MorphGrip: Haptic Guidance Using a Shape-Changing Grip

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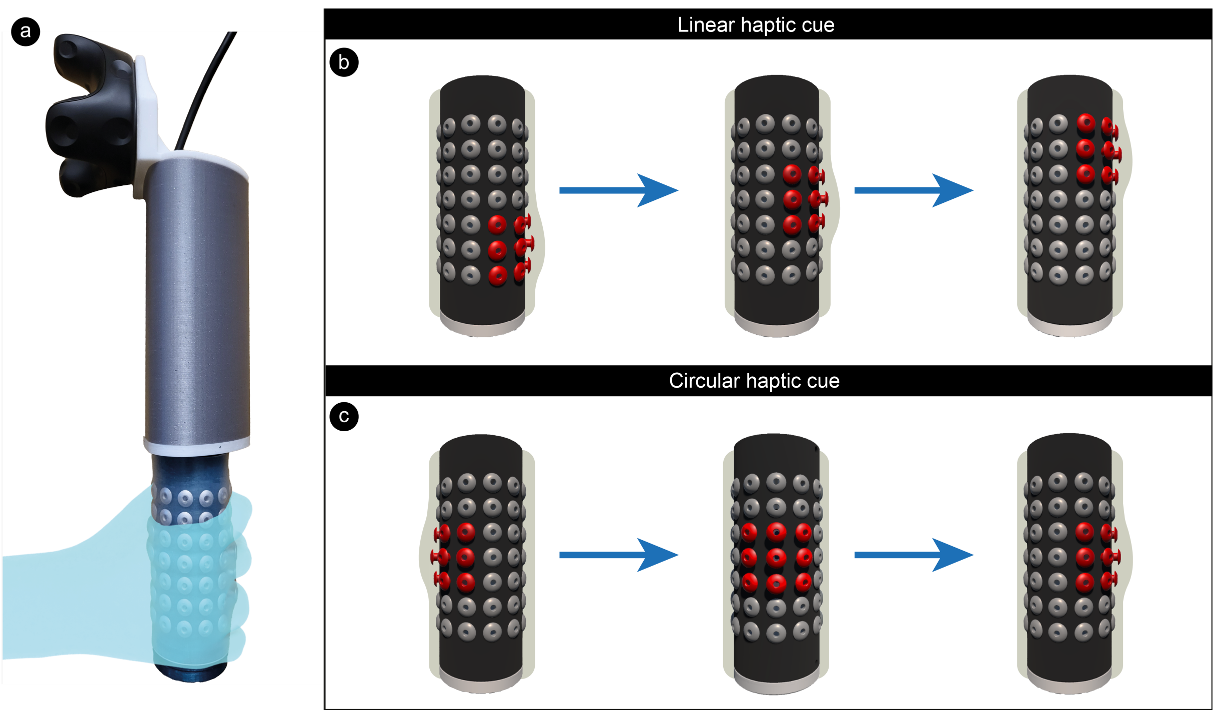

Figure 1: a) A hand user holds MorphGrip while its shape dynamically changes. b) *linear haptic cue*: the surface deforms upwards. c) *circular haptic cue*: the surface deforms circularly.

ABSTRACT

MorphGrip is a novel shape-changing grip that aims to guide the pose and position of controllers or handheld devices or tools. In a

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user study, we explored how well such directional shape changes felt at the user's palms and fingers can serve as guidance. The results indicate that haptic cues in horizontal and vertical guide users significantly better than cues that suggest moving MorphGrip in tilt and roll direction. While haptics have lower bandwidth than vision and auditory feedback, MorphGrip can be supportive in scenarios with a risk of audiovisual overload. Accordingly, we identify promising use cases for integrating MorphGrip into the grips of handheld devices for applications, such as rehabilitation therapy, smart tools, and guidance in special environments, like underwater.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

haptic guidance, shape-changing, handheld, ungrounded, controllers, tools

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1 INTRODUCTION

Handheld devices, virtual reality (VR) controllers, and tools, often operate as passive instruments, lacking the ability to respond to user input or their surroundings to assist during task execution. This passive nature can limit efficiency and accuracy, especially in complex or unfamiliar scenarios [23]. Researchers have focused on visual and audio guidance. In particular, visual guidance has found applications in various fields, including augmented reality for surgical support [5], car [13], and robot repairing [27]. Similarly, auditory guidance has been utilized for navigating spaces [18] and supporting visually impaired individuals during standing in line [19] and filling printed forms [8]. However, these technologies often rely on external actuators not integrated into the tools themselves, and these methods can fail when the channels are obstructed or busy. For example, guidance using augmented reality is limited by the small field of view of augmented reality technology [6], and guidance using auditory commands can be disrupted by street noise [3], thus complicating guidance.

Since we need to hold handheld devices, VR controllers, or tools, to use them, haptic feedback from the devices themselves appears to be a promising alternative for guidance. Recently, researchers have been investigating controllers capable of dynamically changing shape, known as shape-changing controllers, to provide haptic feedback [4, 12, 14, 41, 42]. However, only a few have used it for haptic guidance [20, 30, 36, 38], and further research is needed to explore the benefits of different types of shape changes for haptic guidance. The application of shape-changing interfaces, specifically those utilizing dynamic grip deformations, has not yet been evaluated in the context of guiding manual motor tasks.

This paper presents MorphGrip, a shape-changing controller that can provide haptic cues by dynamically changing its grip's form. MorphGrip has a matrix of movable pins on its surface. The pins can be extended, using a mechanism embedded within MorphGrip, to provide haptic feedback by stimulating the palm of the hand that holds the grip. MorphGrip leverages the fact that the palms possess a high mechanoreceptor sensitivity [2, 21, 40] to provide haptic feedback. With its versatile design, MorphGrip can be embedded in different grip types.

In a user study with 24 participants, we investigated the effectiveness of two haptic signals, *linear haptic cue*, i.e. along the grip, and *circular haptic cue*, i.e. around the grip, in guiding users to change the position and orientation of the held MorphGrip prototype. We tested four tasks: two translations (*horizontal* and *vertical*) and two rotations (*tilt* and *roll*). Overall, participants are faster in following verbal cues as they are used to them, while MorphGrip is novel and requires a learning curve. However, verbal cues do not fit into every context, particularly in noisy environments. Accordingly, 23 out of 24 participants found haptic cues helpful as guidance. Looking into the data in more detail, we found that haptic cues were better suited to indicate a translation of the hand rather than a rotation.

Based on these findings, we propose scenarios for integrating MorphGrip into handheld tools, particularly in environments where auditory and visual cues are overloaded or unavailable, such as noisy industrial settings for guiding tool manoeuvres, underwater environments, and in rehabilitation therapy to assist individuals with hearing impairments.

2 RELATED WORK

In our review of related work, we initially examine studies focusing on visual and auditory guidance. We then explore existing devices of haptic guidance, in particular, shape-changing devices. Following this, we look into the domain of shape-changing interfaces and the different types of shape-change that could be used for guidance. Finally, we clarify the research gap that our study aims to address.

2.1 General guidance

Visual guidance have received considerable attention in research. For example, several studies [29, 35] have explored methods to provide physical therapy without constant supervision of a therapist. In the SleeveAR project, visual cues are projected onto the user's arm and the floor, enabling patients to practice hand rehabilitation exercises independently at home [29]. Physio@Home introduces a dynamic on-screen movement guide that provides real-time visual guidance to users during physiotherapy exercises, this can guide arms for a range of movement and maintaining position or angle [35]. Outside the therapy scope, LightGuide helps guide the hand during path-following by projecting visual cues directly onto the user's hand, including arrow and path representations in 2D and 3D formats [28]. In addition, Condino et al. investigated the impact of visual cues on user performance, visual comfort, and workload during manual tasks using optical see-through head-mounted displays (OST HMDs) [6]. The findings of this study revealed that user performance was better in naked-eye tests compared to AR-guided tests. This study highlighted one of the limitations of current OST HMD technology for high precision tasks.

