Move or Be Moved: The Design of a Haptic-Tangible Manipulative for Paired Digital Education Interactives

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Abstract. One of the current limitations in digital educational experiences is the lack of touch. Touch is a critical component in the learning process and in creating inclusive educational experiences for sensorially diverse learners. From haptic devices to tangible user interfaces (TUI), a growing body of research is investigating ways to bring touch back into the digital world, yet many focus on a specific dimension (e.g. haptic feedback or kinesthetic manipulation) of touch. Learning, however, is a multi-dimensional touch experience - it is about moving and being moved. This work presents the Action Quad - a novel haptic-TUI design for teaching geometry (specifically quadrilaterals). The Action Quad is a multi-point-of-contact, reconfigurable tool that synergizes the affordances of both kinesthetic interaction and haptic feedback into a single form factor. We present findings from an initial user study (N=11) investigating how sighted-hearing individuals approach, interact, and experience the Action Quad, and we present a case study with an individual with blindness. We share key takeaways from the design process and participant feedback on interactions with this novel haptic-TUI device, sharing design insights on an emerging area of research that could support a new class of educational learning tools rooted in touch.

Keywords: Haptics · Tangible User Interfaces · STEM Education · Inclusive Design

1 Introduction

There has been a rapid shift of educational content to the digital space—from online videos and instruction to interactive educational simulations [11]. This shift was heightened during the COVID-19 pandemic, which opened a new era of digital education offerings and opportunities, but also highlighted the challenges of the lack of interactive, hands-on learning experiences [23, 34]. What once used to be manipulated and learned through movement and tangible interaction, is often now consumed visually and aurally on-screen. The lack of touch-based interactions is particularly detrimental for inclusion of sensorially diverse learners, such as those with blindness and low vision (BLV), where touch is a primary mode of information access [10]. Beyond access, however, touch is a key component in the learning process for all individuals; interactive, kinesthetic learning opportunities bring more of our sensory and motor functions into the cognition process, a well-known component of active learning and conceptual understanding in embodied cognition [8, 2].

Several efforts have focused on bringing touch back into the digital world, with two primary communities pioneering advancements: tangible user interfaces (TUIs) and haptics. Both haptics and TUI research aim to provide novel touch experiences, but do so through different means. TUIs are designed as physical representations of virtual objects, enabling users to control objects in the digital space by manipulating the tangible interface [28]. TUIs primarily serve as one-way, input devices, and often take on form factors similar to the virtual objects they represent. These interfaces can be challenging to design effectively, as noted by Shaer; it is vital to understand how a user approaches and makes sense of such a tool for effective design of physical form factor and haptic experiences [28].

TUIs, such as Media Blocks [31] or Block-Jam [21], bring enhanced interactivity to digital spaces through hands-on learning [17, 35], opportunities for collaboration [4, 7, 30], and accessibility benefits [16, 22]. Early work demonstrated the efficacy of TUIs in education applications, such as Programmable Bricks [25] which offers students a physical set of toy bricks that pair to a digital space, acting as handles or controllers for on-screen electronic objects. Recently, more efforts have been focused on TUIs for mathematics, such as a tabletop interactive space for trigonometry [32], a set of freeform objects for early-childhood numeracy conception [5], or 3D-printed tangibles for geometry learning [3]. These efforts have highlighted some of the benefits of tangible learning experiences in classrooms, especially for students with learning disabilities, and particularly in mathematics.

Haptic devices, on the other hand, are inherently focused on providing a user with touch feedback (primarily force or tactile), representative of interactions within a virtual or remote environment. Haptic devices often focus on the output to the user and have form factors that are wearable, graspable, and touchable [6] depending on the varied applications of use. The Phantom OMNI [19], a pioneering haptic device, was first introduced in 1994. This table-top device provides precise force feedback through a pen-like interface, allowing virtual objects to be felt with high resolution, and has been used in educational applications including biology [20] and physics [33]. Another educational haptic device is the Haptic Paddle [26]: this low-cost haptic tool has been used to demonstrate principles of dynamics, mechatronics, and controls [18, 9], and has shown effectiveness in improving student performance in dynamics laboratory courses [27]. Though not exhaustive, these examples represent the varying form factors, types of feedback, and contexts that haptic devices can provide within education. Unlike TUIs, which have a primary focus on manipulation, haptic devices tend to focus on the display and fidelity of feedback. Yet, learning is a compilation of all of these interactions - moving and being moved.

