Mental Rotation Skill Shapes Haptic Exploration Strategies

Fabrizio Leo, Giulio Sandini, and Alessandra Sciutti

***Abstract*—Haptic exploration strategies have been traditionally studied focusing on hand movements and neglecting how objects are moved in space. However, in daily life situations touch and movement cannot be disentangled. Furthermore, the relation between object manipulation as well as performance in haptic tasks and spatial skill is still little understood. In this study, we used iCube, a sensorized cube recording its orientation in space as well as the location of the points of contact on its faces. Participants had to explore the cube faces where little pins were positioned in varying number and count the number of pins on the faces with either even or odd number of pins. At the end of this task, they also completed a standard visual mental rotation test (MRT). Results showed that higher MRT scores were associated with better performance in the task with iCube both in term of accuracy and exploration speed and exploration strategies associated with better performance were identified. High performers tended to rotate the cube so that the explored face had the same spatial orientation (i.e., they preferentially explored the upward face and rotated iCube to explore the next face in the same orientation). They also explored less often twice the same face and were faster and more systematic in moving from one face to the next. These findings indicate that iCube could be used to infer subjects' spatial skill in a more natural and unobtrusive fashion than with standard MRTs.**

***Index Terms*—Haptics, Spatial skill, Mental rotation, Exploration strategies, Perception and action.**

I. INTRODUCTION

HAPTIC perception is the ability to experience and recognize external objects through touch. This process is made possible by integrating inputs from cutaneous and kinesthetic receptors embedded in muscles, joints and tendons [1]. Thanks to this perceptual system, we are very good at recognizing common objects also when using touch without the contribution of vision [2], as when we need to find the right key in our pocket.

From a more functional perspective, haptic perception accomplishes its goals through specific exploration procedures based on the kind of information we need to extract about a particular object [3]. For instance, we may perform sideways movements between skin and object surface (i.e., lateral motion) if we need to discriminate the texture of an object, or we may follow its contour if we would need to determine its exact shape. Similarly, the pattern of touches has been shown to vary depending on whether a person explores the object to encode haptic information or to recall it [4]. Collectively, these findings demonstrated that touch and movement cannot be disentangled when considering haptics. Despite this, most studies investigating tactile perception traditionally used only passive tactile stimulation [5], [6]. This may be due also to the difficulty in dealing with and studying the large variability of hand movements that humans perform while touching or exploring an object. Recently, a new device, namely iCube, has been proposed to integrate touch and movement [4]. It is an instrumented cube which measures its orientation in space as well as the location of the contacts on its faces and communicates these data wirelessly to a computer. Its main novelty lies in the possibility to investigate haptic exploration with a three-dimensional sensorized object that can be also manipulated and moved freely in space. Therefore, unlike previous studies, e.g., [7], it is also possible to avoid using video annotations by human observers, which other than being fatiguing, could cause missing important exploratory behaviors due to drop in attention or to occlusions [8]. This device has been, for instance, used to characterize the visuo-haptic exploration patterns in developmental age [9], [10]. To do so, the authors fixed small pins on cube faces in varying number and asked participants to perform tasks with increasing level of difficulty, such as finding the cube face with a specific number of pins, finding the face with largest number of pins or counting the total number of pins. Subjects did the task in various conditions: with the cube fixed or with the possibility of freely moving it, in a haptic-only modality or with the help of vision. Results indicated that haptic behavior depended on the level of development. For instance, seven years old children showed adult-like visuo-haptic performance, whereas haptic exploration reached adult-like levels only later in development (at about nine years). Additionally, the possibility of rotating the cube represented a difficulty rather than an advantage for younger children. This may be due to the fact that spatial skill was not yet completely developed in those

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Manuscript received July 8, 2021; revised December 28, 2021 and February 28, 2022; accepted March 22, 2022. Date of publication March 28, 2022; date of current version June 27, 2022. The work of Fabrizio Leo and Alessandra Sciutti were supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme, under Grant Agreement 804388, wHiSPER. This article was recommended for publication by Associate Editor Prof. M. Marchal and Editor-in-Chief Dr. S. Choi upon evaluation of the reviewers' comments. *(Corresponding author: Fabrizio Leo.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Comitato Etico Regione Liguria under protocol IIT_INT_HRI, and performed in line with the Declaration of Helsinki.

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Digital Object Identifier 10.1109/TOH.2022.3162321

children. Previous findings showed indeed better performance in adults in both two- and three-dimensional mental rotation tasks, e.g., [11]. Mental rotation is associated with activation in the right parietal cortex, left and right precentral gyrus, as well as the right superior parietal lobule [12], [13], that is a neural network that may mature later with respect to the age of the children tested in the studies described above [14].

Taken together, these findings suggest that spatial skill could directly influence the way we manipulate objects as well as our performance in haptic tasks. By spatial skill we mean “the ability to visualize, manipulate and interrelate real or imaginary configurations in space” [15].

Our study is aimed at elucidating how spatial skill modulates haptic exploration in adults. To do so, we asked participants to perform a challenging spatial task with the iCube. In particular, they had to count the number of pins on specific types of faces (i.e., faces with either even or odd number of pins). We designed this novel task which differs from the tasks used in [16], [17] because we aimed at increasing the level of difficulty in a study not involving children but only adults. This would maximize the probability of discriminating between high and low performers. This task requires indeed the need of collecting and memorizing multiple, complex, spatial information (i.e., haptic working memory), as well as decision making processes (i.e., decide which faces are relevant). We then correlated the haptic variables with an independent and standardized measure of participants’ spatial skill: their score in a visual mental rotation test of three-dimensional shapes. The goal of this study is threefold: first, we aimed at investigating how spatial skill influences final performance (i.e., accuracy and exploration time) in a haptic task; second, we aimed at understanding how participants reached their level of haptic performance in terms of pattern of touches and rotation of the object; finally, we wanted to identify the haptic exploratory strategy associated with a better performance with the cube. For instance, we may hypothesize that high performers would touch more the relevant faces compared to the irrelevant ones. High performers might indeed be more able to keep track of the relative orientation of the task relevant faces while rotating the cube. They also may rotate the cube more quickly and complete the task before low performers. Collectively, this information would also inform us whether iCube could help quantify the visual mental rotation abilities of participants in a more natural and unobtrusive way.

II. RELATED WORKS

We are considering two different lines of research that are relevant for our study. The first one includes studies that investigated the integration of touch and movement. The second comprises the characterization of the interplay between haptics and spatial skills. In the sections below, we briefly report some representative works for each line of research.

