Automatic real-time hand tracking enhances adolescents' spatial skills by eliminating haptic feedback

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***Abstract*—Spatial skills underlie how humans acquire, represent, organise, manipulate, and navigate their environment, and therefore are fundamental for survival and proper function. Spatial skills involve the integration of sensory-motor information with higher-order cognitive representations. Previous research showed that spatial skills can be improved through training, yet it is unknown what sensory information is better for training. Here, we tested a new application for real-time hand tracking as a manipulator of sensory information that enhances spatial skills in late childhood. To that end, children (*n* = 29; ages 14-15) completed a 7-week school training programme (eight 30-minute sessions) to improve their spatial skills. Children were randomly assigned into one of two training regimens: Hapto-Visual (HV; students constructed a physical 2D polydron net from different perspectives of a 3D cube) or Visual-Only (VO; students constructed a digitised version of the 2D polydron net without tactile information). Children's spatial skills were assessed before and after the training programme using established tests (Modified Mental Rotation and Mental Paper-Folding Tasks). We found significant improvement in both groups, with a significantly enhanced performance by the VO group compared to the HV group. Our findings suggest that omitting haptic feedback during spatial training compels reliance on mental representations, thereby bolstering spatial skills more effectively. These findings present a new application for real-time hand-tracking technology in educational settings and demonstrate its cost-effective potential to advance spatial abilities in young students.**

Keywords—spatial skills; hand-tracking; adolescents; learning; mental rotation; sensory modality

I. INTRODUCTION

Spatial skills are a cluster of competencies that enable individuals to interpret and interact with their three-dimensional environment effectively. These skills encompass the ability to mentally rotate objects, understand different perspectives, visualise spatial relationships, remember spatial information, and coordinate movements [1]. They emerge from the intricate integration of sensory information gleaned from one's surroundings and the high-level mental representations that individuals construct in their minds. Proficiency in spatial tasks is thus a product of the dynamic interplay between sensory experiences and cognitive capabilities [1]. The development and refinement of these skills are essential for adapting to the ever-changing spatial demands of both the immediate physical spaces and the broader environments humans encounter throughout life.

Developmental and educational researchers highlighted the critical role that spatial skills play during late childhood and adolescence, a time when these abilities significantly influence cognitive development [2, 3]. The advancement of spatial skills has also been linked to broader educational achievements, indicating their profound impact on an individual's academic trajectory and lifelong learning potential [4-6]. For example, spatial skills predict success in science, technology, engineering, and mathematics (STEM) disciplines, often demanding spatial reasoning and the ability to visualise and manipulate objects and data [7, 8].

Efforts to improve spatial skills through training in late childhood and adolescence have been successful [9, 10]. However, no experimental work has tested whether training spatial skills depends on the type of sensory information given to the learners. The current study aims to bridge this gap by manipulating sensory manipulation during the training of spatial skills. We hypothesised that the source of sensory information influences the outcomes of training. Specifically, we predicted that eliminating haptic feedback during training will 'force' children to rely on their mental representations and will improve training outcomes. Based on previous research [11, 12], our underlying assumption was that the absence of tactile feedback would necessitate a greater reliance on internal cognitive representations, thereby potentially enhancing the effectiveness of spatial skill training.

We tested our hypothesis in a 7-week training programme in which children completed spatial tasks with and without haptic feedback, and we evaluated the effects of training using established tests for spatial skills. We tested children in mid-adolescence (14-15 years) because this age marks a dynamic phase in cognitive development, making it an ideal time to impact spatial skills that are crucial for academic and real-life challenges.

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Similar training programmes for spatial skills without haptic feedback can only be done with advanced motion-tracking technologies, which are constrained to laboratory settings and limited to a small number of participants. However, recent breakthroughs in sensor technology have enabled us to use cost-effective equipment suitable for educational environments—a standard computer and one small-sized motion sensor. Consequently, the training programme was integrated into a standard classroom setting and children's curriculum. This added real-world relevance to the training programme, ensuring our findings would be applicable in the very places where these skills are often required and developed (e.g., in STEM education).