Concerning auditory guidance, there are multiple solutions focused on assisting visually impaired individuals. For example, LineChaser is a smartphone-based navigation system designed to support visually impaired individuals in navigating queues in public areas [19]. It utilizes information captured by the camera to provide audio commands such as "Walk to the 2 o'clock, 2.1 meters ahead" to guide users in the right direction. Similarly, NavCog is a smartphone-based navigational cognitive assistant designed to assist individuals with visual impairments in navigating unfamiliar environments [1]. It uses instructions such "turn left or right" or “approaching”. WiYG guides users through the form fields with audio instructions, enabling them to align and fill out the required information without relying on sighted assistance [8]. This solution uses instructions such as "move left" or "you are close,".

While previous visual and auditory solutions have been effective in guiding under specific conditions, it's important to note their limitations. Factors such as occlusion and restricted field of view can hinder visual guidance, while noisy environments make auditory guidance difficult. The following section explores how haptic feedback offers a promising alternative for guidance.

2.2 Haptic guidance

Haptic guidance leverages the sense of touch to convey information about the direction, force, or movement required to achieve a specific goal.

2.2.1 Overview. For instance, GuideBand is a device worn on the forearm, equipped with a mechanism controlled by servo motors that pull a wristband, simulating the sensation of being guided by a virtual character [36]. GuideBand delivers directional cues to guide hand movements to the left or right, up or down, forward or backward, and along diagonal paths. This resistance force enables users to interpret and follow instructions seamlessly, reducing cognitive load and enhancing task execution efficiency. Additionally, WAVES (Wearable Asymmetric Vibration Excitation System) produces three-dimensional haptic feedback by attaching voicecoil actuators to guide fingers [7]. This setup induces the sensation of being pulled or twisted in a specific direction, enabling it to generate both translation and rotation cues, which are particularly useful for navigation tasks.

2.2.2 Haptic vs auditory guidance. Previous researches have compared haptic guidance with audio guidance. Grindlay [10] compared audio, haptic, and combined audio-haptic cues for the acquisition of drumstick movements. The authors utilized an exoskeleton-like device designed for musical motor learning tasks. The study revealed that incorporating haptic guidance, either independently or alongside audio cues, significantly improved note timing and velocity recall. This improvement translated into a more consistent and precise performance, particularly during the initial stages of skill acquisition.

In a study closely related to our work, Weber et al. evaluated the haptic guidance provided by VibroTac, a wristband featuring vibrotactile stimulation, in comparison to verbal guidance for tasks involving translation and rotation. The results showed that participants performed better in rotational tasks when using vibrotactile feedback rather than verbal instructions [38]. While vibrotactile feedback was effective in providing continuous spatial cues, participants reported challenges in distinguishing the different translational cues, suggesting the need for improvements in signal clarity and interpretation. Furthermore, Ploch et al. compare haptic and auditory navigation cues for distracted drivers using a steering wheel that stretches the skin [22]. During a simulated distraction task, the effectiveness of haptic cues, provided through lateral stretching of the steering wheel skin, and auditory cues were tested. The results showed that haptic cues led to slightly higher navigation accuracy and better performance in the distraction task, while reducing cognitive load compared to auditory cues. Mugge et al. used a PHANTOM [1], a grounded device that provides force feedback, to ask participants to navigate to a specific target point, following certain force feedback cues as a guide. Authors reported that for force guidance to be effective, it needs to be aligned with the user's mental model of how force should be applied to achieve the desired outcome [20]. In this way, force feedback cues directed towards the target significantly enhance motor performance compared to opposing forces.

In the context of navigation aids, Bharadwaj et al. investigates the effectiveness of a tactile belt for navigational guidance in comparison to traditional auditory aids for blind individuals [3]. The findings showed that while auditory cues were more effective in quiet settings, the tactile feedback proved to be a strong alternative in noisy environments, highlighting its potential as a viable navigation aid. Additionally, NaviRadar is a tactile navigation system that uses a radar metaphor to convey directional information through haptic feedback, generated by a single vibrator on a mobile device [25]. Comparisons between NaviRadar and auditory navigation showed that both methods provided similar levels of usability and performance.

These studies [3, 10, 22, 25, 38] compared haptic cues against verbal or auditory cues, highlighting the distinct advantages of haptic feedback in certain scenarios. Specifically, they demonstrate that haptic feedback can offer navigational tasks and reduces cognitive load in noisy or multitasking environments.

2.2.3 Haptic guidance using shape-changing. Recent studies have started to use shape-changing devices to provide haptic guidance. For instance, the S-BAN is a shape changing device, with a rectangular shape, that can bend, extend and retract to guide users during their navigation [30]. The S-BAN can provide direction, distance, and environmental cues to users. Authors found that communicating both direction and distance enhances navigation performance. Similarly, Animotus is a shape-changing cube that can translates and rotates its upper half section to guide users during their navigation [31, 32]. In addition, the handheld device studied by Walker et al. provides haptic feedback to guide users' hand movements across four degrees of freedom, two translational and two rotational [37]. It generates these haptic cues using pantograph mechanisms driven by motors, which moves a surface that exert tangential forces on the user's thumb and index fingertip, inducing sensations that encourage specific hand movement directions. These three devices [30–32, 37] can only change their shape by changing their orientation. However, other types of shape-change handheld devices have been

[1] https://www.3dsystems.com/haptics-devices/3d-systems-phantom-premium

investigated to communicate information, as presented in the next section.

2.3 Shape-changing interfaces

Shape-changing interfaces can communicate information by dynamically changing their shape[15]. Rasmussen et al. classified the different types of existing shape change in eight categories [24]. For the aim of our research, we focus solely on the six categories that maintain topological equivalence, as MorphGrip aims to offer continuous feedback through continuous deformation of the shape. In the following, we present handheld shape-changing interfaces designed to communicate information, structured according to these categories.

Orientation. Hemmer et al. implemented a phone with a rotating back to communicate information without looking at the phone [12]. The angle of the back of the phone can, for example, represent the battery percentage or download status. GamesBond utilizes grip deformation technology within a pair of distinct controllers to simulate the sensation of physically linked objects in VR [26]. Each controller features segments capable of bending and twisting, enabling dynamic deformations facilitated by five servomotors and tendon mechanisms. PaCaPa is a handheld VR device equipped with two adjustable wings that dynamically apply pressure to the user's palm and fingers [34]. By interpreting the angle of the virtual tool, PaCaPa renders haptic feedback that simulates the size, shape, and stiffness of virtual objects. HaptiVec employs embedded tactile pin arrays within a cylindrical VR controller to render directional pressure feedback [4]. This allows users to sense pressure on their fingers and palms corresponding to different directions or angles, such as north, south, east, west, and the diagonals in between. Such feedback enables users to recognize the orientation of virtual objects or impact forces from within the virtual environment, enhancing their spatial awareness and immersion. Such haptic cues could be used for haptic guidance but, to our knowledge, it was never tested.

Form. PoCoPo is a handheld device that employs an array of pins, dynamically adjusting their movement to render a variety of shapes, including rectangular and curved shapes, dynamic transformation surfaces [41]. The Inflatable Mouse is a device that can be stored inside a laptop computer and can be inflated to achieve the shape of a conventional computer mouse, the device can also provide haptic feedback to users by changing the surface of the balloon shape. [17]. Drag:on is a VR controller inspired by the design of manual folding fans [42]. The device dynamically adapts its shape to induce more or less resistance, when moved in the air, simulating a sensation of increased, or decreased, weight.

