Spatial Ability Improvement by Tangible Interaction: A Case Study with EasySRRobot

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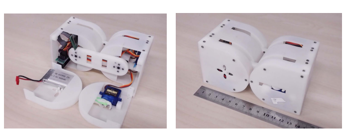
Abstract
Spatial ability is a category of human reasoning skills that plays an important role in affecting a person's development in science, technology, engineering and mathematics. Spatial ability has been demonstrated to be malleable and can be improved through training. In this paper, we present a training scheme by tangible interaction with a reconfigurable robot called *EasySRRobot*. A preliminary user study based on behavioral and EEG data analysis shows that via interaction with EasySRRobot, users can significantly improve their performance on a task related to spatial ability.

Author Keywords
Tangible interaction; spatial ability; reconfigurable modular robot; behavioral and EEG data.

ACM Classification Keywords
H.1.2 [User/Machine Systems]: Human factors

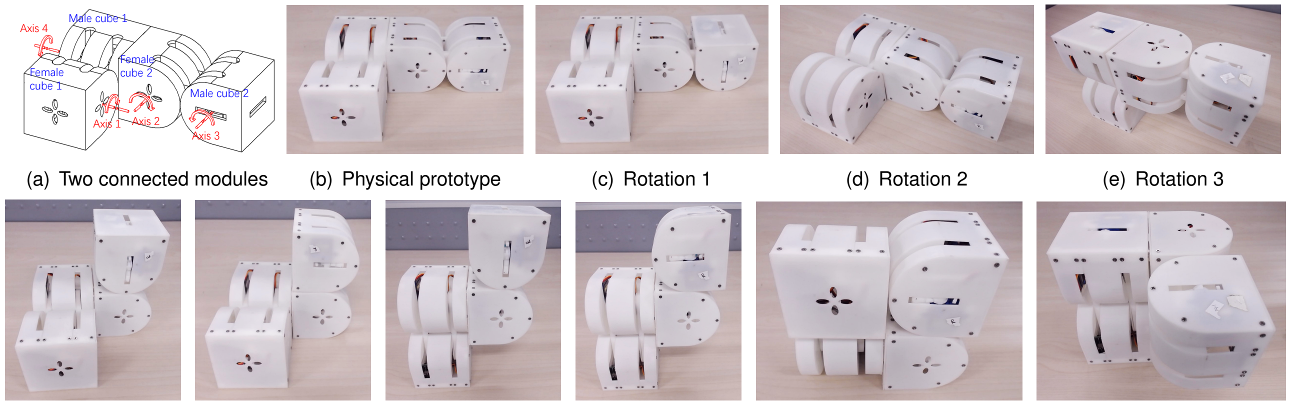
Introduction
Spatial ability (a.k.a. visuo-spatial ability) is a category of human capacity to understand, reason and remember the spatial relations among objects, which makes use of basic memory for shape and position [2]. Spatial ability of children or teenagers is highly correlated with their achievement in advanced science, technology, engineering and mathematics (STEM) [8].

EasySRRobot
EasySRRobot [9] is a type of self-reconfigurable modular robot that can change their shapes according to different tasks. Such a robot consists of edge-hinged modules (Figure 2). Each module has two linked cubes and each cube can rotate independently. Two or more modules can be assembled together using mechanical connectors. To implement these functions, the on-board components in each module include actuators (two HX1218D servomotors for cube rotation and three SG90 servomotors for mechanical connectors), micro-processors (ATmega328P CPU), inter-module communications (a HC-05 bluetooth module and an nRF24L01 transceiver IC), and a battery (Li-Po7.4v 500mAh).



(a) Interior (b) Overall

Figure 2: Interior structure (a) and overall shape (b) of EasySRRobot.



(a) Two connected modules (b) Physical prototype (c) Rotation 1 (d) Rotation 2 (e) Rotation 3

(f) Rotation 4 (g) Rotation 5 (h) Rotation 6 (i) Rotation 7 (j) Rotation 8 (k) Rotation 9

Figure 1: Two connected modules can support totally $3 \times 4 \times 4 = 48$ rotations and nine rotations are illustrated here. More details are in accompanying demo video.

