Tactile Hand Motion and Pose Guidance for 3D Interaction

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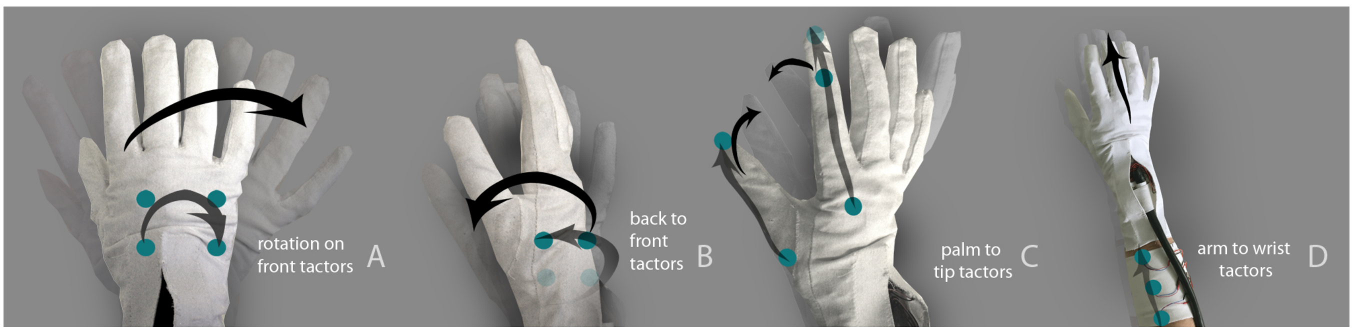

Figure 1: Hand pose and motion changes and associated vibration patterns using the TactaGuide interface: radial/ulnar deviation (A), pronation/supination (B), finger flexion (pinching) (C) and hand/arm movement (D). Tactor locations are green.

ABSTRACT

We present a novel forearm-and-glove tactile interface that can enhance 3D interaction by guiding hand motor planning and coordination. In particular, we aim to improve hand motion and pose actions related to selection and manipulation tasks. Through our user studies, we illustrate how tactile patterns can guide the user, by triggering hand pose and motion changes, for example to grasp (select) and manipulate (move) an object. We discuss the potential and limitations of the interface, and outline future work.

KEYWORDS

Tactile Feedback; 3D User Interface; Hand Guidance

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1 INTRODUCTION AND MOTIVATION

Over the last decade, 3D user interfaces have advanced rapidly, making systems that support a wide range of application domains available [29]. Despite these advances, many challenges remain to be addressed. In this paper, we focus on how we can improve hand motor planning and coordination for 3D selection and manipulation tasks, i.e., the different actions of moving and reorienting a hand through space. Especially in visually complex 3D scenes, such actions can be difficult to perform as they can be constrained by visual conflicts, resulting in difficulties in judging spatial interrelationships between the hand and the scene. This often results in unwanted object penetrations. In real life, we often depend on complementary haptic cues to perform tasks in visually-complex situations. However including haptic cues is not always straightforward in 3D applications, as it often depends on complex mechanics, such as exoskeletons or tactor grids.

1.1 Cues for motor planning and coordination

Motor planning and coordination of selection and manipulation tasks is generally performed in a task chain with key control points that relate to biomechanical actions [22]. These actions contain contact-driven **touch** events that can inform the planning and coordination of hand **motion** and **pose** actions. For example, a user may grasp an object (touch informs hand pose to grasp) and change its rotation and translation in space by moving and reorienting the hand (motion, pose) while avoiding touching other objects (touch) [29]. As the hand-arm is a biomechanical lever system, hand motion can be accomplished by arm motion, but also by wrist rotation.

Within this article, we specifically focus on motion and pose guidance, and reflect on interrelationships with touch in our discussion. Pose not only relates to the orientation of the hand itself but also to its specific postures needed to select and manipulate an object, e.g., to grasp or move an object through a tunnel. While contact-point feedback on a user's hand may provide useful feedback to avoid touching other objects during pose and motion changes, such actions can also be performed independent of (or even avoid) touch contact. To do so, both in real life and in 3D applications we may rely on proprioceptive cues, which are typically acquired through motor learning [45]. However, cues beyond proprioception and visual feedback about the scene may be required to perform (or learn) a task correctly. So-called augmented feedback – information provided about an action that is supplemental to the inherent feedback typically received from the sensory system – is an important factor supporting motor learning [30]. While learning how to optimally perform a task – regardless if it is in a purely virtual environment or a simulated real-world task – most interfaces unfortunately do not provide feedback to encourage correct hand motions and poses, i.e., no form of *guidance*. However, selection and manipulation tasks, and potentially subsequent motor learning, likely will benefit from such guidance. For example, consider training users for assembly tasks where knowledge acquired in a virtual environment needs to be transfered to the real world [11].