A. *Integration of Touch and Movement*

An attempt to integrate touch and movement has been performed by Kappers and colleagues who took advantage of a movement-tracking device to measure the relevance of movements while exploring shape and surface properties of two-dimensional stimuli [16], [17]. Briefly here, they determined relations between patterns of movement and specific object properties (e.g., texture, hardness, etc.), thus extending Lederman and Klatzky’s findings on exploratory procedures to two-dimensional shapes, although with the limitations due to the reduced complexity of the stimuli. Other approaches took advantage of sensors to measure hand movements while exploring. Using this method, Thakur *et al.* [18] asked blindfolded participants to recognize the shape of several objects through touch. Authors found a set of synergies or hand movements that were similar across subjects and across manipulation of different objects. They argued that these synergies may represent the building blocks of the exploratory procedures defined by Lederman and Klatzky. However, this approach requires attaching markers to the hands which is a time-consuming procedure needing calibration and potentially limiting freedom of movement.

The integration of touch and movement characterizes also the so-called hybrid devices that have been developed in several domains of Human-computer interaction, for 3D visualization, manipulation, virtual and mixed reality [see, for a review, 19]. For instance, Issartel and coauthors developed a prototype of cube, a “tangible volume”, whose surface is entirely covered in screens on which a virtual scene is displayed. The user can reach different parts of the virtual scene by moving the cube in real space, use it to grasp virtual objects through fingers pressure and so on [20]. Cordeil *et al.* developed a similar touch-sensitive cube, provided with gyroscope and accelerometer, to allow users to manipulate 3D data with direct spatial manipulation of the cube itself [21]. Besançon *et al.* also focused on visualization and manipulation of complex 3D data through self-tracked tablets with touch screen [e.g., 22]. However, these approaches had very different research goals than identifying haptic exploration strategies and correlating them with spatial skill as in our study.

B. *Haptic Perception and Spatial Skills*

Previous studies focused on how haptic perception can be exploited to generate, manipulate and improve mental representations of spatial information. For instance, Tivadar and coauthors [23], [24] used a haptic tablet to present letters at different orientations to blindfolded sighted or blind persons that were asked to indicate if the letter was either in a normal or mirror-reversed form. Results showed higher performance for normal letters compared to mirrored letters and for trained as compared to untrained letters, thereby demonstrating mental rotation of haptic letter stimuli. Other studies took instead advantage of haptic tablets to generate and improve mental representations of spatial environment for navigation [25]–[28]. For instance, Romeo *et al.* used a force feedback tablet to display simple room layouts to visually impaired people. They found participants were able to recognize different types of room layouts with a rather good accuracy in discriminating different angles between walls [28]. Brayda and coauthors also showed that visually impaired persons could take

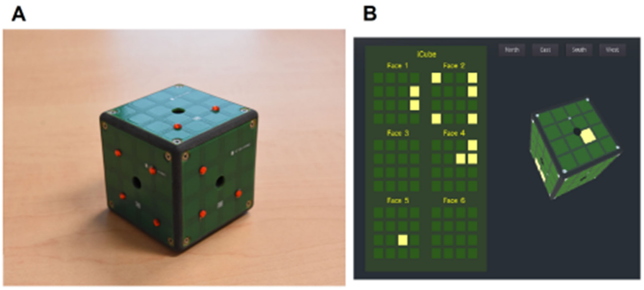


Fig. 1. The iCube. (a) Picture of iCube with raised pins positioned on its faces. (b) Example of real-time 3D rendering of iCube orientation with a snapshot of tactile sensors on each of the six faces. Yellow indicates cells currently touched.

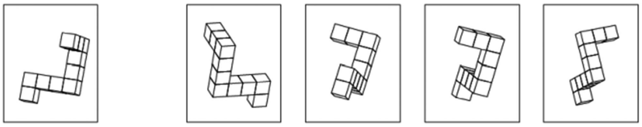


Fig. 2. Example item from the Mental Rotation Test taken from Peters *et al.* [27]. The drawing on the left is the target shape. Participants had to determine which two of the four sample shapes on the right are rotated versions of the target shape. The first and third drawings are correct.

advantage of previously learned maps displayed on a haptic tablet to successfully navigate in a small room [27].

Another research approach, closer to our study, investigated how spatial skills modulate haptic perception. For instance, Lebaz *et al.* found that persons with high visuospatial imagery better recognized tactile shapes than low visuospatial performers [29]. Similarly, Kalisch and coauthors [30] found that older adults characterized by a larger decline in cognition did worse in recognizing objects through touch. However, these studies only investigated the final outcome of the haptic process, i.e., shape recognition accuracy and time to complete it, while no investigation was conducted on the way participants touched or rotated the shapes (in case of solid objects) when exploring. Leo and coauthors [31] moved a step forward in this direction by investigating the complex interrelation between spatial skill, haptic performance and exploration strategies in three groups of youngsters differing in visual ability (blind, very low vision and blindfolded sighted). Participants had to memorize single or double spatial configurations, featured as two-dimensional matrices. Results showed that visually impaired youngsters had more difficulties than their sighted peers when they had to memorize and recall two different matrices (see also, [32]). Furthermore, authors identified some exploration strategies that were associated with performance. For instance, using only one hand correlated negatively with recalling performance. However, in that study no independent evaluation of spatial skill was executed, but it was only inferred based on the degree of visual impairment.

III. MATERIALS AND METHODS

A. Participants

Twenty participants took part in the experiment on a voluntary basis (mean age: 29.9 ± 4.6 (SD) years; 10 males; 3 left handed). Participants had no conditions affecting tactile perception, nor did any have cognitive impairment. The experimental protocol was approved by the Regional Ethical Committee (comitato Etico Regione Liguria). All participants provided their written informed consent.

B. Haptic Device: the Icube

The iCube (version 3) is a sensorized cube designed at IIT which measures its orientation in space as well as the location of contacts on its faces. This information is conveyed wirelessly to a standard laptop. iCube is of about 5 cm side, it has 16 cells per face and a weight of about 150 g (see Fig. 1). Touch sensing is based on a 4x4 array of Capacitive Button Controllers (CY8CMBR2016) developed by Cypress Semiconductor Corporation. These are based on Multi Touch technology, allowing detection of simultaneous touches and support up to 16 capacitive cells (6 x 6 x 0.6 mm), which could be organized in any geometrical format, e.g., in matrix form. Each face of iCube is made with one of these boards. Their sensitivity, i.e., the smallest increase in capacitance that could be detected clearly as a signal, is set to 0.3 pF, so as to allow the device to sense contacts without the need to apply pressure. Spatial orientation of the cube is estimated by a Motion Processing Unit^{TM} (MPU), a nine axes integrated device, combining a three axes MEMS gyro, a three axes MEMS accelerometer, a three axes MEMS magnetometer and Digital Motion Processor^{TM} (DMP). The MPU combines information about acceleration, rotation and gravitational field in a single flow of data. Data from iCube are sent to a laptop through a serial protocol. The transmission is performed through a radio module NRF24L01 (Nordic Semiconductor, Trondheim, Norway). The firmware of the device is designed to maximize the speed of capture of information from the boards measuring touches. The acquisition is always as fast as possible: faster when least faces are touched simultaneously and slower when it needs to encode information from multiple faces. As a result, the sampling occurred on average every 192 ms (± 90 ms, SD) with 92.6% of data between 98 ms and 250 ms, and only 7.5% of data above 250 ms (max = 1.81 s) or below 98 ms (min = 73 ms). Data were subsequently interpolated (see details in "Data Analysis" section) to analyze the temporal evolution of exploration at a 0.2s fixed temporal rate. Data generated in this study was further analyzed in Python (Python Software Foundation) to extract the pattern of touches, the amount of iCube rotation and the speed of rotation (see "Data Analysis" section).