Volume. Pneu-Multi-Tools is a device designed to inflate in the palm and dynamically render different shapes in VR. Thus, users can perceive that they are grasping objects such as bricks and flashlights [14]. X-Rings, is a cylindrical VR controller able to change the volume and the shape of the grip to represent different virtual objects and volumes [9].

Texture. HapticRevolver is a device able to provide multiple textures in VR. It has a cylinder with multiple texture such as paper, metal and plastic. This cylinder is located under the index finger and rotate to provide the sensation of a different virtual object [39].

Viscosity. MetamorphX is able to render viscosity by utilizing a method known as impedance control, specifically in rotational motion [11].

Spatiality To our knowledge, spatiality has never been used with handheld objects. However, they have been used for haptic guidance. For instance, SwarmHaptics employs a swarm of robots to push the user's arm or leg in a direction [16].

2.4 Research gap

In the end, previous researches have used shape-changing devices to guide users using a change in orientation and volume. However, while form cues have been used to indicate directions, no prior research has investigated the use of such cues to guide users in manual motor tasks. In this paper, we address this gap by proposing MorphGrip, an ungrounded shape-changing grip, to guide users in translational and rotational tasks using form cues.

3 DESIGN & IMPLEMENTATION

In this section, we discuss the design and implementation of MorphGrip, a shape-changing grip that can take advantage of the palm's high sensitivity to deliver haptic messages to guide users in performing manual motor tasks with handheld devices.

3.1 Design goals

Our design focuses on developing a handheld device that generates shape changes to guide users in executing translation and rotation tasks, similar to real-life manual motor activities. The design of MorphGrip needed to overcome three primary challenges:

Haptic cues. Implementing a moving protruding area on the grip's surface creates a sliding wave crest that moves linearly and circularly, generating distinct haptic cues on the cylindrical grip. These linear and circular haptic signals have been chosen to be differentiated by users. They enable a direct mapping to the translation and rotation movements required for manual tasks, mirroring real-world activities. The details of both haptic cues are described below.

Embed mechanism. Integrating the shape-changing mechanism into the cylindrical grip of a handheld device, capable of providing haptic cues by stimulating both the palm and fingers of the user.

Mechanism complexity. Ensuring that the mechanism remains uncomplicated to avoid bulkiness, excessive weight, or high cost.

By addressing these challenges, MorphGrip offers users freedom of movement and allows for interaction through a simple grasp of the device. This design makes MorphGrip especially suitable for eyes-free, such as those involving handheld devices, VR controllers, and tools.

3.2 Haptic cues

Performing manual motor tasks in the physical world often requires translating and rotating handheld devices to reach specific targets. This aligns with studies that have demonstrated the importance of providing guidance through both translational and rotational movements for manual operations [7, 37, 38]. In this study, we focused on guiding users through translation (*horizontal* and *vertical*)

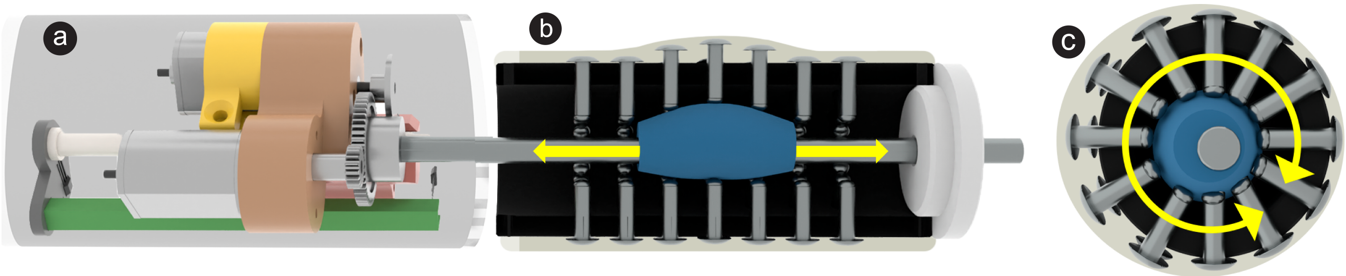

Figure 2: a) MorphGrip DC motors and gears. The eccentric cam-follower mechanism moves outward a set of pins that generate b) *linear haptic cue* and c) *circular haptic cue,* on the handle surface.

and rotation (*roll* and *tilt*) tasks using a MorphGrip device. To fine-tune these haptic cues with MorphGrip, preliminary studies were conducted.

Linear haptic cue. The change of form moves up or down during 0.7 seconds, then pauses for 0.7 seconds, Figure 1a. This duration is based on the work of Weber et al. [38]. The pattern alternates cycles of movement and pause until it reaches the top or bottom of the grip. If it has reached the top, or respectively the bottom, of the grip, the change will go down for a small distance then up, respectively up then down. Once the participant reaches the target, the deformation movement stops. In the preliminary studies revealed that participants could reliably detect the haptic cue at a velocity of 1.04 cm/s.

Circular haptic cue. The change of form rotates, clockwise or counterclockwise, for 0.7 seconds, then pauses for 0.7 seconds, Figure 1b. These durations are based on the work of Weber et al. [38]. The pattern continuously alternates between movement and pause until the participant reaches the target, at which point the rotation stops. In the preliminary studies indicated that participants could reliably perceive the haptic cue at a speed of 5.19 cm/s

The accompanying video shows the animation of the two haptic cues. In the next section, we describe our study to evaluate MorphGrip's performance in guiding a user.

3.3 MorphGrip mechanism

The MorphGrip mechanism generates both *linear haptic cue* and *circular haptic cue*, by utilizing extendable pins within its cylindrical grip to create shape changes. When extended, the pins modify the surface of MorphGrip's outer silicone skin. Each pin can be extended up to 3.40 mm controlled by a cam-follower mechanism that activates a set of 16 pins, forming a protruding area of 16 cm^2. This wave crest of pins is driven by a dual DC motor system: one motor is responsible for generating the *linear haptic cue*, while the other motor produces the *circular haptic cue*. The cam is an eccentric ovoid that can slide along the handle and turned on itself, see Figure 2, and Figure 8 for the specification of the eccentric cam in the Appendix A. Due to the size of the cam, only a few pins are extended at a time, creating a moving bump, akin to a wave crest. The change in shape is therefore localized and can be moved along and around the handle by translating and rotating the cam, see Figure 1. Further details on the MorphGrip mechanism can be found in Figure 8 in Appendix A.

4 USER STUDY

To evaluate the performance of MorphGrip in guiding users, we conducted a user study comparing MorphGrip to verbal guidance. This approach aligns with methodologies employed in similar past research that evaluated haptic signals versus verbal signals [3, 10, 22, 25, 38].

4.1 Verbal cues

We defined four verbal cues, which are recordings containing the words "up", "down", "right" and "left" independently of each other. Verbal cues alternate between pronouncing the word and pausing for 0.7 seconds until the target is reached. These verbal cues are similar to the ones used in the study conducted by Weber et al. [38].

4.2 Study design

Our study design is based on the study conducted by Weber et al. [38] where they compared haptic cues and verbal cues to guide users through manual motor tasks.

Independent variables. We designed a controlled study with a 2×4 within-subject design. The two independent variables are modality (*haptic cues*, *verbal cues*) and task (*horizontal*, *tilt*, *roll*, *vertical*). In *vertical*, and *tilt* tasks, users are guided by the *linear haptic cue* to perform, respectively, arm translation perpendicular to the ground and forearm rotation using the elbow, see Figure 3a-b-c. In *horizontal*, and *roll* tasks, users are guided by the *circular haptic cue* to perform, respectively, arm translation parallel to the ground, and arm rotation on itself, see Figure 3d-e-f. Additionally, three difficulty levels (*easy*, *medium*, *hard*) were defined, corresponding to target sizes of 5 degrees, 3 degrees, and 1 degree, respectively.

Dependent variables. The study involved three dependent variables including *performance*, *task load*, and *qualitative feedback*.