This work presents the first steps in designing a novel haptic-TUI: Action Quad (Figure 1). Action Quad is a multi-point-of-contact, reconfigurable tool that promotes both kinesthetic interaction (moving) and haptic feedback (being moved), while maintaining a form factor that is representative of the object itself. Action Quad synergizes principles of haptics and TUIs, emphasizing the affordances of tactility as a sense-making modality. This intersection promotes the opportunity of providing dynamic haptic feedback [12] and enhanced manipulation [13] from a singular platform. Action Quad was designed for an educational context of learning geometry, specifically quadrilaterals, which dictated its initial form factor. This paper presents the design of Action Quad and a first usability assessment on how individuals approach and interact with this hybrid TUI-haptic interface.

In Section 2, we detail the hardware and software framework that supports this new interface. Through an initial user study (*N*=11) presented in Section 3, we evaluate the usability of the Action Quad in two dimensions: how users approach and interact with the device, and how device performance impacts user assessment of the system. We discuss our findings in Sections 4 and 5, highlighting user approach and exploration strategies, how users distinguish characteristics of the Action Quad using both local and global descriptions, and participant-assessed performance of the Action Quad. In Section 6, we present a case study with an individual with BLV, toward uncovering insights on how a user's approach, interactions, and assessment of the system may vary from a nonvisual perspective. We conclude and share future work in Section 7. This work sets the stage for a new genre of educational tools—hybrid haptic-TUI systems—with an initial focus on how such systems can be designed to support usability and intuitive interaction with a broader goal of bringing touch back in multiple dimensions in digital education contexts.

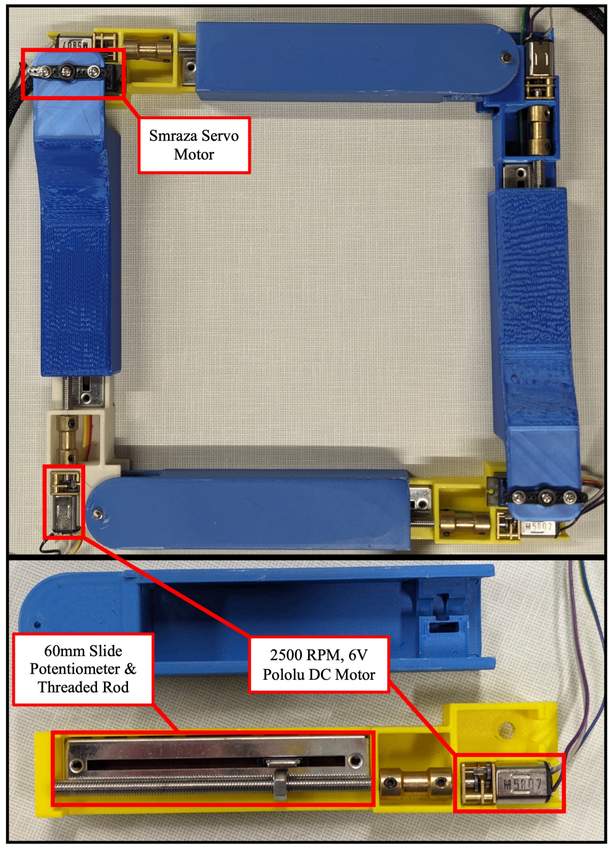

Fig. 1: Top: The Action Quad's 3D printed shell houses all components. Bottom: Each link contains a potentiometer, threaded rod with lead screw, coupler, and DC motor.

2 System Design

Context: The Action Quad is part of a broader set of inclusively-designed geometry learning tools that consist of both hardware and software components [15, 14], collectively called The Quad. The hardware consists of variants of a 3D printed tool—from a base design (Base Quad) that has no electronics and can be used as a standalone tool to a smart design (Smart Quad) that has sensors built in for length and angle tracking. The software consists of the *Quadrilateral* simulation (or "sim"), developed by the PhET Interactive Simulations project [29, 24]). The *Quadrilateral* sim can serve as a self-contained, accessible learning experience with interactive visual, auditory, and speech displays and multiple input options. For example, the Smart Quad can be paired with the *Quadrilateral* sim. The Action Quad represents the next constituent in this hardware lineage—providing the capability to move or be moved when paired to the sim.