C. Mental Rotation Test

All participants were asked to perform the 24-item Mental Rotation Test (MRT-A) paper-and-pencil set from the redrawn MRT test described by Peters *et al.* [33], [34]. Briefly here, participants were given items such as the one shown in Fig. 2. They had to determine which two of the four stimuli on the right were rotated versions of the target stimulus shown on the left. Each item had two and only two correct matches. A score of "1" was given only if participants correctly recognized both matches. Hence, the maximum score was 24. The 24 items

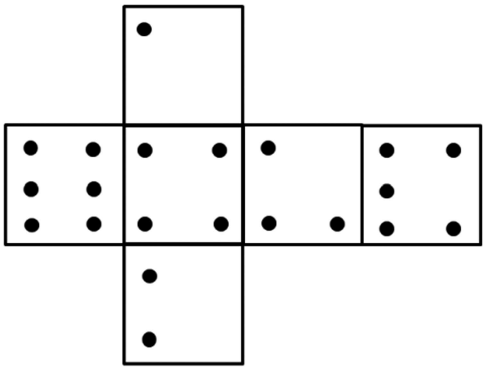


Fig. 3. Example of pins configuration of one trial. Even though this diagram shows a configuration with all different faces, there was no limitation of the presence of two or more faces with equal number of pins.

were divided in two subsets of 12 items. Participants had a maximum of 5 minutes to complete each subset of items.

D. Procedure

Before experiment initiation, the experimenter positioned on iCube faces a set of raised plastic red pins (diameter: 0.3 cm, height: 0.2 cm). Each face contained from 1 to 6 pins (see Fig. 3 for an example) with no limitation of the presence of two or more equal faces.

The participant was comfortably seated in front of a table, where the iCube was positioned on a support. A cardboard panel was placed on the table between the participant and iCube in order to avoid any visual inspection of the device, while allowing comfortable movements of participants' upper limbs (see Fig. 4). Before the experiment, participants were invited to touch and explore iCube to familiarize with the device. In particular, they were asked to count the number of pins on the faces with either odd or even number of pins. For the sake of simplicity, from now on, the faces with even number of pins and the faces with odd number of pins will be named even faces and odd faces, respectively. No time limit was given for this familiarization which lasted on average about 2 minutes and was eventually repeated once, in case of wrong answer. In the experiment, participants were asked to do the same task for three trials. They were asked to respond as quickly and accurately as possible. Half participants had to sum the pins on the even faces, whereas the other half had to sum the pins on the odd faces. No feedback on performance was given to participants. Between trials, the experimenter rapidly changed pins configuration (e.g., by removing or adding pins to one or more faces) with an interval between explorations lasting on average less than a minute. An equal number of even and odd faces was presented to each participant across the three trials. Participants also performed other exercises with the iCube which are not the object of the present study. Half of them did these exercises before and half of them after the task reported in this article. As we did not find differences in performance between these two subsamples of participants, we treated them as a single sample. We recorded videos of these experimental sessions in 12 out of 20 participants. No recording was possible for the other eight participants due to technical issues. At the end of the experiment with iCube, participants were asked, after a brief interval, to perform the MRT. They were given no time limit to read the instructions and to complete the item examples. Then, they were given 5 minutes to complete each 12-items subset with a few minutes break in between.

Fig. 4. Experimental setup. The device was hidden from view thanks to a cardboard panel.

E. Data Analysis

Data about touches and rotations recorded by iCube were processed in Python as described in the following subsections.

1) Touches: From each of the six boards, representing the faces of iCube, the device reported for each timestamp a tactile map, i.e., a list of 16 elements of zeros and ones, where one represents a touched cell. These tactile maps were linearly interpolated at a fixed sample rate of 0.2 s, i.e., a value close to the average sample rate of the device. The interpolation was independently executed for each cell of each face. The output of the interpolation was then rounded to the nearest integer (1 or 0) to establish whether the cell was active or not at that timepoint.

As we were interested only in explorative touches, i.e., touches directly related to the exploration of a face to detect and count its pins, as opposed to the touches that only reflect the holding or support of the device, we spatiotemporally filtered the tactile maps as follow: 1) first, we applied a temporal filter with which we removed all cells that were consecutively active for more than 2 s, likely indicating holding of the device [4]; 2) we computed for each pair of consecutive samples for each face their simple matching coefficient (SMC: $\frac{number\ of\ matching\ attributes}{number\ of\ attributes} = \frac{M00+M11}{M00+M01+M10+M11}$) which is a measure of similarity of samples sets with scores between 0 and 1, where 1 indicates perfect similarity and 0 indicates perfect diversity. M_{11} is the total number of cells where sample1 and sample2 both have a value of 1 (active); M_{01} is the total number of cells where the status of sample1 is 0 (inactive) and the status of sample2 is 1 (active); M_{10} is the total number of cells where the status of sample1 is 1 (active) and the status of sample2 is 0 (inactive); M_{00} is the total number of cells where sample1 and sample2 both have a value of 0 (inactive). Then, we based on the assumption that explorative touches are characterized by higher variability in space and time than holding touches. For instance, the lateral motion exploratory procedure often associated to active exploration of tactile features of a surface such as texture is characterized by highly dynamic movement of the hand in contact with the object. This kind of movement would translate for our sensors in a rapid change of status of cells activation in a face, resulting in lower SMC for consecutive temporal samples. Therefore, at each time interval we only considered as explorative touches those measured on the faces with lowest SMC computed with respect to the previous sample.

In addition, to identify the exploration patterns, i.e., the transitions from one explored face to another, we defined a face as explored if it showed the lowest SMC for at least 0.8 s consecutively. This value was chosen empirically and will be discussed in detail in section ‘Transition Matrices’ of ‘Results’.

We also computed the exploration duration as the time between the first and last touch of the participant (via automatic cutting for each file the initial and last phases of recording, when less than two cells were active). Then, we divided the number of touches by exploration duration to compute touch frequency, i.e., the number of touches per time unit.