4.3 Measurements

We measured performance using four subscales: *success rate*, *task completion time*, *travel distance*, and *overshooting*. The *success rate* subscale is a binary value indicating whether the participant has reached the target point within 40 seconds. The *overshooting* subscale represents the number of times the participant went over the target point and failed to identify it. The *travel distance* subscale is related to the distance that the participant spent from the starting

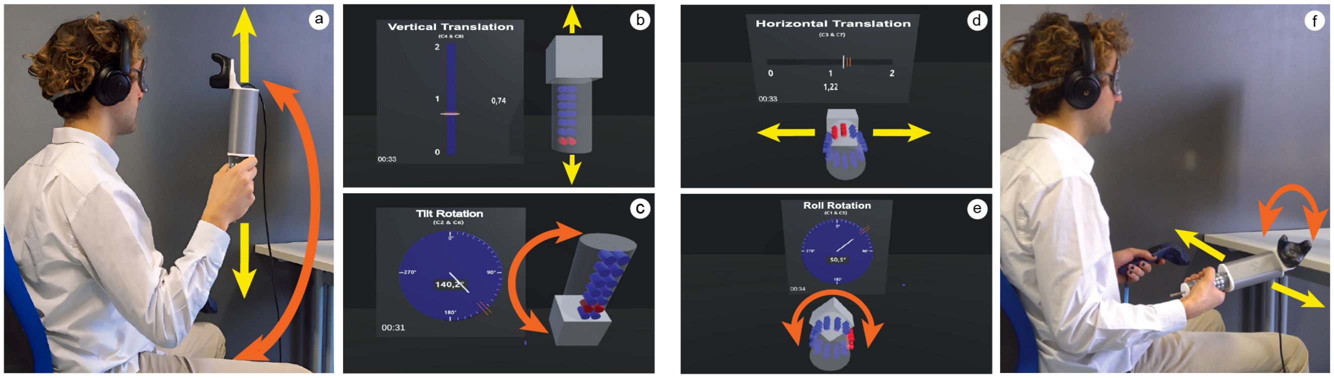

Figure 3: a) Blindfolded participant performing the study for *tilt* (orange arrow) and *vertical* (yellow arrow) tasks while guided by the *linear haptic cue*. Training session visualizations presented to participants for b) *vertical* c) *tilt* d) *horizontal* and e) *roll* tasks. f) Blindfolded participant performing the study for *roll* (orange arrow) and *horizontal* (yellow arrow) tasks while guided by the *circular haptic cue*.

point to the target point, including the distance after overshooting. To measure the *task load*, we used the raw NASA TLX, simply referred to as NASA TLX in the following. To obtain *qualitative feedback* and examine how MorphGrip helped or hindered users in performing the task, we asked two semi-structured questions:

- Q1. In what ways does MorphGrip successfully assist you in reaching the target?
- Q2. In what ways does MorphGrip limit you from reaching the target?

4.4 Apparatus

An HTC Vive tracker was attached to MorphGrip to track the orientation and location of MorphGrip during manual motor tasks such as translations and rotations, as depicted in Figure 1a. Furthermore, participants utilized the trigger button of a standard HTC Vive controller to indicate when they reached the target point. The study software was developed using Unity and executed on a PC equipped with an Intel(R) Xeon(R) CPU 3.60GHz and 16 GB RAM memory, along with an NVIDIA GeForce RTX 2080 Ti graphics card.

4.5 Tasks & Procedure

A total of 24 participants (7 female, 17 male), all right-handed and aged between 21 and 62 years (mean = 25.63, SD = 7.49), participated in our study. Each participant completed 8 conditions, representing the possible combinations of modality (*haptic cues*, *verbal cues*) and task (*horizontal*, *tilt*, *roll*, *vertical*). For each condition, we asked participants to conduct 6 trials, two per each difficulty level (*easy*, *medium*, *hard*), and for each difficulty level, we defined two possible target points.

The experimenter first provided verbal instructions on how participants should sit on a chair and hold the MorphGrip device. During *horizontal*, *roll* and *tilt* tasks participants were asked of making a right angle between the forearm and upper arm and grasp the handle forward in parallel with the ground, see Figure 3f. For the *vertical* task, participants had to place the HTC Vive tracker on MorphGrip at eye level and orient MorphGrip perpendicular to the ground, see Figure 3a.

To familiarize the participants with the tasks, they first conducted a series of training exercises for both *haptic cues* and *verbal cues*. The training contains three target points for each condition. These target points are not reused during the study. Participants were shown a representation of their current position and the target to reach. Additionally, during the training exercises for the *haptic cues*, participants were shown a 3D visualization of MorphGrip that mimic in real-time its orientation and translation, see Figure 3b-c-d-e. This enabled participants to associate the *haptic cues* with the manual motor task they were to perform.

In the *vertical* task, participants were instructed to orient MorphGrip upright, keeping it perpendicular to the ground, while moving it up and down, guided by the *linear haptic cue*, until they reached a randomly assigned target point within a height range of 0.70 m and 1.40 m from the ground, see the yellow arrow in Figure 3a. The *tilt* task, also guided by the *linear haptic cue*, required participants to orient MorphGrip similarly to tipping a jug to pour. The target point was randomly assigned within a range of 0 and 180 grades, with 0 degrees correspond to an upward tilt and 180 degrees to a downward tilt, as illustrated by the orange arrow in Figure 3a. In the *roll* task, participants were instructed to rotate MorphGrip around its axis while keeping the device parallel to the ground and facing forward, like opening a lock with a key, guided by the *circular haptic cue* until they reach a randomly assigned target point, within an angle range of 0 degrees and 180 degrees, with 0 degrees indicating rotation to the right and 180 degrees to the left, as illustrated by the orange arrow in Figure 3f. In the *horizontal* task, also guided by the *circular haptic cue*, participants were instructed to move their hand laterally from right to left, while keeping the device parallel to the ground. The target point was randomly assigned within a lateral range of 0.70 m, see the yellow arrow in Figure 3f. Following the training exercises, participants began the study with the order of conditions (modality × task) controlled using a Latin square design. The difficulty levels and target positions were randomized. During the study, participants were blindfolded for all

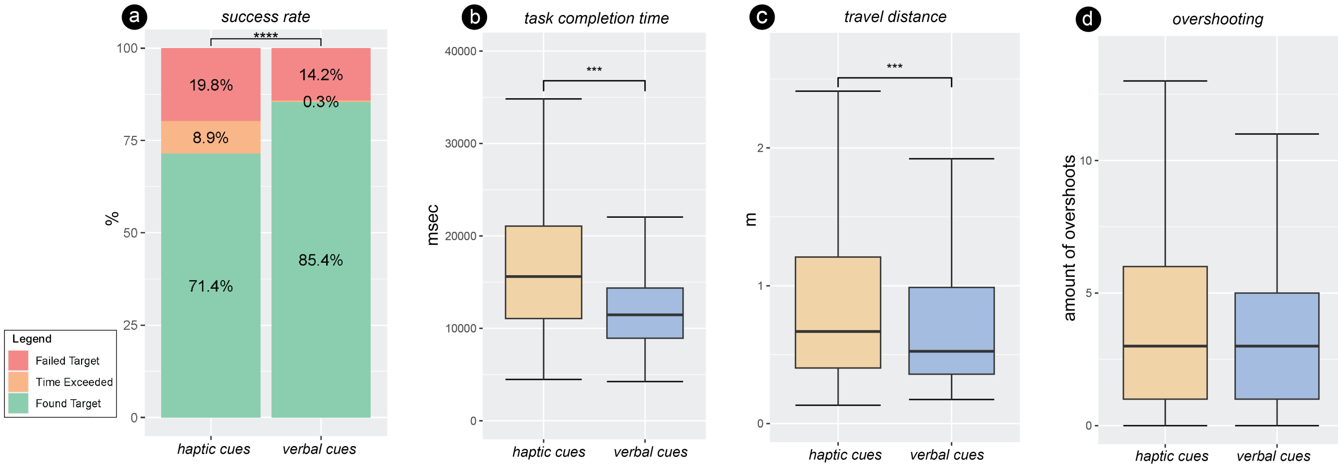

Figure 4: a) *success rate*, b) *task completion time*, c) *travel distance* by modality (*haptic cues*,*verbal cues*).