1.2 Limitations of haptic devices for pose and motion guidance

Traditional haptic interfaces, such as the (Geomagic) Phantom, can guide hand motion to a certain extent to improve selection and manipulation task performance, often in a contact-driven manner. As such, haptics can potentially overcome limitations caused by visual ambiguities that, for example, make it difficult to judge when the hand collides with an object [12]. However, there are certain limitations that directly affect motion and pose guidance. Most common haptic devices depend on a pen-based actuation metaphor instead of full-hand feedback. How we hold an actuated pen does not necessarily match how we interact with many objects in real life. Furthermore, while typical contact-driven haptic feedback models support overall motion guidance, they do not aid users in achieving a specific pose, unless a full-hand interface like an exoskeleton is used. Finally, most haptic devices are limited in operation range, imposing constraints on the size of training environments.

1.3 Approach

To overcome these limitations, we investigate the use of tactile feedback, even in non-contact situations. Tactile feedback is unique in that it directly engages our motor learning systems [31], and performance is improved by both the specificity of feedback and its immediacy [2]. Deliberately, we give tactile feedback independent of visual cues, to avoid confounds or constraints imposed by such visual cues. Normally, designing tactile cues is challenging, as haptic (force) stimuli cannot be fully replaced by tactile ones without loss of sensory information [24]. To avoid this issue, we provide instructional tactile cue patterns, instead of simulating contact events. Also, tactile devices can provide light-weight solutions with good resolution and operation range [33, 53]. Current touch-based vibrotactile approaches typically do not provide pose and motion requirement indications. In our study, we look specifically at feedback that addresses these issues, by providing feedback to guide the user to move in a particular way or assume a specific hand pose. Our methods use localized vibration patterns that trigger specific bodily reconfigurations or motions. Previous work, e.g., [43, 46, 47], indicates that vibration patterns – independent of touch actions – can aid in changing general body pose and motion, which we extend in this work to support more fine-grained selection and manipulation actions.

1.4 Research questions

To design an effective tactile interface for motion and pose guidance, we need to address several challenges. In this paper, we examine how we can guide the user to perform specific **motion** and **pose** actions along key control points in the task chain, ideally independent of contact events. Doing so, we can identify the following three research questions (RQ).

RQ1. How well can tactors be localized and differentiated across the hand and lower arm?

RQ2. How do users interpret tactile pose and motion patterns and what are their preferences?

RQ3. How does tactile pose and motion guidance perform in a guided selection and manipulation task?

In this paper, we assess each RQ through a respective user study. In study 1, we measure the effects of vibration on localization/differentiation, which informed study 2, which looks into the interpretation of tactile cues on pose and motion changes, while analyzing user preference for patterns. Study 3 takes the main user preferences and uses a Wizard-of-Oz methodology to assess the cues in a simulated selection and manipulation task, where we measured the effectiveness of operator-controlled cues. This study is designed to illustrate cue potential in real application scenarios.

1.5 Contributions

In this paper, we present the design, implementation and validation of a tactile pose and motion guidance system, TactaGuide, which is a vibrotactile glove and arm sleeve interface. We show that our new guidance methods afford fine hand motion and pose guidance, which supports selection and manipulation actions in 3D user interfaces. We go beyond the state of the art that mainly focused on vibrotactile cues for body and arm motions [5, 25, 37, 46, 47], or general poses [10, 55]. In that, we extend previous work to fine hand manipulation actions through a set of vibrotactile cues provided via TactaGuide, through the following findings:

- Localization and differentiation: we show that tactors can be well localized at different hand and arm locations and illustrate that simultaneous vibration works best. We also show that the back of the hand (normally used infrequently) scored as good as the index finger, and is a useful location for contact-driven feedback.

- Pattern interpretation: Based on the biomechanical constraints of various hand/arm parts, we illustrate that most users successfully match patterns to the right motion or bodily reconfiguration.
- Selection and manipulation guidance: through a Wizard-of-Oz experiment we show that vibration patterns support finer-grained 3D selection and manipulation tasks, confirming the validity of our approach.

We deliberately performed all studies in the absence of visual cues to reliably identify the effect of tactile guidance in isolation, with an eye towards eye-free interaction scenarios. We reflect on the potential for combinations of visual and tactile patterns for guidance in the discussion section.

2 RELATED WORK

In this section, we outline work in related areas.