Previous studies [7] showed that spatial ability can be improved by training. In this study, we focus on mental rotation which is widely used to evaluate spatial ability [4]. Existing training and tests on mental rotation are based on reading illustrations on printed material and imagining a mental rotation. As a comparison, in this project we present a novel training and test scheme through tangible interaction with a reconfiguration modular robot called *EasySRRobot* [9].

We choose EasySRRobot because its module can provide plenty of rotation degrees of freedom (DOFs). Furthermore, by connecting more modules, more rotation DOFs can be provided. These abundant rotation DOFs make EasySRRobot a good physical prototype as a training tool for mental rotation tests. This project presents an elaborated user study in which participants' behavioral and EEG data are collected. Our preliminary experimental results show that the performance on a transformation task related to spatial ability can be enhanced by training through tangible interaction with EasySRRobot, which is significantly better than traditional reading on printed material.

Methodology
Our hypothesis is that users could improve their spatial ability by directly manipulating the physical representation of the objects. This project studies the role of EasySRRobot in improving spatial ability using two module settings: an EasySRRobot with one module and an EasySRRobot with two connected modules. Although using more modules is possible, we deem that it is appropriate to start from simple configurations, which ensures the experimental task to be not over-complicated for the users and makes the experimental results more controllable.

The rotation DOFs provided by these two settings are as follows. Given one module, each of two cubes can rotate around its own axis or the axis of the other cube, and therefore, can support $2 \times 2 = 4$ types of rotations. Two mod-

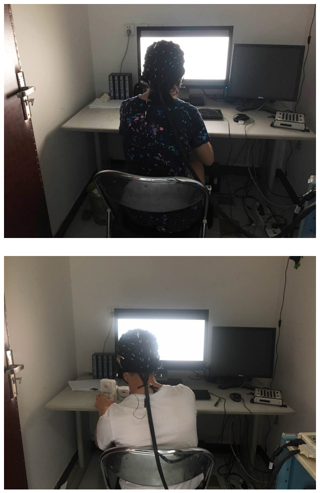


Figure 4: Training by (top) reading a printed material and (bottom) interacting with EasySRRobot. Participants put on an electrode elastic cap (Neuroscan Inc., Charlotte, NC) with 64 active electrodes.

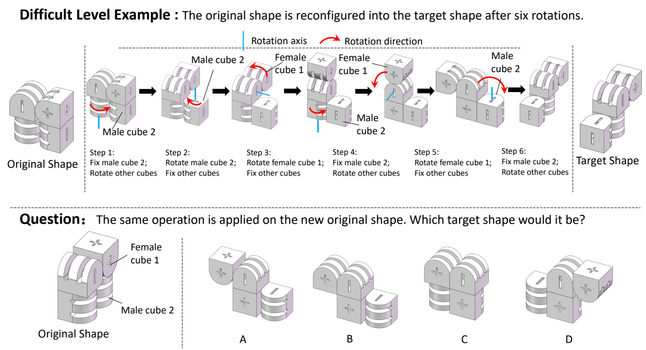


Figure 3: An example of the task at difficult level, in which two connected modules are involved. More examples are in accompanying demo video.

ules can be connected in three different ways, according to the faces between which the connection is established. Given that each module supports four different rotations, users can interact with two modules by realizing totally $3 \times 4 \times 4 = 48$ rotations (Figure 1).

Users can interact with EasySRRobot in two ways:

- the robot changes shape autonomously according to different levels of tasks (easy or difficult) and a user observes the transformation process;
- a user holds the cubes and interactively rotate them.

User Study

Measure of spatial ability

This project chose the Purdue visualization of rotations (ROT) test [1], which is one of the most commonly used measures of spatial ability and is suitable for testing individuals who are at least thirteen years old.

Transformation task description

Participants were presented with pairs of drawings of EasySRRobot (ref. Figure 3). In each pair, the upper item shows a reconfiguration of EasySRRobot with given rotations, i.e., an original shape of an EasySRRobot is reconfigured into a target shape and this transformation is achieved by applying given rotation operations. The lower item is the question to be answered, i.e., by changing the original shape and applying the same rotations as in the upper item, the participants were asked to choose the correct target shape.