Design Requirements: Working in the context of a pedagogical toolset for learning geometry, several requirements guided the Action Quad's design. The Action Quad needed to be small enough such that two hands could explore the entire top surface and large enough to allow for two-handed interactions along each link. A user must be able to interact with the tool in any location they choose to promote free kinesthetic explorations. The links and corners must actuate to reconfigure the Action Quad to a range of four-sided shapes: rectangles, trapezoids, parallelograms, squares, and rhombuses. The Action Quad needed to consist of readily-available, inexpensive parts to enable broad deployment, while keeping total cost under \$100 to support adoption in educational settings. The Action Quad must be able to be commanded to any configuration in under 4 seconds and within 5% accuracy for both lengths and angles to provide timely responses between other components, such as the Smart Quad or the *Quadrilateral* simulation. The Action Quad setup must be powered via a standard wall outlet. Finally, the Action Quad must be able to receive input from multiple software interfaces, including the *Quadrilateral* sim or the Smart Quad, to offer flexibility in its use.

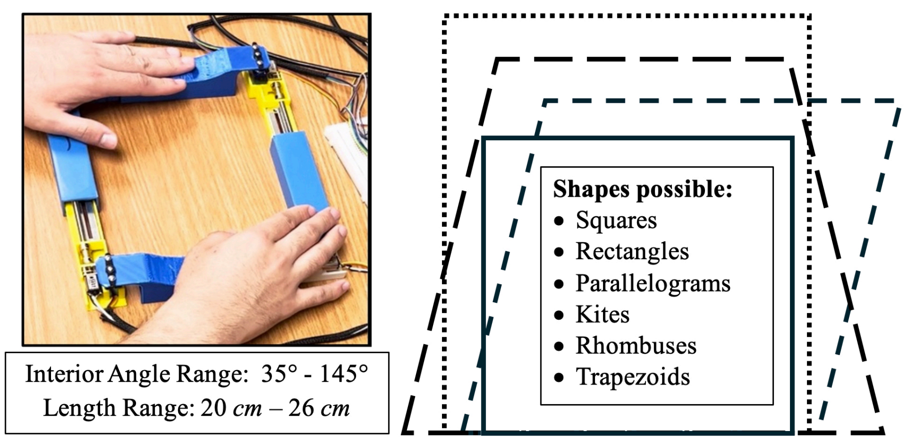

Fig. 2: The functionality of the Action Quad enables all convex four-sided shapes to be made with a range of sizes while enabling users to interact with the shapes using their hands.

Design and Electronics: We employed a human-centered, iterative design approach in the creation of the Action Quad, drawing on findings from our previous Quad tool developments and frequent feedback from end users, including those with BLV. Specifically, prior to designing Action Quad, we iterated through over 10 design cycles and iterations across the Base and Smart Quad designs, determining the appropriate total footprint range ($225cm^2$ to $625cm^2$), link size ($2cm$ x $2cm$ x $15cm$) and link geometry (rectangular vs. cylindrical). With Action Quad, our goal was to maintain these inherent form factor characteristics, while increasing capability. Initial designs employed motorized slide potentiometers in a 3D printed enclosure which were found to have insufficient strength for reliable, accurate actuation. The final Action Quad design (Figure 1, top) consists of 4 links with 2 primary housing parts and 5 internal components per link, plus additional external components for a total of 31 parts. Aside from its internal components, it is entirely 3D printed and uses a lead-screw based mechanism which enables rapid and precise extension and retraction of the lengths.

The 4 links of Action Quad are connected at three corners via M3 screws for free rotation and at one corner via a housed servo motor (Smraza, SG90). Each link consists of two parts: a lower part that houses the DC motor (Pololu 15:1 Micro Metal Gearmotor LP 6V @ 860RPM) coupled to a $100mm$, $0.5mm$ pitch M5 threaded rod, and slide potentiometer (Mouser Electronics PTB6043-2010BPB103), and an upper part that houses an M5 nut that moves along the threaded rod as the motor spins (Figure 1, bottom). A 60mm slide potentiometer was implemented as a length sensor as our previous Quad tools had demonstrated its accuracy and ease of use.

The system is controlled by an Arduino MEGA with a L298N Motor Shield, powered by an external power supply, delivering 12 volts @ 2 amps. It is connected via USB port to a PC to enable Serial connection to digital tools.

