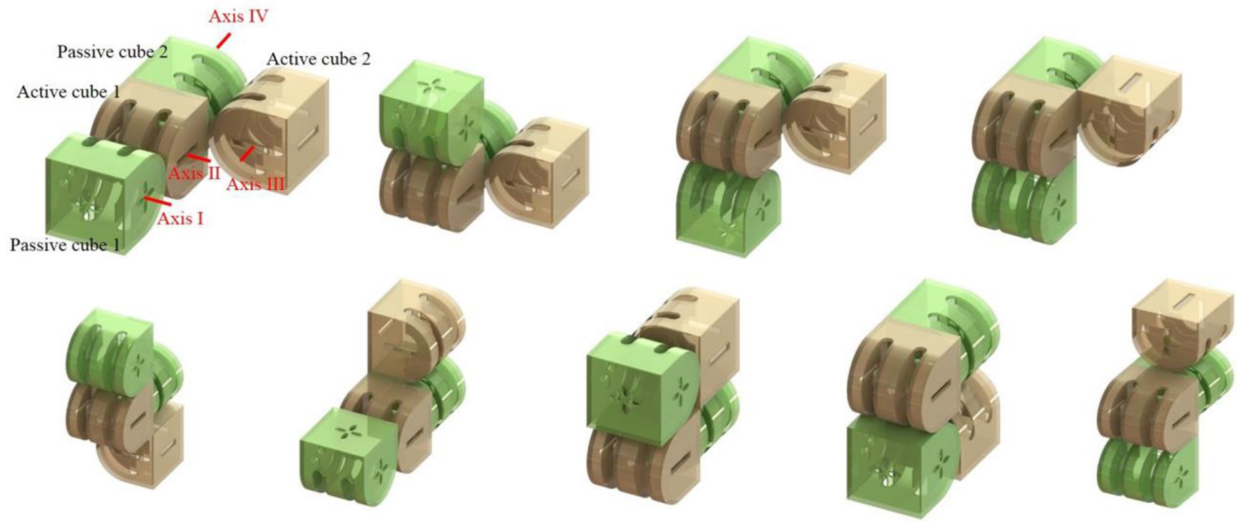

Fig. 3. There are three different ways to connect two EHModules. Since each EHModule has four rotation DOFs, a total of 3 × 4 × 4 rotation DOFs can be provided for users to interact with the two EHModules. One way to connect the two EHModules (top-left) and their nine possible rotations are illustrated in this figure. See accompanying video for more details.