There were 20 successive tasks (10 easy and 10 difficult). Easy level only involved one module and difficult level involved two connected modules. Tasks were presented at the center of a 27-inch LED screen with a recommended 1680×1050 pixel resolution. The screen was located 60cm from the participants' eyes. All participants were instructed to complete the tasks as quickly as possible on the premise of ensuring the correct rate.

Participants

18 undergraduate and graduate students (9 males and 9 females) were selected to take part in this user study. Their ages ranged from 19 to 34 years old ($average = 24.33$, $SD = 3.93$). They were screened to ensure that

- They had normal or corrected-to-normal visual acuity and hearing and;
- They did not have any background for interacting with and make use of reconfigurable modular robots.

The experiment was conducted with the informed written consent of each participant and was approved by the Institutional Review Board of the Institute of Psychology at the Chinese Academy of Sciences.

Experimental procedure

Upon arrival, each participant put on an EEG cap with the assistance of two experimenters. Prior to the formal test, each participant went through a ROT test for evaluating his/her spatial ability. Then participants were partitioned

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

Table 1: Mean and standard deviation (in bracket) of normalized alpha power of EEG signals at 10 electrode sites.

into two groups (namely experimental group and control group) and the ROT test results of two groups were ensured at the same level.

We used a 2×2 mixed design with group as a between-subject variable (i.e., experimental group and control group are with and without training by interaction with EasySR-Robot respectively) and testing session as a within-subject variable (pre-test vs. post-test). Each participant completed three consecutive sessions: a transformation task (i.e., pre-test), training session, and another transformation task (i.e., post-test). The pre-test and post-test were the same for two groups of participants. All participants were instructed to complete 10 successive transformation tasks (5 easy and 5 difficult) for examining the effect of training. To avoid a potential confounding effect, the operation order was counterbalanced in both pre- and post-test. During the training session, the experimental group was required to interact with EasySRRobot for familiarizing themselves with the rotation rules in EasySRRobot, while the control group was required to learn by reading a printed material (Figure 4).

EEG acquisition
EEG data were continuously recorded from 64 active electrodes attached to an electrode elastic cap (Neuroscan Inc., Charlotte, NC). Electrode positions included the standard International 10-20 system locations and intermediate sites. The left mastoid was used as an online reference for all channels. The EEG data were digitized at 500 Hz.

The alpha power (8-12Hz) spectral features of the EEG signals on 10 channels were extracted and the results were summarized in Table 1. These 10 channels located in the frontal (F3, F4, Fz, F7, F8), midline (FCz, Cz), and parietal (P3, Pz, P4) areas. The power values when experiencing the transformation tasks minus the power values of the resting period, which was finally normalized to the range [0,1].

Results
We first examined the difference in the accuracy of ROT test to ensure that the spatial ability of two groups was at the same level before completing the transformation task. There was no significant difference in the accuracy of ROT test for mental rotation between two groups. The average accuracy was 0.83 ($SD = 0.11$) for the participants in the experimental group, while the average accuracy was 0.79 ($SD = 0.13$) for those in the control group.

Then we analyzed the differences in the transformation task performance between the pre-test and post-test sessions and between two groups. We found that the experimental group achieved better performance on the transformation task by interaction with EasySRRobot. Three behavioral responses, *time to completion* (TTC), *time to correct completion* (TTCorrect) and correct rate, were recorded:

- TTC measures the amount of average time (in seconds) that a participant spends to complete a transformation task.
- TTCorrect measures the amount of average time (in seconds) that a participant spends to correctly complete a transformation task.
- Correct rate measures the ratio of correct answers in all tasks.

We compared the training effects on TTC and TTCorrect between experimental and control groups. There was a significant $group \times testing\ session$ interaction for the TTCorrect ($F(1, 16) = 7.09, p = 0.017$) and a marginal significant $group \times testing\ session$ interaction for the TTC ($F(1, 16) = 3.65, p = 0.074$). As illustrated in Figure 5, the simple effect analysis showed that participants in the experimental group spent less TTCorrect time ($M = 93.09$, $SD = 29.18$) after the training through interacting with

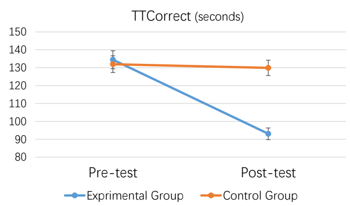


Figure 5: The comparison of training effects between experimental and control groups, in terms of time to correct completion (TTCorrect) in seconds. Error bars indicate one standard error.