Assembly and Function: The Action Quad weighs 388 grams and is capable of creating shapes as small as $20cm$ x $20cm$ and as large as $26cm$ x $26cm$, with an angle range at each corner of 35° to 145°, enabling a wide range of quadrilaterals to be created (Figure 2). The Action Quad housing for each link is $2.0cm$ tall by $2.5cm$ wide, 3D printed, and assembled in 8 hours. Each link requires 5 soldered connections (3 to the potentiometer, 2 to the DC motor) for wiring to the microcontroller, and installation of the motor, coupler, threaded rod, and potentiometer into the housing. The total cost of materials and components is approximately $65.

Communication and Control: The Action Quad can be controlled in two ways: 1) directly from the virtual *Quadrilateral* sim or 2) via the Smart Quad which transmits shape data via Bluetooth to the *Quadrilateral* sim. The sim connects to Action Quad through the p5.serialcontrol application [1], which runs on the user's computer. This app receives messages from the sim and relays the commanded configurations (four desired length values and one desired angle value) to the Arduino Mega, where the information is parsed, calibrated, and commanded to the Action Quad via a serial connection. The movement scheme for each length is position-based, using positional measurements from the potentiometer readings to reach desired configurations. A configuration was considered "reached" when the position was within $0.14cm$ (2.35% of the full extension length) of the commanded position. This range was found to be the smallest tolerance for reliable movement results. The dual input for Action Quad enables a variety of use cases for a learner in a pedagogical context: 1) experiencing configurations of the Quad being produced in the sim; and 2) experiencing configurations of the Quad being produced by another tangible device, which can be controlled by the same or a different learner. While the studies in Section 4 focus specifically on the tangible interactions with the Action Quad in isolation and the Smart Quad to Action Quad, we detail the full integration of communication and control for completeness as it impacted the design of Action Quad.

Performance Validation: To evaluate the performance of the Action Quad, we ran a series of benchtop tests that measured the extension and retraction speeds, accuracies, and forces displayed. The Action Quad was powered by a 12 volt external power supply connected to the motor shield, and was laid flat on a tabletop with $1cm$ grid markings for length measurement. A PC was used to send configurations to the Arduino via serial communication. In the speed test, each length in the fully assembled device was moved through a series of lengths ($20cm, 26cm, 20cm, 26cm, 20cm$) 3 times each to give 15 total trials, with time from initial position to final position being recorded. With the current design, each length individually can fully extend from a base value of $20cm$ to an extended value of $26cm$ in an average of 1.34 seconds ($SD = 0.1$), moving at a speed of $4.47cm/s$. When operating all four motors simultaneously, the Action Quad can extend from the home position (all lengths at $20cm$, all right angles, area $= 400cm^2$) to fully extended (all lengths $26cm$, all right angles, area $= 676cm^2$) in an average of 1.54 seconds ($SD = 0.1$). All rotation commands are stepped through over 450 milliseconds to create smooth movements. Similarly, 3 trials were run to assess accuracy of reaching commanded configurations. Each length in Action Quad was moved through the same series of lengths as in the speed test. In each trial, the achieved length and angle measurements were compared against the desired length and angle values. Each length was accurate to within $\pm 0.22cm$. The corner actuation via servo motor was accurate to within $\pm 3°$.

Lastly, the forces for extension and retraction were measured using a Kistler Quartz Force Sensor (Type 9203) calibrated using a set of gram weights connected to a Kistler Charge Meter (Type 5010). In extension, one link of the Action Quad was constrained to the tabletop while the opposite end was extended into the force sensor. The maximum value before motor stall was recorded. Similarly in retraction, one link was constrained to the tabletop while the opposite end was connected via mounting screws to the force sensor and retracted, pulling the force sensor. The maximum force value before stall was recorded. This was repeated 10 times per link. Overall, the average maximum force during extension was $3N$ ($SD = 0.13$) and $2N$ ($SD = 0.24$) during retraction. Collectively, these results demonstrate the benchtop performance of the Action Quad—illustrating speeds, accuracies, and force displays that are appropriate for the educational context it is designed to work within.