conditions to avoid bias from visual cues. Additionally, participants wore noise-canceling headphones. During the haptic conditions, the headphones played white noise to avoid any audio cues related to MorphGrip's shape change or environment interference. Before starting each condition, participants were provided with a brief reminder of the task they needed to perform. After each condition, participants completed questionnaires and were allowed to take breaks as needed to prevent fatigue.

subscale	*haptic cues* medians	*verbal cues* medians	*statistics*	*p-value*
sr	71.4%	85.4%	Z = 37.5	**< .001**
tct	17056	11958	W = 141291	**< .001**
td	1.18	0.89	W = 114789	**< .001**
os	4.44	4.02	W = 95942	> .001

Table 1: Significance test results for performance between modalities. *sr*: *success rate*, *tct*: *task completion time*, *os*: *overshooting*, *td*: *travel distance*.

5 RESULTS

5.1 Quantitative data

5.1.1 Performance. We compared *haptic cues* and *verbal cues* using four subscales: *success rate*, *task completion time*, *travel distance* and *overshooting*. As *success rate* is a dichotomous variable (success/failure), we employed McNemar tests for comparative evaluations across modalities. Considering the non-normal distribution of our data and its transition to unpaired, as detailed below, the analysis of the remaining subscales (*task completion time*, *travel distance*, and *overshooting*) were conducted using Mann-Whitney U tests to discern statistical differences between modalities.

Initially, our examination of performance centered on assessing disparities in the *success rate* between *haptic cues* and *verbal cues*. A McNemar test unveiled significant distinctions ($p < .001$) between the modalities. Specifically, we observed a *success rate* of 71.4% for the *haptic cues* and 85.4% for the *verbal cues*. Error targets were attributed to trials with time exceeded and failed targets, as shown in Figure 9 in Appendix B. Building on these results and to ensure that our analysis is not influenced by error trials, we excluded 165 trials (28.6%) for *haptic cues* out of a 576 and 85 trials (14.6%) for *verbal cues* out of a total of 576. This allowed us to conduct an analysis on the subscales *task completion time*, *travel distance* and *overshooting* focusing our investigation on the successful trials that correctly found the target within the delimited time, see Figure 4 and Table 1.

5.1.2 Performance for haptic cues. Due to the fact *verbal cues* shows better Performance than *haptic cues*, except for *overshooting* where they are statistically equal, we focused only on the analysis of the *haptic cues* to identify opportunities for MorphGrip. In this way, to determine significant differences between the four tasks (*horizontal*, *tilt*, *roll* and *vertical*) in the *haptic cues* for *task completion time*, *travel distance* and *overshooting* subscales of Performance, we employed Kruskal-Wallis tests on the data obtained as omnibus test, see Figure 5. Further, post hoc analyses involving Mann-Whitney U tests were conducted to examine pairwise comparisons.

Concerning the *task completion time* subscale of Performance, a Kruskal-Wallis test revealed significant differences between the tasks employed ($\chi^2 = 98.472$, df = 3, $p < .05$). Subsequent Mann-Whitney U tests with Bonferroni correction indicated that the *tilt* tasks (mean = 23333.36, SD = 7672.95) exhibited significantly higher *task completion time* when compared to *horizontal* (mean = 13664.85, SD = 7252.38), *roll* (mean = 16152.64, SD = 6886.19), *vertical* (mean = 15122.66, SD = 6221.50) tasks. Similarly, the *horizontal* task is significantly faster compared to the *roll* and *vertical* tasks. In contrast, the *roll* task exhibited no statistically significant variation when compared to the *vertical* task in the *haptic cues*.

In terms of the *travel distance* subscale of Performance, a Kruskal-Wallis test revealed statistically significant differences between

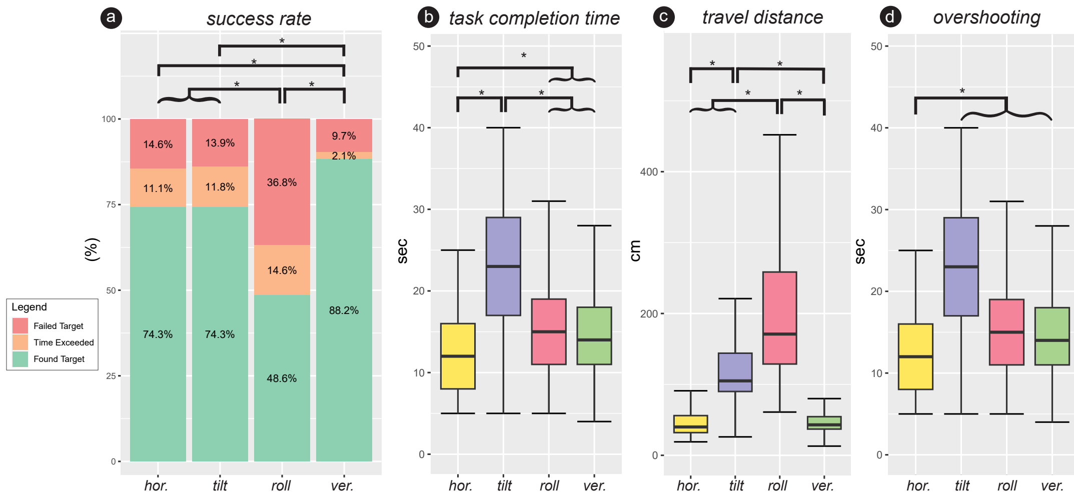

Figure 5: a) *success rate*, b) *task completion time*, c) *travel distance* and d) *overshooting* for *haptic cues* between tasks (*hor*: *horizontal*, *tilt*, *roll*, *ver*: *vertical*).

the tasks utilized (χ^2 = 254.44, df = 3, p < .05). Subsequent Mann-Whitney U tests with Bonferroni correction demonstrated that the *roll* task (mean = 216.04, SD = 142.32) exhibited significantly higher Distance in comparison to the *horizontal* (mean = 52.90, SD = 39.02), *tilt* (mean = 119.02, SD = 54.94), *vertical* (mean = 47.51, SD = 18.84) tasks. Similarly, the *tilt* task exhibited significantly higher *travel distance* when compared to the *horizontal* and *vertical* tasks. However, the *horizontal* task did not exhibit any statistically significant differences compared to the *vertical* task using *haptic cues*.

In terms of the *overshooting* subscale of Performance, a Kruskal-Wallis test revealed statistically significant differences between the tasks utilized (χ^2 = 30.348, df = 3, p < .05). Subsequent Mann-Whitney U tests with Bonferroni correction demonstrated that the *horizontal* task (mean = 2.75, SD = 3.91) exhibited significantly minor *overshooting* in comparison to the *tilt* (mean = 4.89, SD = 4.75), *roll* (mean = 6.29, SD = 6.80), *vertical* (mean = 4.46, SD = 5.63) tasks. However, *tilt*, *roll* and *vertical* tasks does not exhibit any statistically significant differences between them for *haptic cues*.

In the analysis of tasks, the omnibus Cochran's Q test revealed significant differences between tasks in the *success rate* subscale of Performance. A pairwise comparison conducted by McNemar test revealed there are significant differences in *roll* task between *horizontal* (p<.001), *tilt* (p<.001) and *vertical* (p<.001) tasks. Also, a significant difference was observed between *horizontal* and *vertical* tasks (p<.001). Also, a significant difference was observed between *tilt* and *vertical* tasks (p<.001), error trials comprehend time exceeded and failed targets.