II. RELATED WORKS

A. Development of Spatial Skills: A Focus on Mental Rotation

Traditionally, developmental researchers used mental rotation (MR)—the ability to envision rotated visual stimuli—as a model system for understanding how spatial skills emerge [13]. The origins of spatial skills can be traced back to infancy [14], with MR becoming more distinct by 16 months [13]. The developmental progression followed a steady upward trajectory, with improving outcomes in MRT at 3-5 years old [15], 7-10 years old [16] up to 16 years old [17].

Neuroimaging studies supported this developmental trajectory by revealing a developing link between activity in the prefrontal cortex (PFC) and MR performance from preschool years [18] to adolescence [19] and into university-level STEM education [20]. The PFC's developmental timeline is protracted, with a peak in plasticity extending from mid-adolescence into early adulthood [21]. This plasticity suggests that late childhood is ideal for spatial skill enhancement, providing a window of opportunity for impactful educational interventions [22].

B. Training Spatial Skills & Multisensory Experience

Indeed, interventions aimed at honing spatial skills during late childhood have proven effective [9, 23]. Engaging in spatially demanding activities, from sports to strategy games [24], is linked to the enhancement of spatial thinking [10]. Various training approaches have been used, from physical objects to digital and virtual environments, tailored to the learner's age. For younger children, puzzles [25] and desktop programmes [17] are common, whereas adolescents more frequently use advanced simulations including virtual reality navigation tasks or interactive geometric shape manipulation [9, 10]. These diverse approaches highlight not only the adaptability of spatial skill training to various age groups but also point towards the inherent multisensory nature of spatial tasks.

Training spatial skills aims to facilitate the synthesis of immediate sensory information to the mental representation of one's surroundings. Neuroimaging studies have revealed that engaging in mental rotation activates a network of sensory brain regions, including the superior parietal, frontal, and inferotemporal cortices, which are instrumental in processing visuospatial information. Training tools such as video games and virtual reality that stimulate these areas notably boost mental rotation skills by sharpening visual attention, processing, and embedding in mental representations [9].

However, solving spatial problems is a complex, multisensory process that extends beyond the visual domain. It necessitates the integration of haptic feedback, which is the physical sensation of touch, with visual inputs to construct a comprehensive mental model of spatial relationships. Previous training programmes have primarily focused on the visual aspect of spatial skills, neglecting the significant role that haptic perception plays [9]. Previous behavioural and neural data suggested that in the absence of haptic information, learners compensate for the lack of tactile input by enhancing their mental representation [11, 12]. Therefore, testing the impact of haptic information on spatial skill acquisition is essential. Such testing is limited by the ability to track human movement in real time as it requires disentangling the haptic feedback from the visual feedback during spatial tasks.

C. Time Hand-Tracking Technology

In the last decade, technology that allows rapid, real-time tracking of human movements has begun to carve out a significant niche in diverse sectors, transcending beyond its initial entertainment and gaming applications. In education, rapid tracking allows students to engage with complex geometrical concepts without the need for physical manipulatives, offering an immersive learning experience that deepens students' understanding and retention of abstract concepts [26].

Real-time hand tracking is also used in healthcare, serving as a cornerstone for rehabilitative practices [27]. For example, translating hand movements into a digital format provides patients with a dynamic platform for practising fine motor skills [28, 29]. This is especially beneficial in occupational therapy, where the restoration of hand dexterity post-injury is critical [29]. The ability to monitor and record progress in real-time also allows for more personalised and adaptive rehabilitation programmes [30, 31].

The field of virtual and augmented reality has also leveraged hand-tracking technology to create more natural and intuitive user interfaces [32]. In VR, real-time hand tracking has been instrumental in developing simulations for surgical training, where the precise control of virtual instruments is paramount [33]. Similarly, AR applications use hand-tracking to blend digital elements seamlessly into the physical world, enhancing individuals' interaction with objects [28].

Finally, in the creative industries, this technology has revolutionised how artists and designers conceptualise and create [34]. With the ability to manipulate digital objects and environments as they would with physical clay or models, creatives can iterate designs with newfound speed and flexibility [35]. This has implications not only for individual creation but also for collaborative processes, where team members can work together in a shared digital space despite being miles apart.