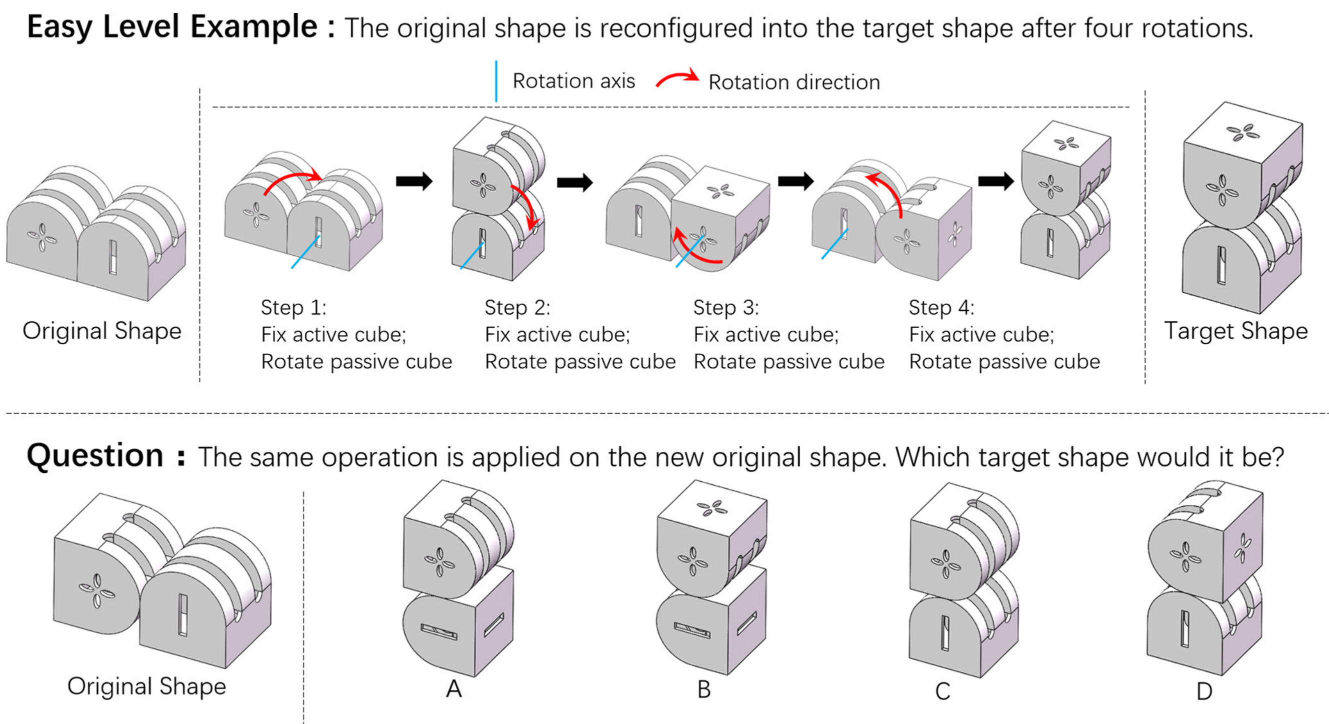

Fig. 4. One example of the easy-level tasks. Participants were presented with a pair of drawings of a single module. The top row shows a 4-step transformation of the module. The bottom row is the question that participants need to answer, i.e., find the correct target shape by applying the same rotations shown in the top row to reconfigure a new original shape. See accompanying video for all tasks.

spatial ability in educational research (in particular, for the academic disciplines of STEM). Therefore, in this section, we present a user study on the relation between the ROT test and the performance of a task by interacting with EHModules.

A. Participants

Twenty-four volunteers with normal or corrected-to-normal visual acuity and hearing took part in this user study. The average age of the participants was 24.1 years (range = [19], [34], SD = 3.53 years). No participants had a background in interacting with or using EHModules.

B. Transformation Task

As shown in Figs. 4 and 5, a pair of drawings of the EHModules were presented in each trial. An example was shown in the upper part, in which an original shape was reconfigured into a target shape by a certain number of rotations.