5.1.3 NASA TLX for haptic cues. To identify significant differences between the four tasks (*horizontal*, *tilt*, *roll* and *vertical*) for *haptic cues*, to analyse these numerical subscales, we employed a Friedman test as an omnibus test, followed by post hoc analyses using Wilcoxon tests to examine pairwise comparisons.

Concerning the mental demand subscale of the NASA-TLX questionnaire, a Friedman test revealed significant differences between the tasks employed (χ^2 = 15.487, df = 3, p < .05). Post-hoc Wilcoxon tests with Bonferroni correction indicated that the *tilt* task (mean = 10.62, SD = 4.76) exhibited significantly higher mental demand when compared to the *vertical* task (mean = 7.04, SD = 5.61). Similarly, the *roll* task (mean = 11.33, SD = 5.52) is significantly higher compared to the *vertical* task. In contrast, the *horizontal* task (mean = 8.92, SD = 6.47) exhibited no statistically significant variation when compared to the other tasks while conducting using *haptic cues*, Figure 6.

In terms of the Performance subscale, a Friedman test revealed statistically significant differences between the tasks utilized (χ^2 = 20.022, df = 3, p < .05). Subsequent Wilcoxon tests with Bonferroni correction demonstrated that the *tilt* task (mean = 10.62, SD = 5.59) exhibited significantly higher Performance in comparison to the *vertical* task (mean = 14.12, SD = 5.16). Likewise, the *roll* task (mean = 9.46, SD = 5.70) exhibited significantly higher Performance when compared to the *vertical* task. However, the *horizontal* task (mean = 11.50, SD = 6.00) did not exhibit any statistically significant differences compared to the other tasks for *haptic cues*.

Regarding the effort subscale, a Friedman test showed statistically significant differences between the tasks utilized (χ^2 = 15.525, df = 3, p < .05). Subsequent Wilcoxon tests with Bonferroni correction demonstrated that the *tilt* task (mean = 10.96, SD = 4.26) exhibited significantly higher Effort in comparison to the *vertical* task (mean = 7.83, SD = 5.07). However, the *roll* task (mean = 11.79, SD = 5.39) did not exhibit any statistically significant differences in Effort when compared between tasks for the haptic modality. Similarly, the *horizontal* task (mean = 9.96, SD = 6.44) did not exhibit any statistically significant differences in Effort between tasks for *haptic cues*.

A statistically significant difference in the frustration subscale was observed across the employed tasks based on the Friedman test results (χ^2 = 20.887, df = 3, p < .05). Further analysis utilizing Wilcoxon tests with Bonferroni correction revealed that the *tilt* task (mean = 9.25, SD = 5.69) showed significantly higher frustration

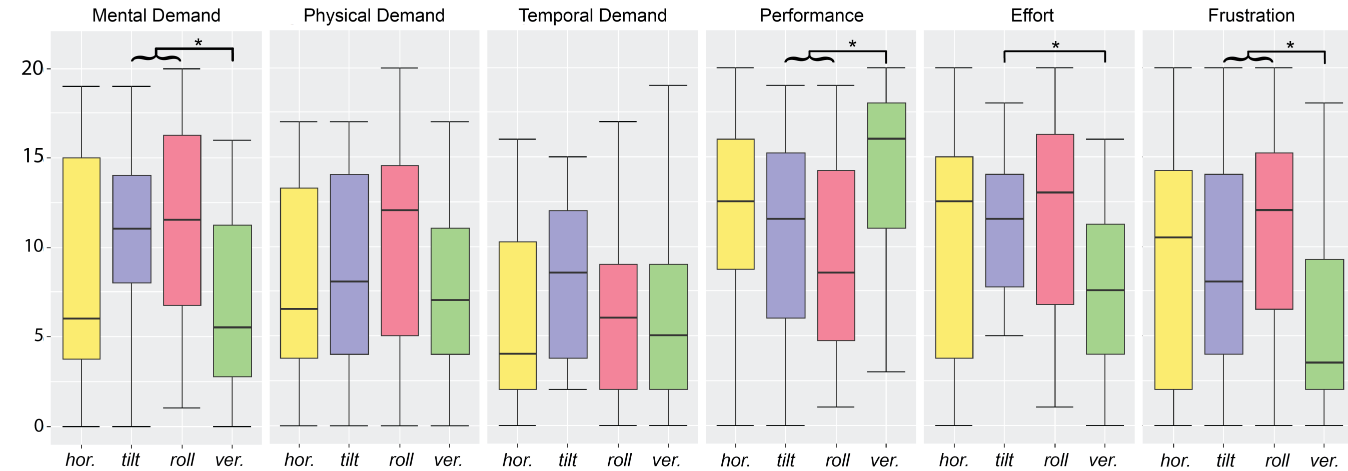

Figure 6: Results of the NASA-TLX subscales by tasks (*hor: horizontal, tilt, roll, ver: vertical*)

scores compared to the *vertical* task (mean = 5.46, SD = 5.38). The *roll* task (mean = 10.75, SD = 6.00) also demonstrated significantly greater frustration levels when compared to the *vertical* task. In contrast, the *horizontal* task (mean = 8.88, SD = 6.78) exhibited no statistically significant differences in frustration levels relative to the other two tasks. Friedman test for physical demand (χ^2 = 5.9863, df = 3, p-value > .05) and temporal demand (χ^2 = 5.1606, df = 3, p-value > .05) subscales showed no significant differences between the tasks used.

5.2 Qualitative data

To gather qualitative insights about MorphGrip performance, we conducted semi-structured interviews, collecting data from participants (n = 24). Following each experimental condition, participants were queried about how MorphGrip facilitated or impeded their ability to reach targets. A total of 192 responses were collected and subsequently categorized using axial and selective coding methodology, in accordance with Ground Theory [33]. Two researchers independently conducted an initial coding. A unified codebook was established through subsequent discussion and applied to re-code all data. All coding discrepancies were resolved through consensus. The qualitative findings are presented in this section.

5.2.1 Helpful guidance. We conducted a comparative analysis of qualitative responses, considering the four tasks (*horizontal*, *tilt*, *roll*, *vertical*) within the context of guidance by *haptic cues* and *verbal cues*. This analysis identified four selective codes: cue recognition, accustomization, enhancement and helpfulness. In terms of cue recognition, the majority of participants perceived the *haptic cues* (n = 70) and *verbal cues* (n = 93) as beneficial for reaching targets (out of a total of 96).

Regarding the selective code of understanding guidance, participants (n = 9) reported gradually familiarizing themselves with the *haptic cues* of guidance over time. For instance, participant (P1) stated, "The movement gives you a sense of the right direction when you become accustomed to it." Similarly, some participants employed a metaphor involving deformation to comprehend the haptic stimuli and translate them into guidance. For instance, participant (P21) remarked, "The mental image of a hammer filled with water, either heavier at the top or bottom, helped to better understand the Haptic." However, some participants (n = 4) reported not finding the haptic guidance helpful. The axial codes derived from the cue recognition selective coding are elaborated in the next point.

Helpful Coding per Guidance Modality

Axial Coding	*Haptic*	*Verbal*	Select. Coding
General feedback	23	45	
Direction commands	30	31	
Reaching the target	4	5	Cue recognition
Speed	8	10	
Distance	2	0	
Precision	3	2	
Intuitive	2	5	
Familiarizing	7	1	Accustomization
Deformation metaphor	3	0	
Suggestion	1	0	Enhancement
Not helpful	4	0	Helpfulness

Table 2: Axial coding of the advantages per guidance modality (*haptic cues*, *verbal cues*), indicating its repetitions counted, and its selective coding.