Taken together, these applications suggest that real-time hand-tracking technology holds the promise to facilitate the way humans engage with spatial constructs. As individuals manipulate objects in a virtual space, they mirror the mental representations used in physical spatial manipulation. This mirroring may enhance spatial skills by providing a hands-on experience in a virtual context, effectively training the individual in ways similar to physical interaction. This enhanced spatial ability is not only useful in everyday tasks but also forms the foundation for complex spatial thinking required across various academic and professional fields.

Here, we deployed a cutting-edge technology that meticulously captures the subtleties of hand movements in a rapid, real-time manner. This approach allowed us to isolate the haptic from the visual constituents of participants' multi-sensory experience, affording a unique opportunity to scrutinise the impact of haptic deprivation on spatial skill learning.

III. EXPERIMENTAL METHOD

A. Participants

A cohort of 29 child students was recruited from the selective-entry girls' secondary school in Medway, Kent, UK ($M = 14.15$ years, $SD = 0.83$). Our collaboration with this girls' school resulted in the study being confined to a single gender. Four participants did not perform any training sessions and were excluded from further analyses. Children were recruited through posters and information videos during personal tutor time. Students were rewarded with 'school leadership points' for volunteering in all training sessions. Before testing and training began, all volunteers gave informed consent. The project received ethical approval from the Department of Psychological Sciences Research Ethics Committee of Birkbeck, University of London (Ethics Reference No: 2122078).

B. Procedure & Materials

Children were randomly assigned to either the Hapto-Visual group (HV; n = 13; Fig. 1B-C), in which they constructed a 2D polydron net from three perspectives of a 3D cube; or to the Visual-Only group (VO; n = 12; Fig. 1D-E), in which they constructed a digitised version of the polydron net without haptic feedback. The groups were matched for age. Training included overall 8 sessions during seven weeks (an average of 4 days between training sessions). Each training session lasted 30 minutes. Not all children completed all 8 sessions (average number of sessions for HV group = 6.67; average number for VO group = 5.69).

In each training session, children from the HV group were provided with a box of 16 polydron faces with foam shapes attached to them (Fig. 1A) and printed photos of a 3D target shape from three perspectives (Fig. 1B).

There were three possible foam shapes (cross, circle or square) in five different orientations (centrally or in each one of the corners), and in either hollow (indicated by the shape