2) Rotations: The information about the orientation of iCube in time was provided in the form of quaternions. As for touches, quaternions were interpolated at a fixed sample rate of 0.2 s via spherical linear interpolation (SLERP). Then, we computed the instantaneous angular variation by measuring the angle traversed over time by each of the three unitary axes orthogonal to the faces of iCube. In particular, given one axis:

$$\Delta\mathrm{angle}_{\mathrm{axis}}(\mathrm{t}) = \arctan\left(\left|\frac{\mathrm{axis(t)\ x\ axis(t-1)}}{\mathrm{axis(t)\ \cdot\ axis(t-1)}}\right|\right) * 180^{\circ}/\pi \tag{1}$$

We integrated over time the rotations performed by the three axes to get an estimation of the rotation impressed to iCube in all the possible directions. To quantify the amount of rotation, we considered the maximum value among cumulative sums of the rotations executed by the three axes. The instantaneous rotation speed was instead computed by dividing $\Delta\mathrm{angle}_{\mathrm{axis}}(\mathrm{t})$ for its time interval (i.e., 0.2 s) and averaging the results across the three axes and across all the instants in a trial in which iCube was in motion (i.e., angular velocity > 1°/s). As in Sciutti *et al.* [4], this selection was done to assess the actual velocity of rotation when the rotations were executed, without spuriously reducing the estimate with the analysis of the static phases.

In addition, based on quaternion data, we determined for each timepoint the absolute and relative orientation of each face of iCube. With absolute orientation we mean the cardinal direction of the normal of a face. It was estimated by computing the Hamilton product of the quaternion relative to the timepoint of interest by the quaternion defining iCube initial position. The normal vector defining each face orientation at the beginning of a trial was then rotated by the quaternion obtained with the Hamilton product and subsequently converted in spherical coordinates. Elevation and azimuth were then categorized into the labels ‘north’, ‘south’, ‘east’, ‘west’, ‘up’, and ‘down’. With relative orientation of a face we mean its orientation in the perspective of the participant. For instance, if a participant is facing West, the face of the cube oriented to the North would be on the right of the participant. More in detail, following Sciutti *et al.* [4] a face was considered in front of the participant, for instance, if its normal designed an angle inferior or equal to ±45° with respect to the ideal line connecting participant and iCube center. We assigned the labels ‘up’, ‘down’, ‘front’, ‘rear’, ‘right’ and ‘left’.

F. Statistical Analyses

Statistical analyses were performed using Python and Jamovi [35]. The dataset and analysis scripts can be found at https://github.com/leofabrizio/icube-ToH-analyses. We correlated the exploration variables (accuracy, number of touches, touch frequency, exploration duration, amount of rotation and rotation velocity) using either Pearson (r) or Spearman (r_s) correlation analyses depending on whether the underlying data distributions were normal or not. Similarly, we correlated exploration variables with the scores in the MRT test. In case of binary variables (e.g., accuracy), we used point-biserial correlation analyses (r_{pb}). We assessed whether data were normally distributed using Shapiro-Wilk tests. Statistical significance was set at $p < 0.05$. Correction for multiple comparisons, whenever necessary, was conducted using the False Discovery Rate (FDR) control based on the Benjamini-Hochberg methods. This has been proven to be a less conservative and more powerful technique than the classical Bonferroni’s correction [36], [37]. We also reported 95% confidence intervals and the following measures of effect size: 1) the Cramer’s V ($V = \sqrt{\frac{\chi 2}{n*df}}$) for the χ^2 tests; 2) the Cohen’s d ($d = \frac{mean1-mean2}{std\ dev}$) for the t-tests.

IV. RESULTS

A. Descriptive Analyses

Participants’ mean accuracy in counting the pins was 80% (± 40, Standard Deviation). The average exploration duration per trial was 45.3 s (± 14.4). The mean number of touches per trial was 679.5 (± 222) with a mean touch frequency of 15.35 touches/s (± 3.2). The mean amount of rotation per trial was 790.2° (± 307) with a mean rotation velocity of 17.1 °/s (± 6.4). None of these variables showed a sex difference (all $p > 0.56$). When considering only correct responses, the average exploration duration per trial was 43.2 s (± 14.2). The mean number of touches per trial was 659 (± 208) with a mean touch frequency of 15.6 touches/s (± 3.1). The mean amount of rotation per trial was 767.7° (± 283) with a mean rotation velocity of 17.5 °/s (± 6.5). The mean score in the MRT test was 13.6 (± 4.7; min = 5, max = 21) with no sex difference ($p = 0.23$).

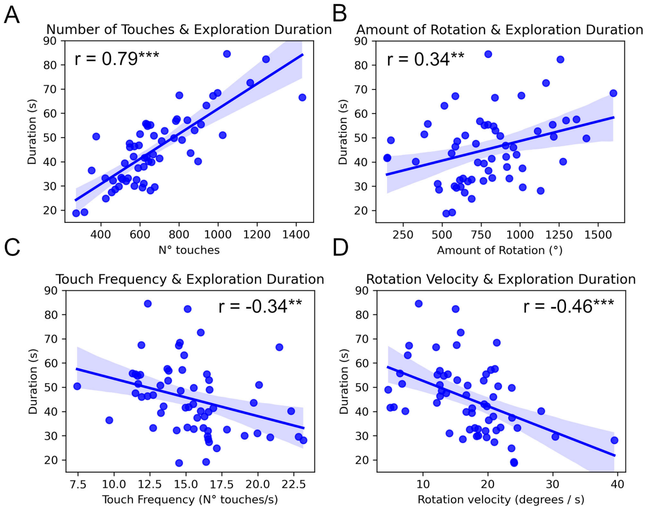


Fig. 5. Correlations between exploration variables in the iCube task. (a) Correlation between number of touches and exploration duration. (b) Correlation between amount of rotation and exploration duration. (c) Correlation between touch frequency and exploration duration. (d) Correlation between rotation velocity and exploration duration. ***, $p_{FDR} < .001$; **, $p_{FDR} < 0.01$.

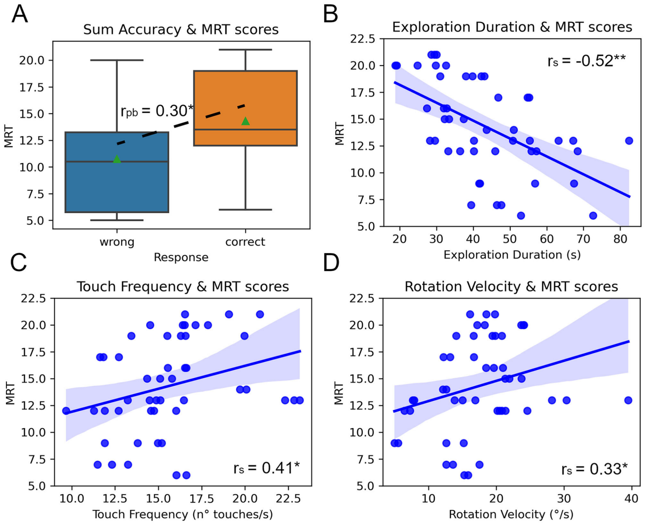


Fig. 6. Correlations between exploration variables in the iCube task and MRT score. (a) Correlation between accuracy with iCube and MRT. Boxplots show MRT distribution in trial with wrong and correct answers, respectively. Horizontal lines indicate medians and green triangles indicate means of the distributions. Whiskers extend to points that lie within 1.5 interquartile ranges of the lower and upper quartile. (b) Correlation between exploration duration and MRT. (c) Correlation between touch frequency and MRT. (d) Correlation between rotation velocity and MRT. **, $p_{FDR} = 0.0002$; *, $p_{FDR} < 0.05$.