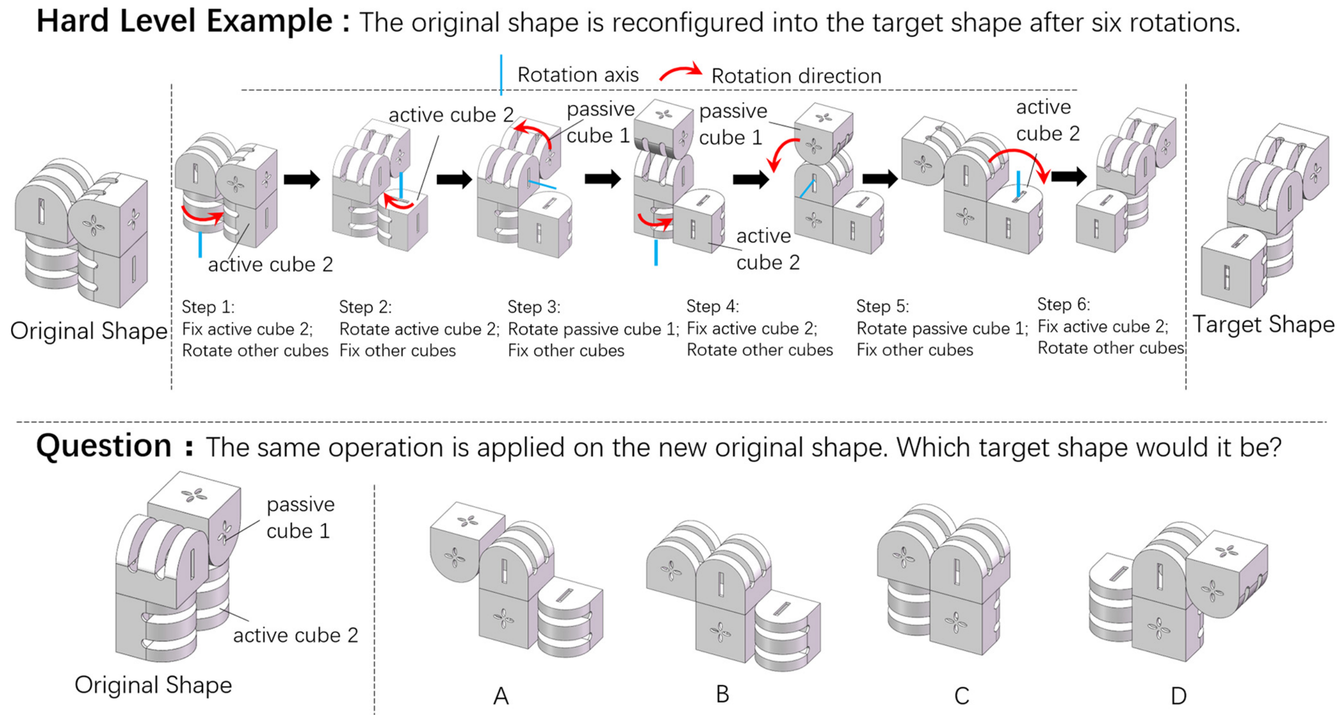

Fig. 5. One example of the difficult-level tasks. Two connected modules are involved with 6-step transformation. The task is the same as the easy level (Fig. 4). Refer to accompanying video for all tasks.

The participants were then instructed to select a correct target shape in the lower part, which is reconfigured from a new original shape by the same operations provided in the upper example.

All participants were required to complete ten transformation tasks, of which half of the tasks were easy and the other half were difficult. In the five easy tasks, there was only one EHModule that can reconfigure an original shape into a target shape with 2–4 rotations. In the five difficult tasks, two connected EHModules were applied, and the target shape was achieved with 3–6 rotations.

C. Experimental Procedure

After signing a consent form, each participant subsequently completed the ROT test. The ROT has 20 items that consist of 2-D isometric drawings of 3-D objects (e.g., cubes or cylinders). The participants were asked to mentally rotate an object in the same direction as the sample case and select the correct answer among five options.

After the ROT tests, the participants completed a 10-min practice session to become familiar with the EHModules. The participants were subsequently instructed to complete ten successive transformation tasks as quickly as possible on the premise of ensuring the accuracy. The operation order was counterbalanced to avoid a potential confounding effect. A 27-in LED screen with a 1680 × 1050-pixel resolution was used to present tasks. Participants sat approximately 60 cm from the screen. The entire experiment lasted for 1–1.5 h, and the participants were paid RMB ¥50/h.

D. Results

Three behavioral responses—the time to completion (TTC), the time to correct completion (TTCorrect), and the correct rate (CR)—were recorded in this paper.

1) The TTC represents the time spent (in seconds) that a participant completed a transformation task. If a participant spends x seconds to complete all ten tasks, then the TTC is equal to $x/10$.
2) The TTCorrect measures the average time (in seconds) for a participant to correctly complete a transformation task. Thus, in all ten tasks, if a participant correctly answers $a = 10$ tasks and the total time spent on these a tasks is T', the TTCorrect equals T'/a. If $a = 0$, TTCorrect is assigned to a very large value, e.g., 10^6.
3) The CR represents the percentage of correct answers in all tasks. Note that wrong answers occurred when the participant failed to complete a transformation task or chose a wrong answer.