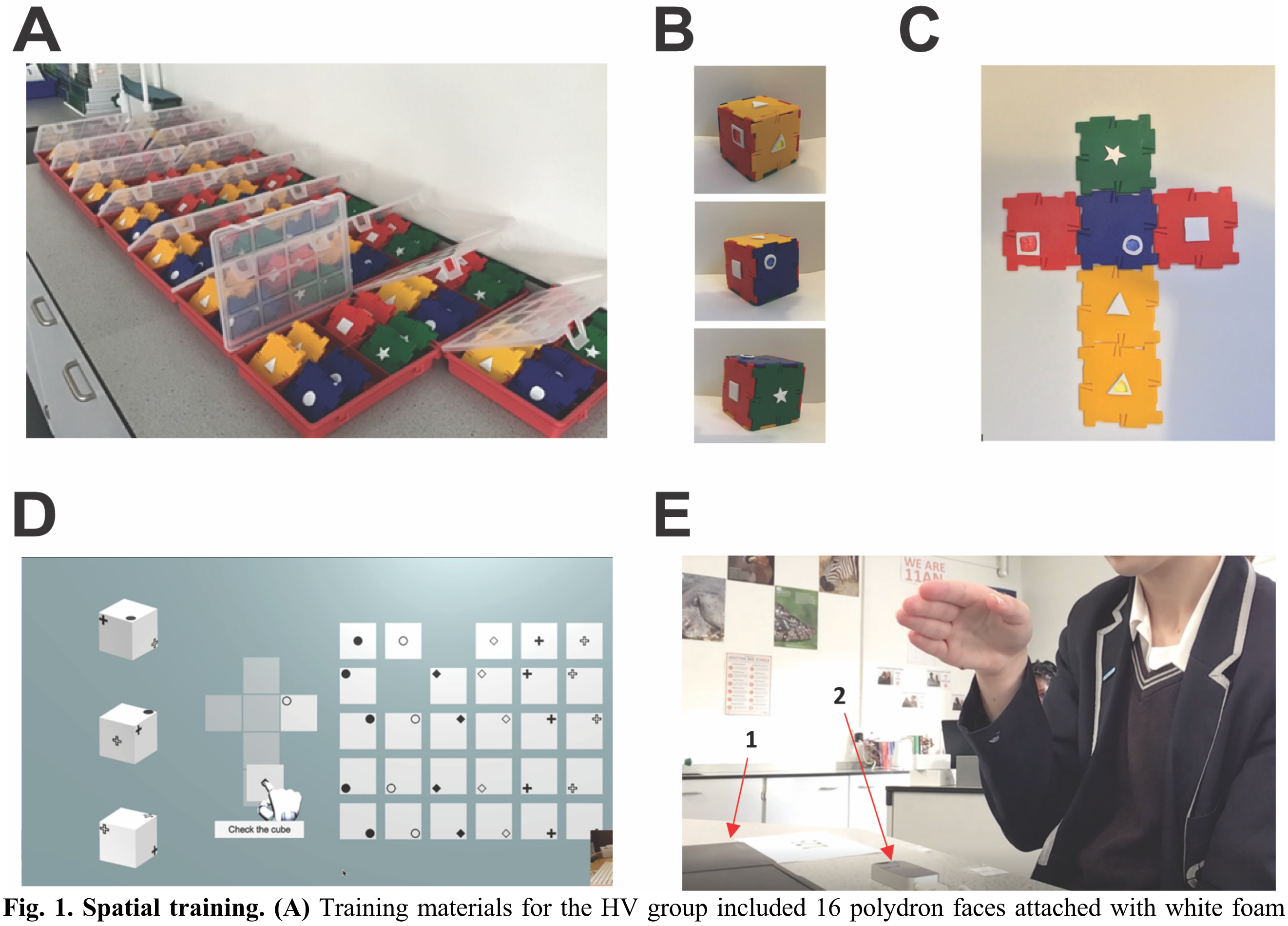

Fig. 1. Spatial training. (A) Training materials for the HV group included 16 polydron faces attached with white foam shapes. Each child received one red box at the beginning of each training session. **(B)** Each child from the HV group received three photos with of a target shape from different perspectives. Once completed successfully, more target shapes were given until the training session ended after 30 minutes. **(C)** Children were asked to create a 2D net of polydrons based on the different perspectives. The polydron net is the solution for the target shape shown in panel B. **(D)** Virtual version of the polydron task, rendered in Unity. Children from the VO group could manipulate the virtual polydrons and cubes using hand gestures. **(E)** Children set in front of a standard laptop (1) and put their hands on top of a Leap Motion sensor (2) to complete the task using hand gestures.

outline only) or solid format. Children were asked to construct a correct 2D net from the polydron faces according to the pictures which indicated the shape, orientation, and format of each polydron. Fig. 1C shows the polydron net solution for the target shape in Fig. 1B. The perspectives of the target shape remained visible throughout the entire session, and children could fold the net and compare it against the target shape during the session by manipulating them.

When completed, children raised their hands to have their net checked by the experimenters. If correct, The polydron faces were reset within the training box and children were provided with new perspectives of a new target cube. If incorrect, children were told the number of incorrect faces and asked to try again. Videos of the experiment can be found in https://nyu.databrary.org/volume/1551.

IV. REAL-TIME HAND-TRACKING INTERVENTION

Children in the VO group completed a virtual version of the polydron task (Fig. 1D) which involved real-time automatic tracking of their hand movements. The polydron faces and the perspectives of the 3D target cubes were displayed to the left of the screen (Fig. 1D). Children could manipulate the polydrons similar to the HV group by using hand gestures in the air (Fig. 1E) without any touch. The rest of the procedure was similar to the HV group.

In this training regimen, children sat in front of laptops and a LEAP Motion sensor (Version 2.3.1; https://www.ultraleap.com/) that was positioned below their dominant hand (Fig. 1E). We integrated the multiple infrared cameras within the sensor with the rendered polydron stimuli, allowing children to control and interact with the polydrons through natural hand and finger movements but without receiving haptic information. In other words, we harnessed the LEAP technology to create a three-dimensional interaction space where fine-grained motion details are captured, thereby 'forcing' children to rely on their mental representation.