B. *Effect of the Type of Icube Face*

We verified whether the task relevance of the faces influenced number of touches, touch frequency and exploration duration. We refer as relevant the faces that are associated to the goal of the task: e.g., even faces when the participant had to sum the pins on the faces with even number of pins. We could not find any modulation of the type of face over these exploration variables (all ps > .13).

C. *Correlation Between Exploration Variables*

First, we correlated accuracy with each exploration variable. Results showed a negative correlation between accuracy and exploration duration ($r_s = -0.30$, $p = 0.02$, $p_{FDR} = 0.1$, CI [-0.52,-0.05]). In other words, accurate trials tended also to be faster. All the other correlations were not significant (all $p_{FDR} > 0.3$).

Then, we correlated exploration duration with the other exploration variables. Exploration duration positively correlated with number of touches and amount of rotation ($r = 0.794$ and $r = 0.345$, respectively, $p_{FDR} < 0.001$ and $p_{FDR} = 0.007$, CI [0.68,0.87] and [0.1,0.55]; see Fig. 5(a) and (b) and negatively with touch frequency and rotation velocity ($r = -0.34$ and $r = -0.46$, respectively, $p_{FDR} = 0.008$ and $p_{FDR} = 0.0004$, CI [-0.55,-0.09] and [-0.64,-0.24], see Fig. 5(c) and (d). In other words, as it could be expected faster trials had also lower number of touches and amount of rotation and higher touch frequency and rotation velocity.

D. *Correlation Between Exploration Variables and MRT Scores*

We then correlated exploration variables with the Mental Rotation Test scores. When correlating exploration variables other than accuracy, as in Nouchi *et al.* [38] we selected only the correct responses (80% of total). Accuracy, rotation velocity and touch frequency in the task with iCube positively correlated with MRT ($r_{pb} = 0.3$, $r_s = 0.33$ and $r_s = 0.41$, respectively, respectively, $p_{FDR} = 0.022$, $p_{FDR} = 0.027$ and $p_{FDR} = 0.01$, CI [0.05,0.51], [0.04,0.55] and [0.14,0.62], see Fig. 6(a)–(c). Instead, exploration duration and number of touches with the iCube negatively correlated with MRT (r_s = -0.52 and r_s = -0.38, respectively, $p_{FDR} = 0.0002$ and $p_{FDR} = 0.012$, CI [-0.75,-0.38] and [-0.6,-0.11], see Fig. 6(b). To sum up, participants that were good in 3D visual mental rotation were more accurate and fast in the haptic task with iCube. They also touched less the device, but with higher frequency and rotation speed. This confirms that the task with the cube allows to highlight such differences in mental rotation skill.

E. *Cluster Analysis*

Previous results provide strong evidence of a direct association between the level of skill in mental rotation and performance in the task with iCube. In order to better characterize this association and also to ideally identify high performers and low performers, we clusterized participants based on their MRT score. In particular, we assigned to cluster 0 ($n = 9$) participants with MRT score higher than 13 (i.e., the median of the distribution of MRT scores) and we assigned to cluster 1 ($n = 11$) participants with MRT score equal or inferior to 13.

We then verified whether the two clusters differed in the exploration variables with the cube. Results showed that cluster 0 was faster in exploring (cluster 0 = 36.9s, cluster 1 = 52.1s, $t(57.99) = -4.80$, $p < 0.001$, $p_{FDR} = 0.006$, $d = 1.22$, CI [-21.64,-8.92]), touched less the device (cluster 0 = 606, cluster 1 = 740, $t(54.45) = -2.38$, $p = 0.021$, $p_{FDR} = 0.042$, $d = 0.62$, CI [-246.1,-20.87]) and touched with higher frequency (cluster 0 = 16.5, cluster 1 = 14.4, t(57.7) = 2.67, p = 0.009, $p_{FDR} = 0.027$, $d = 0.68$, CI [0.52,3.59]). On the contrary, accuracy, amount of rotation and rotation velocity did not differ (all ps > 0.06).

F. Transition Between Faces

Previous analyses showed some general features of an efficient iCube exploration in our task. For instance, high performers, that is cluster 0 members, are faster in their exploration and, as a consequence, they touch less the device, but with higher frequency. However, this would be of little help if, for instance, we would need to suggest to a novel participant some guidelines for an efficient exploration. In the attempt to better characterize more specific effective exploration strategies, we analyzed the transitions from a face to another. For instance, we may expect that participants, in general, would explore more times relevant faces as opposed to irrelevant ones. They may indeed return to explore already explored relevant faces to confirm their answer. To do so, we identified the explored faces for each trial and participant using the method described in section "Touches" of "Data Analysis". We opted for a 0.8 s filter because a lower temporal filter (0.6 s) generated too many false positives as assessed by an evaluation operated in a sample of videos. The 0.8 s value represented a good compromise between the needing to minimize both false positives and omissions. Indeed, results showed only 4 uncomplete transitions out of 60 trials, that is trials with one or more unexplored faces. However, all these unexplored faces were irrelevant to the task. Therefore, we cannot conclude they are omissions of the filter because to spot an omission we would need to identify a trial with correct response and a task relevant unexplored face. In other words, it could be possible that participants did not actually explore those faces. Assuming the filter precisely reflects all participants exploration behavior, the absence of unexplored faces in trials with wrong answers indicates that the cause of the error may not be the missing exploration of a task relevant face but rather a sum mistake (e.g., counting twice the same face). If this would be true, we would expect an overestimation of the number of pins in wrong trials. Our results showed it is the case since the mean deviation in wrong trials, i.e., the difference between response and correct answer, was +1.83 (±1.6).

Then, we identified the timepoints at which participants started to explore each face in each trial. We investigated whether the average time between the beginning of exploration of one face and the beginning of exploration of the following face and its variability correlated with MRT score and/or with accuracy in the task with the iCube. We found that the mean rate of face change and its standard deviation negatively correlated with MRT score ($r_s = -0.35$ and $r_s = -0.49$, respectively, $p_{FDR} = 0.005$ and $p_{FDR} = 0.0002$, CI [-0.56,-0.11] and [-0.66,-0.27], see Fig. 7). These variables did not correlate with accuracy in iCube task (both ps > 0.27). In other words, participants with higher spatial skill score changed explored face more quickly and systematically than participants with lower spatial skill.