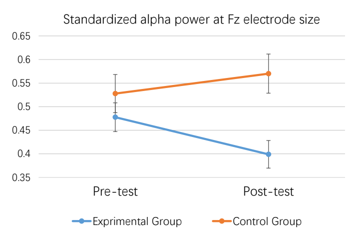


Figure 6: The comparison of training effects between experimental and control groups, in terms of the mean standardized alpha power at the Fz electrode size, which is an important index in EEG correlates of mental rotation. Error bars indicate one standard error.

EasySRRobot, resulting in a 30.76% improvement in the TTCorrect. As a comparison, after training through reading printed material, in the control group the improvement in TTCorrect was only 1.54%. Neither the main effect of group nor the main effect of testing session was significant for the TTCorrect. The simple effect analysis of the $group \times testing\ session$ interaction showed the similar pattern for the TTC. Moreover, there was no significant difference in the correct rate between two groups or between two testing sessions.

In addition to behavioral indices, EEG correlates of mental rotation were also analyzed to examine the neural mechanism underlying the transformation task. Previous study revealed that the suppression of alpha power increased with the task difficulty [5]. We found that when the experimental group completed the transformation task in the post-test session, the alpha power of EEG signals was significantly suppressed (Figure 6), indicating that the experimental group may invest more cognitive resources in the task related to spatial ability after the training process. Specifically, There was a significant $group \times testing\ session$ interaction for the mean alpha power at the Fz electrode size ($F(1, 16) = 5.11$, $p = 0.038$). In particular, the mean alpha power decreased from 0.48 to 0.40, leading to a 16.48% suppression of the alpha activity. As a comparison, the mean alpha power remained at the similar level when the participants in the control group were engaged in the transformation task, after training through reading paper material. Neither the main effect of group nor the main effect of testing session was significant for the mean alpha power at the Fz electrode size. There was no significant difference in the mean alpha power in the midline or parietal areas.

Given the findings at the Fz electrode size, we continued to explore the asymmetric brain activation in the frontal areas. EEG asymmetric features were calculated by subtracting the mean alpha power values in the left hemisphere from the mean alpha power values in the corresponding right hemisphere (e.g., F3-F4, F7-F8). We observed more brain activation in the left frontal area after the training process for both of groups. Specifically, there was a significant main effect of the testing session for the mean alpha power asymmetry at the pair of F3-F4 ($F(1, 16) = 6.99$, $p = 0.018$). After training, the mean alpha power in the left frontal area was significantly less than the value in the right frontal area when participants were engaged in the transformation task. No significant difference in this measure was found between two groups. The mean alpha power asymmetry at another pair of F7-F8 was not significant between two groups or between two testing sessions.

Conclusion and Future Work

The behavioral and EEG results were in line with our expectations in the following two aspects.

First, the participants were required to complete the transformation task as quickly as possible on the premise of ensuring the correct rate. Therefore, there was no significant difference in their correct rates but significant differences in both TTCorrect and TTC between the pre- and post-test for those in the experimental group. These findings on both reaction time and accuracy indicated that training by interaction with EasySRRobot can effectively improve the performance of the transformation task. Based on our current findings, we conclude that the training through interaction with EasySRRobot might improve mental rotation skills and other aspects of spatial ability.

Second, the participants in the experimental group spent less time to complete the transformation task and achieved the same accuracy, which in fact increased the task difficulty. These participants may invest more cognitive resources (e.g., visual effort and mental imagery, etc), which suppressed the alpha activity [5]. Moreover, less alpha activity and more brain activation in the left frontal area was found after training. These findings indicated that tangible interaction with EasySRRobot might improve spatial understanding and reasoning which are highly correlated with mental rotation [3].

Some researchers have argued that training spatial performance in existing types leads only to fleeting improvements and is often restricted to cases in which the trained program and test tasks are very similar [6]. In this work, we propose a new training scheme by using active, physical exploration of the real world through tangible interaction. According to our current results, we expect that the current training scheme can improve not only mental rotation skills but also other aspects of spatial ability. Our future investigation will continue to work along this research line.

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