The virtual renderings of the training materials were programmed using Unity (2021.3.15). The Leap Motion sensor was integrated into Unity using Ultraleap SDK (https://developer.leapmotion.com/unity), which enabled real-time data streaming from the sensor into Unity and interaction with the virtual objects. Prior to training, the experimenter set the target shape on the Unity program. Children were provided with guidance on how to manipulate the polydrons, and they practised gestures to select and move faces onto the net. All materials and codes can be found at https://github.com/Physical-Cognition-Lab/VisualSpatialTraining_Handtracking.

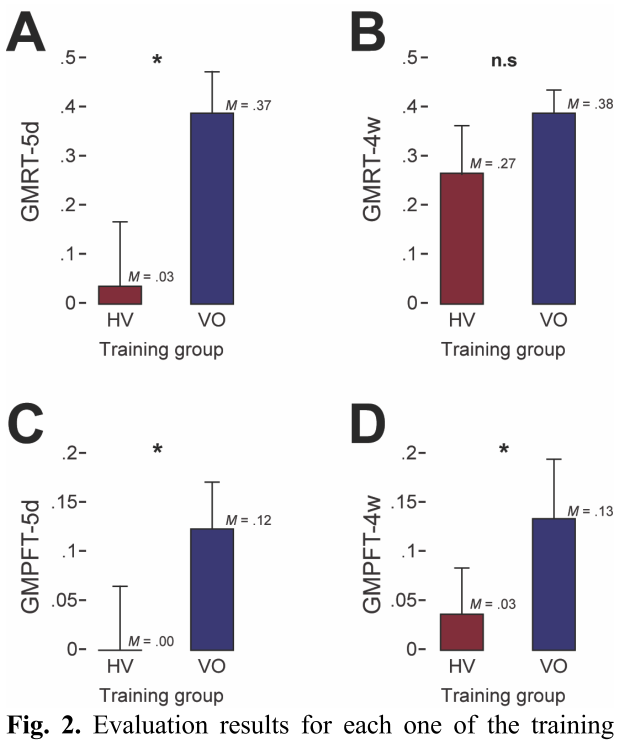

Fig. 2. Evaluation results for each one of the training groups. Children in the VO group had higher values in all four measures compared to the HV group. Asterisks denote significant differences.

V. EVALUATION

To evaluate their improvement, children completed established spatial tests in three testing sessions at three different time points: (1) before the training, (2) five days after the end of training (testing short-term effect), and (3) four weeks after the end of training (testing long-term effect). The spatial tests included the Mental Rotation Test (MRT; [36]) and the Mental Paper-Folding Test (MPFT; [37]). All tests were completed in children's classrooms in a paper-and-pencil format under exam conditions.

The MRT and MPFT are standardised tests of spatial skills, available digitally for research use. In each test session, children completed a black-and-white printed version of the MRT in which they were presented with 3D shapes rotated around multiple axes. They were asked to select two responses that matched the target shape while ignoring three distractors. Children were awarded a mark if they selected two correct responses for each shape. Overall, the MRT consisted of two 12-shape rounds, lasting 3 minutes each.

For the MPFT, we used the Vz-2-BRACE version (available via http://bitly.ws/KNmH) in printed individual copies. The test requires children to mentally visualise the results of a piece of paper being folded and hole-punched, then unfolded, as per pictorial stimuli. Children were awarded 1 mark if they selected one correct response. The test was separated into 2 sets of 10 questions, each taking 3 minutes.

Four children from the HV group and three children from the VO group did not complete the post-training evaluations, and therefore we excluded them from further analysis.