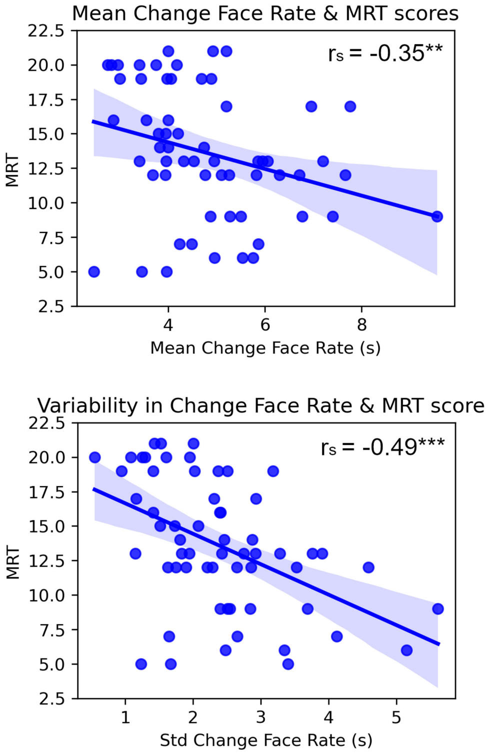


Fig. 7. (top) Correlation between mean rate of face change and MRT score. (bottom) Correlation between standard deviation of rate of face change and MRT score. ***, $p_{FDR} = .0002$; **, $p_{FDR} = .005$.

Participants sometimes returned to explore previously considered faces. We wondered whether the number of returns depended on the type of face (relevant vs. irrelevant) and/or its number of pins. For instance, we may expect that participants would return to explore more often task relevant faces and faces with higher number of pins. Results showed that in the 60 trials of the experiment there were collectively 168 returns to previously explored faces. The number of returns did not depend on the face type (82 (49%) returns to task relevant faces vs. 86 (51%) returns to task irrelevant faces, $\chi^2 = 0.09$, p = 0.75). On the contrary, it depended on the number of pins ($\chi^2 = 95.9$, $p < 0.001$, $V = 1.69$). In particular, the frequency with which participants returned to explore faces with 1 or 6 pins was significantly higher than their expected frequency (see Fig. 8). We computed expected frequency for each face type by multiplying its probability of occurrence (e.g., number of presented faces with 2 pins/total number of presented faces) by the total number of returns. Since different pin numbers were presented with different probabilities, the expected frequency was not uniform across faces. The frequency with which participants returned to explore faces with 4 or 5 pins was significantly lower than their expected frequency. These results seem to suggest that participants gave more attention (i.e., returned more often) to faces presented more rarely.

Then, we aimed at investigating if and how the number of returns would influence exploration performance. For instance, we may assume that this number would directly correlate with counting accuracy: if I visit multiple times the faces I should be able to count the pins more accurately. Fig. 9 shows that,

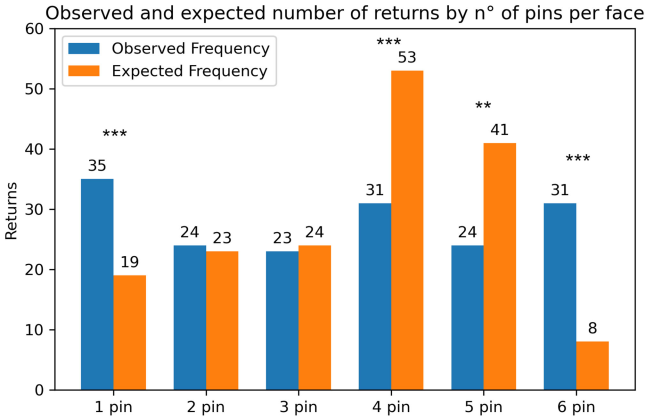


Fig. 8. Observed and expected number of returns to previously explored faces by number of pins per face. Observed and expected frequencies were compared with chi-square analyses. Expected frequency was weighted based on the probability of occurrence of that face. ***, $p_{FDR} < .001$; **, $p_{FDR} < .01$.

actually, returns correlated negatively with accuracy (r_{pb} = -0.38, $p_{FDR} = 0.002$, CI [-0.58,-0.14]) and, as expected, positively with exploration duration ($r_s = 0.56$, $p_{FDR} < 0.001$, CI [0.36,0.71]). In other words, participants who returned to explore more often faces that had been already explored were less accurate and slower in their exploration. We also investigated whether the two clusters of participants differed in number of returns to already explored faces. Low performers (cluster 1) returned to explore faces more often than high performers (mean number of returns = 3.3 vs. 2.1, t(57.9) = = -1.69, p = 0.048, $d = 0.43$, CI [-inf,-0.01], one-tailed).

However, even though the number of pins did not influence the order of exploration of the faces which is rather related to their relative orientation, it influenced the exploration duration. We found indeed a direct correlation between number of pins and exploration duration per face (r = 0.20, p = 0.0002, CI [0.09,0.29]). The most and less explored faces were the upward and downward, respectively, also when considering not only the first, but all the explored faces throughout the experiment (‘up’ face: 28.2%, ‘front’: 17.2%, ‘rear’: 15.1%, ‘left’: 14.5%, ‘right’: 13.6%, ‘down’: 11.3%). In other words, participants during the whole experiment explored more often the face which was facing the ceiling and more rarely the one facing the table.

Then, we computed the transition matrix for all the sixty trials of the experiment, i.e., a 6 by 6 matrix in which each element corresponds to the percentage of cases in which the transition has occurred between the face individuated by the row number and the face corresponding to the column number. For instance, in Fig. 10, the cell in row ‘left’ and column ‘front’ reports the probability (3.2%) in which at first the face to the left of the participants was explored followed by the face directly in front of the participants. Fig. 10 shows that the more likely transition was from up to up (probability of occurrence: 9.5%). In other words, many participants rotated the cube in a way that the explored face was upward. Another well represented transition was between the rear and front face (5.8%) and between the up and down face (5%). All the other transitions were in the range between 0.2% and 4.8%.

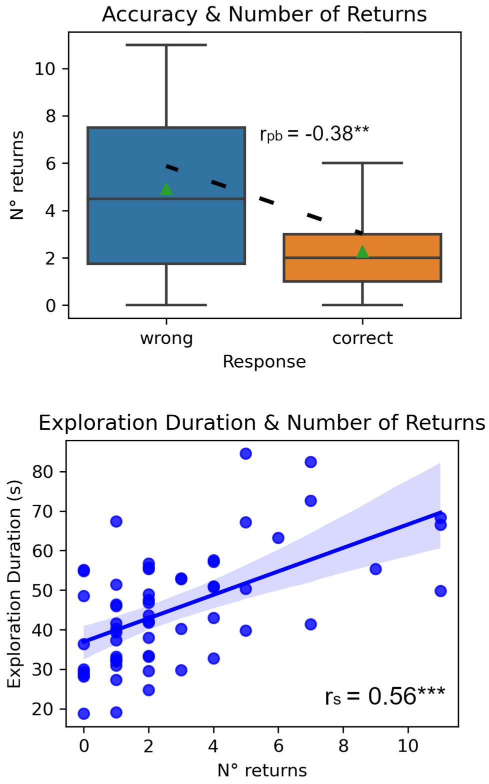
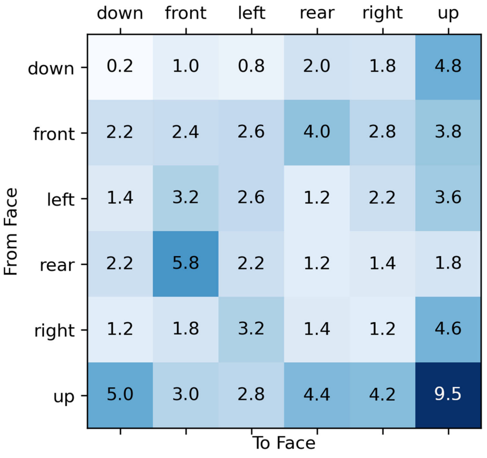