3 Research Study

The Action Quad represents a novel interface with multiple points of contact and affordances of both a haptic device (in its ability to generate forces) and a tangible interface (in its ability to command configurations). This synergy of capability provides interesting usability and interaction questions, which motivate the study in this paper. For example, where, how, and why do users hold the device? How do they respond to "being moved" and "commanding movements"? How do users make sense of the configurations created? Here, we investigate these questions toward assessing the fundamental design and usability of the Action Quad. This study is a necessary first step to refining Action Quad for future assessment in educational contexts. To this end, we conducted a usability study to investigate how users (N = 11) approach interaction with the Action Quad and how its performance in isolation and in the Action Quad-Smart Quad system impacts the users' assessment of it. This study was conducted with 11 sighted participants (18-28 years). Additionally, as the Action Quad exists within a set of inclusive education tools, we wanted to garner inclusive perspectives on the system. To this end, we conducted a case study with an individual with blindness (22 years, diagnosis: Leber congenital amaurosis) (see Table 1 for participant demographics). To understand the Action Quad from both a usability and functionality perspective, we address the following research questions in this work:

1. In what ways do users approach Action Quad, and what interaction strategies are used to make sense of the Action Quad and its reconfigurable features?
2. How did Action Quad's performance affect users' assessment of the system?

To investigate the two research questions, the study was divided into three sections: 1) interactive; 2) observatory, and 3) comparative. In each section, participants completed a series of tasks and prompts that required them to explore the Action Quad and verbally comment about their interaction with the system. For the duration of the study (session length approximately 25 minutes), the experimenter sat across from the participant and controlled the Action Quad via a USB connection to a computer. The computer was running the PhET Simulation *Quadrilateral*. Data collected in each section includes participant comments and responses to feedback prompts specific to each task. All sections were video recorded for post-study analysis of interaction methods.

In the Interactive Section, we wanted to investigate how users organically approached the Action Quad. Here, participants were presented with a series of shape transformations wherein the experimenter configured the Action Quad from one shape to another using the connected computer. This task was designed to observe how participants chose to interact with the device during reconfigurations. Participants experienced 3 sets of the same shape transformations in the same order: 1) square-rectangle; 2) rectangle-parallelogram, and 3) parallelogram-square. Participants were not explicitly instructed on how to interact with the device during the 3 transformation sets, as we wanted to understand how users naturally approached the device. If the participant was reluctant to interact with the device during the first set of transformations, they were encouraged by the experimenter to hold the tool in specific locations (e.g. top/bottom, left/right sides) during the second set. After each set, participants were asked to provide feedback on their interaction with the Action Quad (e.g. "What changed on the device between transformations?","How did that change occur?"). Answers to the above questions coupled with participant interaction strategies

Table 1: Participant Summary

#	Age	Sex	Dominant Hand
1	28	M	R
2	20	F	R
3	30	M	R
4	25	M	L
5	26	F	R
6	25	M	R
7	29	M	R
8	21	M	R
9	28	M	R
10	24	F	R
11	27	F	R

were recorded for analysis. Participants also provided a rating of comfort with their interaction on a 7-point scale (1: uncomfortable, apprehensive, 7: comfortable, familiar). The data collected in the Interactive Section uncovered insights on hesitations or design limitations, addressing Research Question 1.

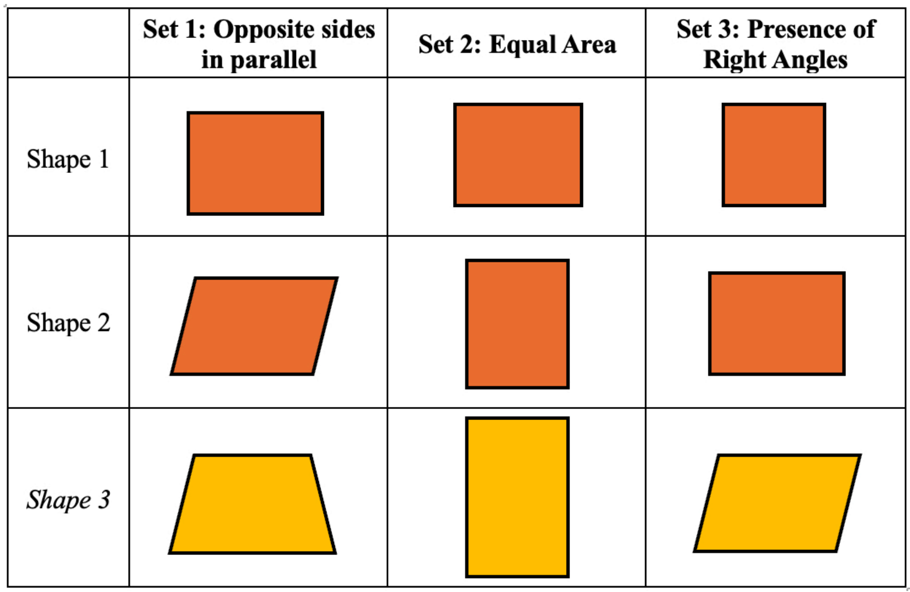

Fig. 3: The shape sets shown in the Observatory Section. Participants could ask to see the set of shapes in order as many times as desired.