5.2.2 Helpful haptic cues guidance. Focusing on the four tasks performed by *haptic cues* guidance, the majority of the participants reported that were able to recognize *haptic cues* were helpful to reach the targets. The amount of participants who reported is divided as follows, *horizontal* (n = 18), *tilt* (n = 14), *roll* (n = 19), and *vertical* (n = 19) out of 24 participants who conducted the experiment. The helpful haptic recognition consist in different such as general feedback, deformation commands, reaching the target, deformation speed, distance and speed. For instance, in general feedback (P13) reported "it guided me to the target", in deformation commands (P2) reported "it helps me to find the way I have to move by giving me haptic directions", in reaching the target (P19) reported "Changed impulses when I was beyond the point".

Some participants reported haptic cues are Intuitive in the *vertical* task (n = 2), for example, (P17) reported "the movement of the pins are intuitive, no need for mental processing", similarly in the same task some participants reported Precision (n = 3) reaching the target, for instance, (P6) "super precise directional navigation with the grip". Regarding, Deformation commands, participants reported that they preferred the *linear haptic cue* used in the *horizontal* and *roll* tasks instead of the *circular haptic cue*. For instance, (P8) reported "The movements up and down are self-explanatory", (P5) reported "It points me in the right direction", and (P3) reported, "The direction is clear and easy to recognize". In addition, (P3) reported an improvement suggestion "Possibly continued turning, without interruption, would be more helpful. Or if the engine turns even more knops, i.e. a larger area".

Helpful Coding for Haptic per Task

Axial Coding	*h*	*t*	*r*	*v*	Select. Coding
General feedback	5	6	8	4	*haptic cues* recognition
Direction commands	7	6	7	10	
Reaching the target	2	0	1	1	
Deformation speed	3	1	3	1	
Distance	1	1	0	0	
Precision	0	0	0	3	
Intuitive	0	0	0	2	Accustomization
Familiarizing	4	2	1	0	
Deformation metaphor	0	2	0	1	
Suggestion	0	0	0	1	Enhacement
Not helpful	0	3	1	0	Helpfulness

Table 3: Axial coding of the advantages of MorphGrip guidance in reaching target, indicating repetitions per tasks (*h*: *horizontal*, *t*: *tilt*, *r*: *roll*, *v*: *vertical*) and categorized by selective coding.

Coding for MorphGrip Improvement

Axial Coding	*h*	*t*	*r*	*v*	Select. Coding
Direction commands	11	9	10	10	*haptic cues* recognition
Reaching the target	4	8	2	6	
Speed	1	1	2	1	
Familiarizing	1	1	0	0	Accustomization
Suggestion	1	0	0	0	Enhancement
Weight	0	1	1	2	
Physical Constrain	0	0	1	1	
Nothing prevents	5	2	0	2	Helpfulness

Table 4: Axial coding of the enhancements for MorphGrip guidance in reaching targets, indicating repetitions per tasks (*h*: *horizontal*, *t*: *tilt*, *r*: *roll*, *v*: *vertical*) and categorized by selective coding.

5.2.3 Haptic guidance Improvements. Qualitative analysis shows some opportunities to improve MorphGrip. Most of the participants reported difficulties in recognizing the deforming haptic feedback as described through different axial codes such as recognizing direction, reaching the target and speed that in overall is as follows *horizontal* (n = 16), *tilt* (n = 18), *roll* (n = 20), and *vertical* (n = 17). Regarding Enhancement, another participant suggested the deforming area could be bigger, "Perhaps the movements of the vibrators are sometimes too small" (P9).

6 DISCUSSION

In this section, we provide a comprehensive discussion of both quantitative and qualitative findings derived from our user study.

6.1 Comparison of Haptic and Verbal Cues

Overall, in MorphGrip the *verbal cues* perform better than *haptic cues*. This is consistent with prior research findings, where *haptic cues* have typically underperformed compared to auditory or *verbal cues* [3, 10, 22, 25, 38]. Specifically, in MorphGrip's case, the main limitation of *haptic cues* seem to be the *task time completion*. In fact, participants were slower and had more time exceeded errors with *haptic cues*. Looking at participants feedback, this could be explained by a difficulty to recognize *haptic cues* (19 out of 24 participants). In particular, we had 2 participants out of 24 stating that they had to firmly hold the device in order to feel the pins. However, participants found *haptic cues* useful to complete the tasks reaching the target (23 out of 24) or fast to learn (5 out of 24). Therefore, most participants experienced both helpfulness and difficulties simultaneously while performing the tasks guided by *haptic cues*. This can be explained by a difference between the four tasks tested.

6.2 Tasks suited for Haptic Cues

Looking at the quantitative results of *haptic cues*, the *roll* task performed poorly in terms of *success rate*, *travel distance* and *overshooting*. Similarly, *tilt* task performed poorly in terms of *task completion time*. These results corroborate those of the NASA TLX questionnaire, according to which participants perceived significantly greater mental demand and frustration within *tilt* and *roll* tasks. In this regard, participants perceived their performance to be significantly worse with the *tilt* and *roll* tasks. These findings suggest that it is more difficult to interpret a haptic cue as a rotation of the hand instead of a translation of the hand. When comparing the *vertical* and *horizontal* tasks, *horizontal* is faster than *vertical* but has more errors. However, it is noteworthy that in the *vertical* task, there was no statistically significant difference in the *success rate* between *haptic cues* and *verbal cues*, as shown in Figure 9 in Appendix B. Looking at users' feedback, the *linear haptic cue* for *vertical* translation task were "self-explanatory" (P8) and intuitive (P1, P17). The main difficulty with the *circular haptic cue* was to understand in which direction to go (P5, P6, P24). These finding could suggest that *haptic cues* work better when there is a direct mapping between the task and the haptic cue itself. This point is aligned with the findings from Mugge et al., as for a haptic cue to be effective in improving the performance, it must be informative, and intuitive within the context of the task. Therefore, there is potential for *haptic cues* and further improvements may focus on reducing the completion time, and therefore the overall error rates. In the next subsection, we propose improvements based on participants' feedback.

6.3 Improvements for Haptic Cues

Two aspects of MorphGrip could be improved: the length and size of the pins, and the control of the pins. Firstly, 19 out of 24 participants reported difficulty in feeling *haptic cues*, and 2 participants out of 24 reported the need to hold MorphGrip firmly. Therefore, increasing the length of pin travel and the size of the pin heads would generate a larger protrusion and may make it easier to perceive. Secondly, 4 out of 24 participants reported difficulties in recognizing *haptic cues*, particularly edge patterns during *linear haptic cue* for *vertical* and *tilt* tasks. Based on Mugge et al.'s findings about intuitive haptic feedback [20], improving MorphGrip's pin control could allow independent pin movements to produce continuous *linear haptic cues* and reducing the need for edge patterns. Further refinement of the *linear haptic cue* could involve rendering bump rings to move along the cue direction, while rotating bump columns could improve the *circular haptic cue*. In addition, better control of the pins could enable different haptic metaphors to be studied. For example, participant (P21) reported using the metaphor of a "hammer filled with water" to better understand *haptic cues*. Nevertheless, even without improving MorphGrip, *horizontal* and *vertical* can already be used for guiding users. In the next subsection, we propose scenarios that expose the potential of such haptic cue tasks when the auditory and visual channels are unavailable or occupied.