Fig. 9. (top) Correlation between number of returns and accuracy. Boxplots show number of returns distribution in trial with wrong and correct answers, respectively. Same graphical conventions as in Fig. 6(a). (bottom) Correlation between number of returns and exploration duration. ***, $p_{FDR} < .001$; **, $p_{FDR} = .002$.

In order to identify exploration strategies that were associated with better performance we considered the transition matrices at the single participant level and we divided the subjects in the two clusters defined in section “Cluster analysis”. Fig. 11 shows transition matrix of a representative participant for each cluster.

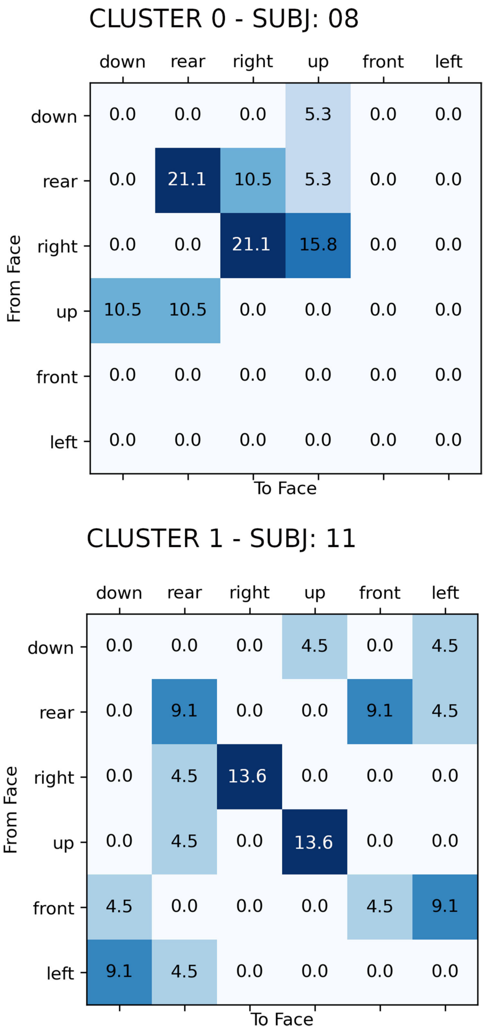
We hypothesized that the two clusters would differ in terms of diagonal scores and number of different transitions (i.e., number of non-zero cells, where a zero-cell indicates the participant has not executed that specific transition, see Fig. 11). Diagonal cells reflect the tendency to select specific relative orientations as object of spatial attention (e.g., a high proportion in the ‘from up to up’ cell indicates that participant preferentially explored the upward face and rotated the cube accordingly). The number of different transitions is a measure of exploration variability (e.g., low numbers indicate participant selected less orientations to explore, i.e., less variability). In particular, we hypothesized that cluster 0 (high performers) would be defined by higher maximum probability in diagonal cells and lower number of transitions than cluster 1. This would indicate a more focused and systematic exploration.

Results showed that clusters did not differ in terms of maximum value in the diagonal (cluster 0 median: 11%, cluster 1 median: 17%; U = 40.5, p = 0.77, one-tailed) as well as in number of different transitions (cluster 0 median = 6, cluster 1 median = 6, U = 370.5, p = 0.13, one-tailed). On the other hand, the number of different transitions negatively correlated



From Face \ To Face	down	front	left	rear	right	up
down	0.2	1.0	0.8	2.0	1.8	4.8
front	2.2	2.4	2.6	4.0	2.8	3.8
left	1.4	3.2	2.6	1.2	2.2	3.6
rear	2.2	5.8	2.2	1.2	1.4	1.8
right	1.2	1.8	3.2	1.4	1.2	4.6
up	5.0	3.0	2.8	4.4	4.2	9.5

Fig. 10. Transition matrix for all trials of the experiment. Each cell represents the probability of transitions from one face location (row) to another face location (column). Cell color codes the magnitude of the probability (from dark blue, higher probabilities to white, lower probabilities). Cells on the diagonal represent percentage of cases in which the participant rotated the cube to explore the new face in the same location as the previous one.



CLUSTER 0 - SUBJ: 08

From Face \ To Face	down	rear	right	up	front	left
down	0.0	0.0	0.0	5.3	0.0	0.0
rear	0.0	21.1	10.5	5.3	0.0	0.0
right	0.0	0.0	21.1	15.8	0.0	0.0
up	10.5	10.5	0.0	0.0	0.0	0.0
front	0.0	0.0	0.0	0.0	0.0	0.0
left	0.0	0.0	0.0	0.0	0.0	0.0

CLUSTER 1 - SUBJ: 11

From Face \ To Face	down	rear	right	up	front	left
down	0.0	0.0	0.0	4.5	0.0	4.5
rear	0.0	9.1	0.0	0.0	9.1	4.5
right	0.0	4.5	13.6	0.0	0.0	0.0
up	0.0	4.5	0.0	13.6	0.0	0.0
front	4.5	0.0	0.0	0.0	4.5	9.1
left	9.1	4.5	0.0	0.0	0.0	0.0

Fig. 11. Transition matrix for a representative participant for each cluster. Cluster 0 (top) was formed by high performers and cluster 1 (bottom) by low performers. Matrices include all trials. Cell color codes the magnitude of the probability (dark blue: higher; white: lower).