The Observatory Section was conducted to assess how well the Action Quad can create shapes and investigate if and how participants used shape properties to differentiate between shape configurations using the Action Quad. In this task, participants were presented with three sets of shape configurations on the Action Quad. These sets consisted of two shapes that highlighted a special property (two sets of parallel sides; equal shape area; presence of right angles, shown in Figure 3) followed by a third shape without this shared property. Participants were instructed to identify a property (if any) shared by the first two shapes that distinguishes them from the third, final shape. The Action Quad was configured by the experimenter through the connected computer into the first shape and the participant was instructed to interact with the device in any way they chose (touch or observation). The Action Quad was configured into subsequent shapes in each set when the participant signaled they were ready. The participant's identification of the shared property of the shapes was recorded, as were their tangible interactions with the Action Quad. Data collected in this section informed how users made sense of the Action Quad as a device to display shapes, as well as highlighted the performance of the Action Quad in its ability to create notably different configurations.

Finally, in the Comparative Section, we assessed the Action Quad's performance in an initial tangible-tangible scenario and user's perception of its ability to replicate shape configurations they created. Participants utilized the Smart Quad tool to create their own configurations and represent them with the Action Quad (see Figure 4). This task evaluated the participant's assessment of the system's accuracy. In this comparative task, participants were asked to change one parameter (a length or an angle) on the Smart Quad and to assess the accuracy of the Action Quad's replicated shape on a 7-point scale (1: completely inaccurate, 7: perfectly accurate). Then, participants were asked to create any configuration on the Smart Quad and assess the accuracy. Tangible interactions and participant ratings and comments were recorded. Participants did this task 3 times.

4 Results

The results are presented through a mixed-methods analysis approach and include both participant responses and ratings to the tasks within each study section and their associated video recording. Due to the low sample size of the study, we elected to use descriptive and summary analysis to better represent our findings.

Interactive Section We analyzed video recordings of all participants observing key themes around: first interaction with Action Quad (with or without prompting); whether the device was held or kept flat; and how users talked about their interaction (e.g. global description of the shape created or local descriptions of the individual components of the shape). During the first set of transformations, only 1 of the 11 participants interacted with the Action Quad without prompting. During the second set of transformations, all participants interacted with the Action Quad (with prompting). Of these, 2 participants lifted the device off of the table, but 9 chose to place their hands flat along the top surface (Figure 5). Nine participants commented on the increased tactile information when holding the opposite pair of sides during actuation (e.g. Holding the top/bottom during left/right actuation or vice versa. One participant noted, "If I hold the top and bottom [during top and bottom actuation], not really... Okay, now [holding the left and right] I do get the sense that... the shape got bigger").

The average comfort rating across all participants and interactions was a 6 out of 7 (SD = 0.86). To understand how participants discussed the movements of the Action Quad, we also analyzed the focus of their descriptions as global (directly mentioning shape by name) or local (commenting on the individual components of the tool

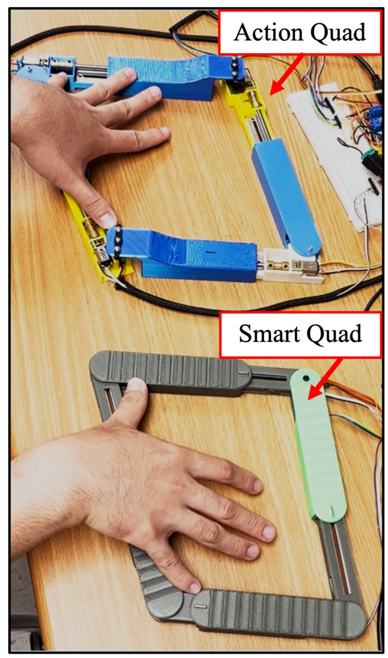

Fig. 4: In the Comparative Section, participants created a configuration on the Smart Quad (bottom) and compared the parameters with the Action Quad (top). Here, the participant in the case study compares the relative lengths of the Smart Quad (bottom) and Action Quad (top) by using their hands as a metric.

such as link extension or corner rotation). Four participants described the device's movements by local changes (e.g. "The left got longer and the top right corner widened."), 3 described only the global changes (e.g. "It went from a rectangle to a parallelogram."), and 5 described both the parameters and shapes. Collectively, we observed that users were quite hesitant to interact with Action Quad, but after prompting, five participants commented on obtaining increased information about the transformation through touching the device: "Initially, visually... it felt like [the sides] pushed apart equally but this time I felt my left hand being pushed."