First, paired-sample T-tests were performed between the easy and difficult task levels. The results showed that there were significant differences between the easy and difficult task levels for the TTC ($t(23) = -8.93$, $p < 0.001$), TTCorrect ($t(23) = -7.59$, $p < 0.001$), and CR ($t(23) = 4.03$, $p = 0.001$). These findings indicated that the participants spent more time to complete ($M = 220.53$, SD $= 95.37$ s) and to correctly complete each difficult task ($M = 193.8$, SD $= 88.48$ s) with lower CRs ($M = 65.8\%$, SD $= 15.01\%$) than the easy task level ($M = 71.53$, SD $= 25.74$ s for TTC; $M = 70.18$, SD $= 25.06$ s for TTCorrect; $M = 85.8\%$, SD $= 19.98\%$ for CR).

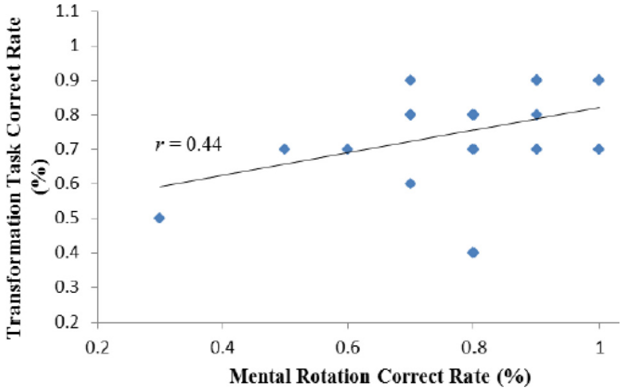

Fig. 6. Significant correlation between mental rotation test score and the CR of the transformation task.

Second, bivariate correlations were performed to examine the relationship between the ROT test and the task performance. The results showed that there was a significantly positive relation between the ROT test score and the CR of the transformation task ($r = 0.44$ and $p = 0.034$) (Fig. 6).

E. Discussion

These results indicated that two levels of difficulty settings were effective. The task performance by interacting with the EHModules was positively related to mental rotation skills. A higher task performance indicates a better mental rotation score and vice versa. Given these findings, it is interesting to further investigate whether mental rotation skills can be enhanced by improving the task performance by interacting with the EHModules. Therefore, another user study was performed to test whether spatial ability, particularly the performance of mental rotation, can be enhanced through training with the EHModules according to the behavioral measurements and EEG features that are related to mental rotation.

V. User Study II

According to the results of the ROT test, which was the same test used in User Study I, the participants were divided into two groups. The experimental group was trained by interacting with the EasySRRobot. As a comparison, the control group was trained by reading an instruction document (Section V-C). Before and after the training, the participants were tested with respect to their spatial abilities via a transformation task, during which the participants were instructed to transfer the learned instance to a new instance.

The requirement of this transformation task applied in this user study was the same as User Study I, which has been proven to be a good indicator of participants' spatial ability based on the results of User Study I. When the participants experienced the task, their behavioral and EEG data were collected (Section V-D). The experimental results showed that after training by interacting with the EasySRRobot, the performance of the transformation task was improved, and the improvement was substantially better than the traditional training of reading an instruction document (Section V-E).

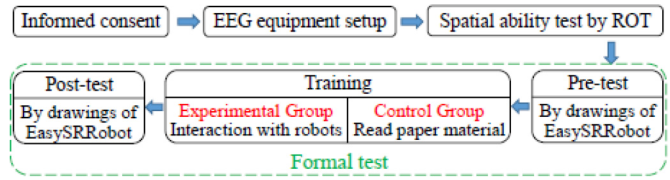

Fig. 7. Experimental procedure in User Study II.

A. Participants

Eighteen volunteers were selected to engage in the second user study, whose average age was 24.33 years (range = [19], [34], SD = 3.93 years). In addition to the screening criteria in User Study I, all participants were required to not have a history of neurological or psychiatric illness and to avoid taking specific medications that may affect the central nervous system.