6.4 Use cases

Building on MorphGrip's demonstrated guidance capabilities, future research could explore its integration as an ungrounded haptic guidance device into various handheld tools across professional and specialized settings, particularly in environments where auditory and visual cues are limited or impractical. Prior studies support the potential of such applications. For instance, Bharadwaj et al. emphasized the benefits of tactile navigation for blind individuals, especially in everyday environments with ambient noise, such as urban settings with street sounds [3]. Similarly, Rümelin et al. found that NaviRadar effectively guides users with haptic cues, requiring no visual attention while walking [25]. Likewise, Weber et al. highlighted VibroTac's applicability in noisy conditions for manual motor guidances [38], and Ploch et al. highlighted haptic cues' utility in capturing attention for drivers with high visual and auditory load [22]. MorphGrip could also provide reliable guidance in industrial settings with high noise during tool manoeuvres, such as reaching target points. Additionally, MorphGrip could be employed in underwater scenarios, where auditory and visual cues are overloaded or constrained. MorphGrip also shows potential for aiding individuals with hearing impairments, particularly in rehabilitation therapy, where repetitive manual motor tasks are required. By leveraging MorphGrip's *haptic cues*, these tasks could enhance overall user experience and task performance.

7 CONCLUSION

This paper introduced MorphGrip, a handheld device that provides *haptic cues* by changing the form of its grip to guide users in conducting manual motor tasks, such as operating controllers or tools. Our user study revealed that while *verbal cues* generally outperformed *haptic cues*, participants still found haptic feedback valuable for achieving task goals. Notably, in the *vertical* task, participants demonstrated comparable *success rate* with *haptic cues* and *verbal cues*, suggesting MorphGrip's potential as a viable alternative guidance method. Furthermore, the lessons learned from our research underline the importance of designing intuitive *haptic cues* and suggest improvements to control mechanisms to enhance *haptic cues* design. Further research into these enhancements in mechanisms and haptic metaphors is essential. Such advancements could significantly improve user recognition and performance in manual motor tasks, potentially enabling MorphGrip to provide valuable assistance in scenarios where visual and auditory channels are saturated or unavailable.

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APPENDIX A

MorphGrip features a cylindrical grip (height = 104 mm, diameter = 40 mm) that houses 84 blind rivets, referred to as pins throughout this document. The bottom ends of these pins act as followers in the cam-follower mechanism, while the pin heads create protrusions on the grip surface when extended outward, see Figure 7 for more details. The mechanism is powered by two DC motors. The *linear haptic cue* is generated by a threaded rod that moves vertically, driven by two gears transmitting motion from the first DC motor. For the *circular haptic cue*, the second DC motor transmits motion to a drive mechanism where the eccentric cam is located, causing it to rotate.

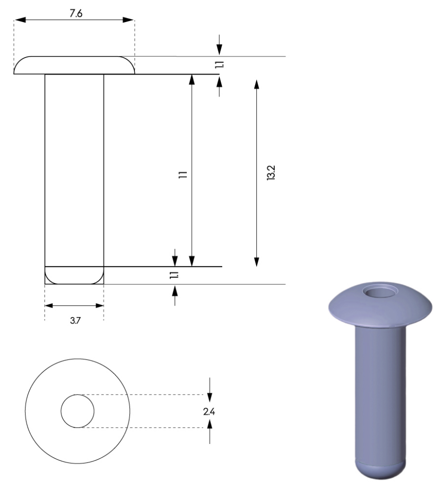

Figure 7: Follower pin

The eccentric cam was initially designed and 3D-printed using PLA filament, followed by machining on a lathe with polyoxymethylene (POM) to ensure smooth sliding within the cam-follower mechanism. Its 1.70 mm eccentric offset results in a sinusoidal displacement spanning 3.40 mm, from −1.70 mm when retracted to 1.70 mm when fully extended. See Figure 8 for further details.

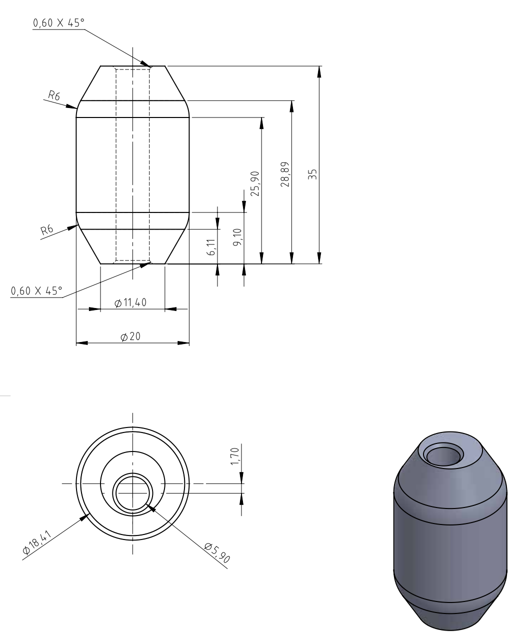

Figure 8: Eccentric Ovoid Cam

APPENDIX B

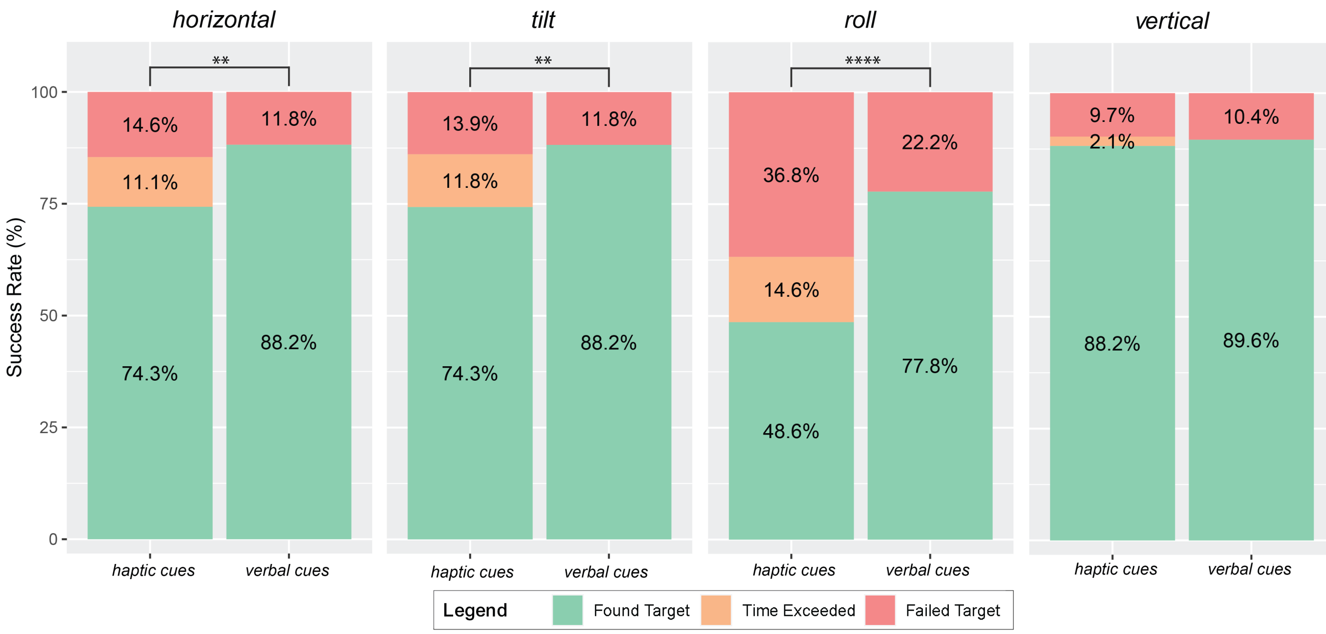

Figure 9: The *success rate* of tasks between modality (*haptic cues, verbal cues*), error targets are caused by time exceeded and failed targets

To calculate the *success rate* between modality, we employed a McNemar test, categorizing the dichotomous variable, where found target was classified as success, while counting time exceeded and failed target were classified as failure.

Tasks	*haptic cues* medians	*verbal cues* medians	*Z-value*	*p-value*
horizontal	74.4%	88.2%	9.09	**0.003**
tilt	74.4%	88.2%	7.41	**0.006**
roll	48.6%	77.8%	25.9	**< .001**
vertical	88.2%	89.6%	0.167	0.683

Table 5: *success rate* between modality