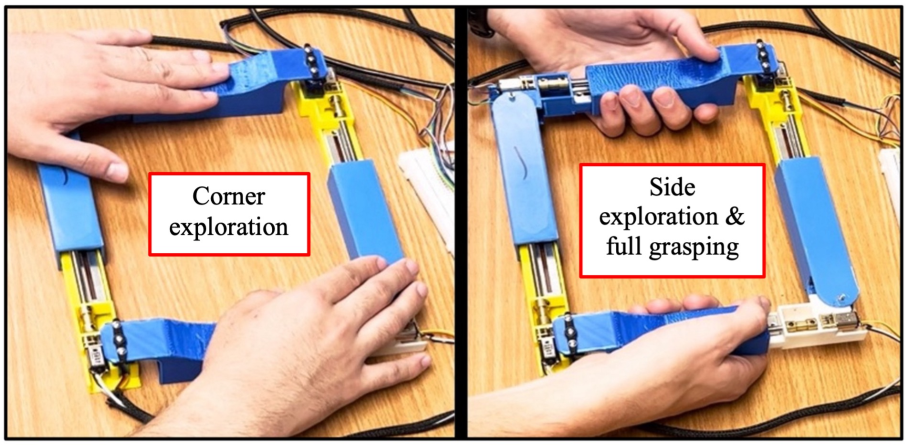

Fig. 5: Common exploration strategies from participants when interacting with the Action Quad. Most common was interaction flat along the top surface (shown on left, 9 out of 11 participants), while some participants chose to pick the device up and fully grasp the links (shown on right, 2 out of 11 participants).

Observatory Section We analyzed participant responses regarding distinguishing features identified through 3 sets of shapes and used the video recordings to analyze participant tactile interactions, if any. In the first set of shapes, 8 of the 11 participants were able to correctly identify the number of parallel lines as the distinguishing feature (geometrically equivalent answers were accepted such as "opposite corners were equal angles" or "opposite sides were equal lengths"). In the second set, 5 participants correctly identified the difference in area between the first two shapes and the final shape, while 3 participants gave no answer. In the third set, all 11 participants correctly identified the presence of right angles in the first two shapes and not in the final shape. During these sets, 3 participants maintained touch throughout, while the remaining 8 opted to observe the shapes only.

Comparative Section We used video recordings to analyze the participant-assessed accuracy of replicated shapes and the overall description of the input shape. When changing one parameter, the average perceived accuracy was a 6.0 out of 7 (SD = 0.77). Participants then created 3 custom configurations, with perceived accuracy averaging to 5.8 out of 7 (SD = 1.38). Configurations included rectangles (3 participants), trapezoids

(5 participants), parallelograms (8 participants), while all 11 participants created non-standard convex quadrilaterals. Comments on the accuracies mainly highlighted angle measurements: "I gave it a perfect 90 [degree angle] to test that, and it nailed it", "The angle between the left side and bottom doesn't quite match what I made". A few comments were related to the Smart Quad - Action Quad system: 3 participants commented on the relative orientation to the table of the Action Quad compared to the Smart Quad, and 2 commented on the overall footprint of the Action Quad being larger than the Smart Quad.

5 Discussion

Taken together, key takeaways from the three part study were 1) Approach and Comfort: Users were initially apprehensive about engaging via touch but quickly became familiar and often used a two-handed exploratory approach upon first use; 2) Interaction: Users were accurately able to distinguish key features of the Action Quad (parallel lines, right angles), used varied language to describe these features (local vs. global), and experienced increased tactile information when holding the opposite pair of sides during actuation; 3) Assessment: Participant-assessed replication accuracy of the Action quad was high, and all participants were eager to create non-standard geometries to probe the limits of the system. Additionally, during the third set of transformations, participants were eager to explore different interaction schemes, with some lifting the device off the tabletop, others exploring the corner joints to investigate where more significant haptic feedback might exist in movements. Interestingly, 5 participants remarked that they gained more information about the movements when holding the device compared to just visual observation, perhaps due to the forces displayed by each link when actuating. This illustrates the value add of haptics embedded into the tangible manipulative which will require future investigations to quantify. Participants described the tool using both local and global descriptions, which may suggest that the reconfigurable nature of the tool plays a role in interpretation of the Action Quad's configurations. Specifically, the use of local language ("the left side extended") suggests interpretations based on the actuation rather than the overall final state. Further investigation into how the reconfigurable nature of the tool and user focus on global versus local features affect mathematical understanding is needed.