B. Experimental Procedure

The overall flowchart of the second user study was illustrated in Fig. 7. After signing a consent form, the participants were seated in an electrically shielded room. Two experimenters assisted each participant to set up an EEG cap. Ten active electrodes within the standard international 10–20 system were used. Another four electrodes were fixed above and below the left eye and placed 10 mm from the outer canthi of both eyes to capture ocular artifacts (e.g., eye blink and movement). The EEG data were digitized at 500 Hz.

Before the formal experiment, the participants completed the ROT test to evaluate the level of their spatial ability. According to the ROT test results, the participants were partitioned into the two groups (experimental versus control group) to ensure that the participants in two groups had the same level of ROT test results. A 2×2 mixed design was used with the training group (i.e., with versus without training through interaction with EasySRRobot) as a between-subjects variable and the test session (i.e., pretest versus post-test) as a within-subjects variable. The formal experiment consisted of three consecutive sessions: 1) pretest; 2) training session (Fig. 8); and 3) post-test. Both pre- and post-tests consists of ten transformation tasks that were the same as User Study I and were the same for the two groups but differed between the pre- and post-test (two set sessions had the same task difficulty). Task performance between the pre- and post-test was expected to elucidate the training effects. Other experimental settings (screen resolution) and requirements (operation order and speed–accuracy tradeoff) were the same as the first user study. The entire experiment lasted for 2–2.5 h, and each participant was paid RMB ¥80/h.

C. Data Acquisition and Analysis

Continuous EEG signals were recorded and processed using SCAN 4.5 software. A 0.1–45-Hz bandpass filter was used to filter the EEG signals and a regression procedure proposed in [41] was used to remove eye blinks and movement from the filtered data. Because the left mastoid was used as an online reference for all channels, artifact-free EEG data were

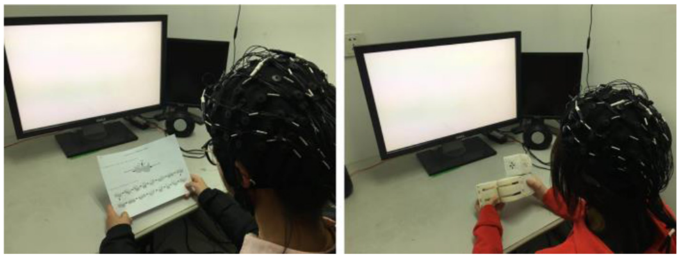

Fig. 8. Training by (left) reading an instruction document and (right) interacting with the EasySRRobot.

rereferenced to the average of the left and right mastoids [42]. Rereferenced EEG data were segmented into several epochs that ranged from the onset of each transformation task to the time when an individual gave the answer. According to the previous EEG studies on mental rotation as mentioned in the related work section, power values within the EEG alpha band (8–12 Hz) were extracted for ten channels (F3, F4, Fz, F7, F8, FCz, Cz, P3, Pz, and P4). We measured the power values of experiencing the transformation tasks. By subtracting the power values of the resting period, these values were normalized to the range [0, 1] [43].

Three behavioral responses—TTC, TTCorrect, and CR—were recorded in the pre- and post-test sessions, which were computed in the same way as User Study I.

D. Results

In terms of the accuracy of the ROT test for mental rotation, there was no significant difference between the experimental group ($M = 0.83$, $SD = 0.11$) and the control group ($M = 0.79$, $SD = 0.13$). This result ensured that the spatial ability (i.e., mental rotation skills) of the two groups was at the same level prior to performing the training and the transformation tasks.

A repeated measures analysis of variance (ANOVA) was performed to examine the training effects on three behavioral measures between the two groups. The interaction between the group and the testing session was significant for the TTCorrect ($F(1, 16) = 7.09$, $p = 0.017$) As shown in Fig. 9, after training through interacting with the EasySRRobot, the experimental group spent less time (30.76% improvement in the TTCorrect) to correctly complete a transformation task ($M = 93.09$, $SD = 29.18$ s). In contrast, the control group only improved their correct completion time by 1.54% after training through reading the instruction document. There was no significant difference between the two groups or the two testing sessions for this measure. Furthermore, between the two groups or the two testing sessions, no significant difference in the CR and TTC was observed.