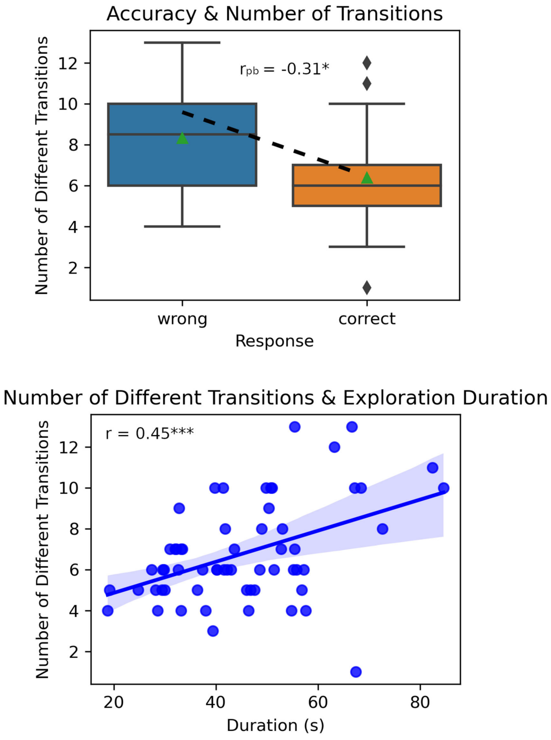


Fig. 12. (top) Correlation between number of different transitions and accuracy. Boxplots show number of transitions distribution in trial with wrong and correct answers, respectively. Same graphical conventions as in Fig. 6(a). *, p $=$ 0.014. (bottom) Correlation between number of different transitions and exploration duration. ***, $p_{FDR} = 0.0007$.

with task accuracy (r_{pb} = -0.31, $p_{FDR} = 0.014$, see upper panel of Fig. 12) and positively with exploration duration ($r = 0.45$, $p_{FDR} = 0.0007$, CI [0.22,0.63], see lower panel of Fig. 12). This means that participants showing accurate and fast performance in the task with iCube focused on less orientations and tended to rotate it to explore faces with those orientations.

V. DISCUSSION

Our study investigated whether spatial rotation skill can be measured through a simple exploration task with a sensorized cube and whether different exploration strategies would emerge. To do so, our participants had to count the number of pins on specific types of iCube faces (i.e., faces with either even or odd number of pins) without seeing the device. One of the main advantages of using the iCube lies in that it allows a natural manipulation while preserving the possibility to accurately measure how it is touched and its orientation in space. We also independently measured the spatial skill of participants through a visual mental rotation test of three-dimensional shapes.

Our results showed that participants with higher spatial skill did better in the haptic task with the cube: they were more accurate and faster than low performers. Furthermore, they showed higher touch frequency than participants with lower MRT scores. These results are in line with previous studies showing that visuospatial ability and other cognitive skills can influence performance in haptic tasks. For instance, Lebaz and coauthors [29] observed that high visuospatial imagers better recognized raised-line drawings than low visuospatial imagers. Similarly, Kalisch *et al.* [24] found better haptic recognition of solid objects in aged persons with high cognitive abilities compared to their less-skilled peers. The fact that a visual mental rotation test positively correlated with the performance in a haptic task is also consistent with a wide literature highlighting the role of a common multimodal representation system processing both visual and haptic information [39]–[47].

In our context, this result is important because it indicates that this task with the iCube could be used as a measure of spatial skill less direct and probably less anxiety-inducing than standard cognitive tests, for instance in the elderly. Similarly, it may be presented as a game to children, strengthening their cooperation (see [48], for an example of haptic testing in children in a game-like context).

Importantly, we analyzed in detail also the haptic patterns of participants. Contrarily to our expectation, participants with higher MRT scores did not spend more time touching relevant faces than irrelevant ones. This might be due to the fact that, in most cases, they did not need to explore the same faces more times, so balancing the time spent for relevant and irrelevant faces. However, participants with higher MRT scores moved from one explored face to the next more quickly and this time was less variable than that observed in less-skilled participants. In addition, low performers returned to explore already considered faces more often than high performers and doing so, were less accurate. This finding may look counterintuitive at a first glance, as we might expect more accurate counting performance when we repeat the exploration more times. We hypothesize that, instead, returning more often to already explored faces might increase the risk of counting twice the pins of a face, causing a wrong answer. This risk is amplified if we consider that we used configurations in which the same number of pins of a face could be repeated in different faces. This hypothesis seems to be confirmed by the fact that participants, when doing a mistake, generally overestimated the number of pins.

Another important result is the identification of an exploratory strategy that is associated with better performance: high performers tended to focus on a reduced number of orientations than low performers. For instance, some of them preferred to explore the face in upward orientation and they rotated the cube to place the face of interest in that orientation. On the contrary, low performers tended to show a strategy more heterogeneous and less systematic by changing more often the explored orientation over time (for instance, from upward to leftward, then rightward, etc.). The tendency to focus on a reduced number of orientations was associated with higher accuracy and faster completion time of the task. This result is also in agreement with other findings showing that children exploring the cube with larger rotations were less accurate in the task [9], [10]. Our result is important also because participants spontaneously developed their strategy without suggestions from the experimenter.

There are several potential limitations in this study. First, using a simple and well-known object as a cube imposes limits in the exploration behavior of participants as well as in task design. For instance, it is difficult to relate our findings to classical studies on exploratory procedures, e.g., [49]. However, it is still possible to create challenging spatial tasks, such as the one presented in the current work. Participants average accuracy was indeed equal to 80% which is quite below ceiling performance. Furthermore, even when participants mostly responded correctly, exploration variables such as number of returns to already explored faces or overall exploration duration clearly differed among subjects. Therefore, the task was difficult enough to make impossible developing a simple and stereotyped exploration. Another limitation lies in the sampling rate of the device, close to 200 milliseconds, which does not allow measuring micromovements. However, our study showed that macromovements are already rather informative and they can be studied to infer human spatial skill. Future technological advancements will allow higher sampling rate for measuring also micromovements. The device does not allow to analyze the relative contribution of the two hands while exploring the cube. Future studies might want to investigate (e.g., using videos) how such aspects of motor activity relate to spatial and haptic skills. Finally, participants performed a small number of trials. Therefore, the possibility of investigating the temporal evolution of the performance and possible changes in exploration strategy is limited. However, the quantity of data that can be extracted by iCube even with few trials is quite massive and largely sufficient to differentiate haptic patterns and correlate them with mental rotation skill.

VI. CONCLUSION

In conclusion, our study showed that visuospatial skill influences performance in a haptic task with a three-dimensional object. More intriguingly, results indicated that our task with the cube can be used to measure spatial skill of participants in a natural and unobtrusive way. Furthermore, using a sensorized cube allowed us to study haptic exploration in motion and to characterize exploration strategies associated with different outcomes in performance. In this sense, some of our findings were unexpected and looked counterintuitive: for instance, the relevance of the kind of face seemed not to matter; fewer returns to already explored faces predicted good performance; a highly dynamic and various exploration pattern affected performance. Future studies might want to verify whether the most effective strategies can be taught to participants with low spatial skills helping them to improve their performance in similar tasks.

ACKNOWLEDGMENT

We thank Antonio Maviglia, Diego Torazza and Elio Massa for the design and realization of the iCube, Marco Jacono for the development of the first version of the software and his suggestions on rotation analyses. We thank Marcello Goccia for the current version of the software running the iCube and Sara Nataletti for helpful comments on an earlier version of this manuscript. Special thanks to all participants.

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