The results from the observatory section illustrate the ability of the Action Quad to create and highlight significant geometric features such as parallelism or right angles between sides, but participants struggled to identify the difference in area. This could be due to a number of factors but is likely attributable to the limit of extension along each link; the links extended $3cm$, from $20cm$ x $23cm$ to $20cm$ x $26cm$, equalling an area change of $460cm^2$ to $520cm^2$, respectively, a 13% increase in area. This suggests a need for a metric along each link to indicate length values, such as tactile indentations at regular intervals along each link.

The participant assessed accuracy in the comparative section was high. When commenting on inaccuracies, participant comments were themed around the angle accuracy more so than the length accuracy, especially with non-symmetric configurations and non-right angled shapes. This is likely due to the embedded actuation mechanisms which create a non-extendable section of each link. This limitation does not exist in the Smart Quad nor the *Quadrilateral* Simulation, and thus is hypothesized as a contributor to some of the inaccuracies. This difference in turn alters the angle relations between links. The wide range of input shapes from participants demonstrated their interest in understanding the affordances and limitations of the system and illustrated the system's ability to accommodate a wide variety of configurations. The resulting average perceived accuracy coupled with the results from the benchtop tests, provide initial validation of the Action Quad's performance.

6 Case Study: Individual with Blindness

The same user study was run with one participant with blindness (22 years; Leber congenital amaurosis) to garner initial impressions of the Action Quad and its functionality from someone with more familiarity with tactile exploration. The participant rated their average comfort with the device throughout the 3 sets of Interactive transformations as 5.75 out of 7 (SD = 0.58) and rated the accuracy of the replicated shapes across the four Comparative trials with an average of 5.25 out of 7 (SD = 2.22).

Overall, this participant had some surprising sense-making strategies that had not been used by the 11 sighted participants. As expected, this participant used the full extent of their hands immediately to approach and understand the device and its capabilities (see Figure 4 for an example of tactile comparison strategy). They also compared the device to other objects available to them such as the table, for even greater understanding of the shapes in relation to the environment. This participant was also the only participant to remark on the ambient sounds of the device and incorporate sound into their sense-making strategy across the different study sections.

To determine the shape was growing larger, they used both tactile interactions ("There was some tactile feedback... I could tell that these two [sides] got larger") coupled with the duration of the mechanical sounds of the device as the Action Quad moved. They could also distinguish the sounds of the servo and DC motors and could map them to the device's angle and length movements, respectively. During the Observation Section, when asked to find the distinguishing feature of the shapes, this participant's initial sense-making strategy involved determining device-centric elements, such as the overall size of the device and its movement during transition, before eventually settling on shape-centric elements such as parallelism and relation between links as time and experience with the task increased. The participant also commented on aspects of the Action Quad that previously had not been mentioned, such as the speed :"The movement is pretty rapid, so it can be hard to follow that", and how tactile exploration can alter their understanding: "As it's mechanically moving, the position on the table changes, or when you touch it. So that loses some geometric integrity when exploring". Overall, the participant had positive feedback for the Action Quad: "It was really neat to watch it come alive".

7 Conclusion

In this paper, we present the design of Action Quad - a haptic-tangible interface to enable a full touch experience (moving and being moved) in the context of an inclusive toolset for geometry learning. We conducted initial user studies that investigate how users approach and interact with the device through a series of open-ended, exploratory tasks. This work offers important key takeaways in designing such interfaces including two-handed usage along the top surface, support for a wide range of shape sizes, and allowing for uninhibited touch interactions by minimizing exposed mechanisms. Future work on the mechanical aspects of the Action Quad will prioritize usage and user experience via enclosed hardware and a more seamless connection to The Quad system, allowing more in-depth evaluation of the educational applications of the multimodal, hardware-software tool, especially with younger student populations. Additional studies will also compare the Quad system with other methods of displaying shapes to evaluate these findings against other media, such as simulation alone. Research will also focus on how devices like Action Quad can be expanded to be more portable and flexible to span across numerous applications and pedagogical settings, enabling both individual and collaborative learning experiences that prioritize touch as a key interaction modality.

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