Another repeated measures ANOVA was performed to examine the EEG indices that were sensitive to the transformation of EHModules. The interaction between the group and the testing session was significant for the normalized alpha power at the Fz electrode ($F(1, 16) = 5.11$, $p = 0.038$). As illustrated in Fig. 10 and Table I, after training by interacting with the EasySRRobot, the alpha activity in the frontal area was clearly suppressed (16.48% suppression) while the experimental group was experiencing the transformation task. As a comparison, when the control group was experiencing the same task after training through reading the instruction document, the alpha activity in the frontal area remained at a similar level. Moreover, there was no significant difference between the two groups or the two testing sessions for this measure. No significant difference was observed for this measure in the midline or parietal areas.

Because of the significant interaction between group and testing session at the Fz electrode size, the asymmetric alpha activity in the frontal areas was further explored. The

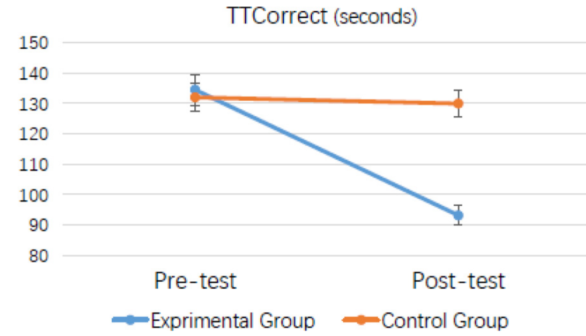

Fig. 9. Significant group × testing session interaction for the TTCorrect. Error bars indicate ±1 standard error.

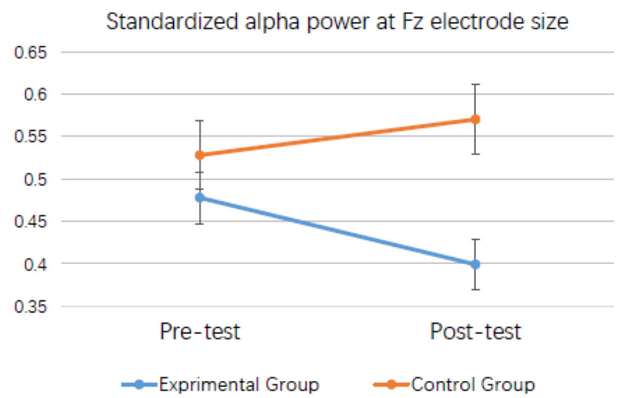

Fig. 10. Significant interaction between the group and the testing session for the mean normalized alpha power at the Fz electrode. Error bars indicate ±1 standard error.

TABLE I
NORMALIZED ALPHA POWER (MEANS AND STANDARD DEVIATIONS) OF EEG SIGNALS AT TEN ELECTRODE SITES

Site	Normalized alpha power			
	Before Training		After Training	
	Experimental group	Control group	Experimental group	Control group
F3	0.487(0.272)	0.546(0.322)	0.441(0.261)	0.560(0.360)
F4	0.527(0.298)	0.551(0.341)	0.573(0.206)	0.654(0.244)
Fz	0.478(0.275)	0.527(0.364)	0.400(0.263)	0.570(0.373)
F7	0.527(0.309)	0.560(0.281)	0.446(0.135)	0.582(0.320)
F8	0.488(0.260)	0.656(0.297)	0.405(0.260)	0.697(0.298)
FCz	0.452(0.250)	0.468(0.358)	0.456(0.237)	0.511(0.365)
Cz	0.432(0.271)	0.467(0.257)	0.453(0.245)	0.535(0.293)
P3	0.489(0.246)	0.510(0.246)	0.471(0.276)	0.595(0.253)
P4	0.401(0.275)	0.539(0.287)	0.406(0.248)	0.560(0.314)
Pz	0.474(0.240)	0.569(0.225)	0.452(0.232)	0.622(0.267)

frontal alpha asymmetry was computed by subtracting the values of mean alpha power in the left hemisphere (F3 and F4) from the values of mean alpha power in the corresponding right hemisphere (F7 and F8) [42], [43]. For the normalized alpha power asymmetry at (F3 and F4), the main effect of the testing session was significant ($F(1, 16) = 6.99$, $p = 0.018$). This result indicated that after training, lower alpha activity was observed in the left hemisphere than that in the right hemisphere when the participants were experiencing the transformation of the EHModules. Moreover, between the two groups, there was no significant difference in this measure. Between the two groups or the two testing sessions, there was no significant difference for the normalized alpha power asymmetry at (F7 and F8).