We compared children's improvements in each one of the tests after and before the training. To that end, we calculate a performance gain index G for each child. The G index is a normalised measure of improvement that accounts for the relative increase in performance while mitigating the impact of extreme values. The normalisation ensures that the gain index reflects proportional improvement, allowing for a consistent comparison of training effectiveness across different levels of initial ability. We calculated the G index according to the following formula:

$$G = \frac{Spost - Spre}{Spost + Spre}$$

Where $Spost$ is the child's success in the test after training and $Spre$ is the child's success before the training. Overall, we calculated four G values *for each child*: (1) $G_{MRT\text{-}5d}$ (performance gains in the MRT five days after end of training;

$Spost$ = success in the second MRT session; $Spre$ = success in the first MRT session); (2) $G_{MRT\text{-}4w}$ (performance gains in the MRT four weeks after end of training; $Spost$ = success in third MRT session; $Spre$ = success in the first MRT session); (3) $G_{MPFT\text{-}5d}$ (performance gains in the MPFT five days after end of training; $Spost$ = success in the second MPFT session; $Spre$ = success in the first MPFT session); (4) $G_{MPFT\text{-}4W}$ (performance gains in the MPFT four weeks after training; $Spost$ = success in the third MPFT session; $Spre$ = success in the first MPFT session).

Fig. 2 shows the comparison between the two groups in each one of the measures. Children in the VO group had higher values in all four measures compared to the HV group. We found a significant difference in $G_{MRT\text{-}5d}$ ($t(16) = 6.19$, $p < .03$; unequal variance t-test), $G_{MPFT\text{-}5d}$ ($t(16) = 3.90$, $p < .05$), and $G_{MPFT\text{-}4W}$ ($t(16) = 3.87$, $p < .05$). For $G_{MRT\text{-}4w}$, the difference was non-significant ($t(16) = 2.38$, $p = .14$).

VI. Summary and Future Work

Our use of real-time hand-tracking technology to enhance adolescent spatial skills demonstrates a novel application for motion sensor technology. Our findings suggest that omitting haptic feedback facilitates the integration of visual information into children's internal representation of the physical world. This finding aligns with existing literature that underscores the malleability of spatial skills during adolescence and illuminates the effect of sensory information on training outcomes.

Our approach also highlights the potential of using automatic and rapid hand-tracking technology as a cost-effective tool to facilitate learning in educational settings. This is particularly important for educational theorists and practitioners who seek to harness the benefits of multisensory learning. We used real-time hand-tracking technology that is not only affordable but also introduces an element of interaction and engagement that traditional educational tools may lack. This could be especially beneficial in schools aiming to provide innovative educational experiences that capture students' interest and facilitate deeper learning of spatial skills.

The study was conducted with a relatively small sample size and only with female adolescents, which limits the statistical power and generalisability of the results. Therefore, future research should test our approach in a wider demographic spectrum, including males, younger ages, varied socioeconomic backgrounds, and neurodiverse populations. Finally, long-term studies would be beneficial to assess the durability of the skills acquired and their potential impact on academic performance, particularly in STEM subjects.

While the absence of haptic feedback in the Visual-Only (VO) group led to greater improvements, it is worth considering how individual differences in baseline spatial abilities could moderate these effects. Specifically, children who initially have lower spatial abilities may benefit differently from the proposed hand-tracking technology compared to those with already high abilities. If hand-tracking technology is more beneficial for children with initially lower spatial abilities, this could have important implications for educational equity. It suggests that such technology could be particularly valuable as an intervention tool to help close the gap between low and high achievers. Thus, as part of a larger-scale examination of our approach, we propose to systematically test a variety of initial spatial skills and compare the effectiveness of the hand-tracking technology across these varied groups. This would involve pre-assessing spatial skills to categorise children into different levels of initial ability and examine whether the gains from the VO and HV training regimens differ based on these initial skill levels.

Our findings are also inconclusive regarding whether removing haptic feedback during spatial training has long-term effects. We found stronger effects five days after the training ended compared to four weeks after. Nevertheless, there were differences between the groups in the MPFT test, raising the possibility that the lack of significance in the MRT results is due to a lack of power. longitudinal studies could be conducted to determine if the improvements are maintained over time and if they translate to other cognitive or academic benefits.

Finally, our findings pave the way for advanced spatial skill training programmes that incorporate a variety of spatial tasks, offering different degrees of haptic feedback. These future training modules could delve deeper into the intricacies of how varying sensory experiences impact the acquisition and refinement of spatial skills, and shed light on the optimal balance between haptic input and visual-cognitive reliance, potentially establishing a more effective paradigm for spatial skill development.

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