E. Discussion

In User Study II, no significant findings were observed in the CR and the TTC. One possible reason was that the participants were required to complete the transformation of the EHModules as quickly as possible on the premise of ensuring the accuracy. On the other hand, between the pre- and post-test, the experimental group showed significant difference in the TTCorrect. This difference was not observed in the control group. Based on these findings on both speed and accuracy, we concluded that training through interacting with the EasySRRobot can enhance the transformation performance of the EHModules to a certain extent.

Additionally, in User Study II, we observed lower alpha activity in the left frontal area after the participants in the experimental group were trained through interacting with the EasySRRobot. One possible explanation was that because these participants achieved the same accuracy with less time to complete a transformation task, they may experience more difficult transformation tasks. As indicated in the EEG literature, the increase in task difficulty suppresses the alpha activity [37]. The participants in the experimental group may have invested more cognitive resources in the processes of mental imagery, comparison, and decision making [36]. Tangible interaction with the EasySRRobot might help participants to distinguish the intrinsic characteristic between active and passive cubes and to interact with them in extrinsic spatial understanding, reasoning, and arrangements. Therefore, the tangible interaction with the EasySRRobot opens up new possibilities for the improvement of human spatial ability.

VI. General Discussion

In User Study I, a significant positive correlation between the transformation performance and mental rotation skills was identified. In User Study II, the alpha activity in the frontal area of the experimental group was significantly suppressed (especially in the left hemisphere) after training with robots compared to the control group, although no significant behavioral differences were found. Based on the current findings in User Studies I and II, we expect that mental rotation skills, as well as other aspects of spatial ability, can be improved by training through interacting with the EasySRRobot [10]. Our future work will continue with the current training method through interacting with the EasySRRobot to enhance not only mental rotation skills but also extrinsic and dynamic spatial ability (e.g., navigation [44]).

However, there are still some limitations for this paper. First, this paper only explored the immediate improvement in spatial ability after interacting with EasySRRobot. A longer term effect needs further verification. Second, a further study would benefit from a larger sample size to characterize the role of demographic characteristics (e.g., age and gender) on mental rotation skills and training effects through interacting with the EasySRRobot.

VII. Conclusion

Reconfigurable modular robots have been widely investigated in robotic research with applications that ranged from adaptive locomotion to exploration with self-repairing abilities. In this paper, we presented a new application of reconfigurable modular robots in the field of human cognitive ability training. Two elaborate user studies were presented, showing that the tangible interaction with reconfigurable modular robots can effectively enhance the performance of the transformation task, which is positively correlated with mental rotation skills.

In this paper, to compare the interactive training through reconfigurable modular robots with a traditional training program, the participants were divided into two groups. The experimental group was trained through interaction with the EasySRRobot. As a comparison, the control group was trained by reading an instruction document printed on paper. Before and after training, the spatial abilities of the participants were tested by transferring the learned instance to a new instance. Behavioral data and EEG signals were collected during the two testing sessions.

Both behavioral and EEG indices demonstrate that interaction with reconfigurable modular robots significantly enhances the transformation performance of the experimental group, i.e., 30.76% improvement in the TTCorrect and 16.48% suppression of the normalized alpha power. In contrast, the performance of the control group is marginally improved after training by reading an instruction document, i.e., only 1.54% improvement of the TTCorrect and higher alpha activity.

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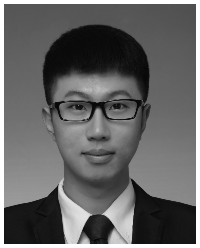

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