Haptic feedback. Haptic feedback for 3D interaction has been explored for many years, though is still limited by the need for good cue integration and control [27, 48], cross-modal effects [40], limitations in actuation range [19], and fidelity issues [38]. The majority of force feedback devices provide feedback through a grounded (tethered) device. These devices are often placed on a table and generally make use of an actuated pen that is grasped by the fingertips, instead of full hand operation, e.g., [36]. In contrast, glove or exoskeleton interfaces can provide feedback such as grasping forces and enable natural movement during haptic interactions [9, 44]. Few haptic devices provide feedback for the full hand. An example is the CyberGrasp (CyberGlove systems), a robot-arm actuated glove system that can provide haptic feedback to individual fingers. Tactile methods afford more flexibility by removing the physical restrictions imposed by the actuated (pen-)arm or exoskeleton construction. However, they can be limited as haptic cues have to be "translated" within the somatosensory system [24]. While substituted cues have been found to be a powerful alternative [26, 28], they can never communicate all sensory aspects. In 3D applications, research has mostly revolved around smaller tactile actuators that are hand-held, e.g., [8], or glove-based, e.g., [16]. Some work has explored the usage of a dense vibrotactors grid at or in the hand, e.g., [17, 35, 42], which is related to our glove design.

Motion and pose guidance. Some systems provide guidance cues to trigger body motions and rotations. Most approaches focus on corrective feedback with varying degrees of freedom. The majority of systems focuses on some form of motor learning, which may be coupled with visual instructions of the motion pattern [31]. Effective motion patterns have yet to be found, as illustrated by the variety of patterns in the different studies [5]. However, one common insight is that the spatial location of vibrations naturally conveys the body part the user should move and that saltation patterns are naturally interpreted as directional information [47]. Such saltation patterns are a sequence of properly spaced and timed tactile pulses from the region of the first contactor to that of the last, allowing for good directionality perception [2]. Yet, there is no conclusive answer for rotation patterns. Researchers have provided cues at arms, legs and the torso [41] to train full-body poses that, for example, help with specific sports like snowboarding [47]. Research has also focused specifically at guiding arm motions [46, 51] in 3D environments. Further variants of this work look at arm [13] or wrist rotation [49] for more general applications. All these methods target only general motions and are not particularly useful for hand pose and motion guidance for 3D selection and manipulation. In contrast, other systems use electromuscular stimulation (EMS) to control hand and arm motions to produce finer motions and poses [50]. The most closely related work looked at triggering muscular actions at the hand and arm via EMS [32]. Yet, EMS systems are awkward to use, and often have limited usage duration or user acceptance. Also, receptors or muscles may get damaged through use of EMS [39].

Proximity feedback. For hand guidance, the usage of proximity models to improve spatial awareness around the body to indirectly trigger hand motion and pose adaptations is another related area. Some researchers have explored proximity cues with a haptic mouse [20], the usage of proximity to trigger actions [7], and auditory feedback for collision avoidance [1].

Extending the state of the art, we introduce a novel set of vibrotactile cues that can guide hand motion and pose configurations that have high relevance for 3D selection and manipulation.

3 POSE AND MOTION GUIDANCE FEEDBACK

We provide tactile feedback through our new TactaGuide system, a vibrotactile glove and arm sleeve (Fig. 2). The device affords a full arm motion operation range, tracked by a Leap Motion. Both glove and sleeve are made of stretchable eco-cotton that is comfortable to wear. In the glove, tactors are placed at the fingertips (5 tactors), inner hand palm (7), middle phalanges (5), and the back of the hand (4), for a total of 21 tactors (Fig. 2). Cables are held in place through a 3D printed plate embedded in the fabric on top of the wrist. The arm sleeve consists of 6 tactors, positioned to form a 3D coordinate system "through" the arm. We use 8-mm Precision Microdrive coin vibration motors (model 308-100). All tactors are driven by Arduino boards. To overcome limitations in motor response caused by inertia (tactors can take up to ~75 ms to start), we use pulse overdrive [35] to reduce the latency by about 25 ms. After that, pulse width modulation (PWM) is used to reduce the duty cycle to the desired ratio under consideration of the corresponding tactor balancing (Fig. 2) to generate different tactile patterns. The system was previously used for another purpose, namely proximity feedback [34], where we showed that proximity cues in combination with collision and friction cues can significantly improve performance

Many selection and manipulation tasks depend on fine control over hand motion and poses. However, in complex 3D scenes, such motor actions maybe be difficult to plan and coordinate. For example, consider training the hand to move behind an object, to grasp a small and occluded object (or part). While adjusting the visualization may solve some issues – x-ray visualization has been used to look "through" an occluding object [4] – the associated visual ambiguities can make performing the task challenging. To overcome such visual limitations, we assume that tactile cues are valuable to guide hand motion and poses. Inspired by related work, e.g., [13, 49], the basic premise of our hand motion and pose guidance system is centered around providing various pattern stimuli –

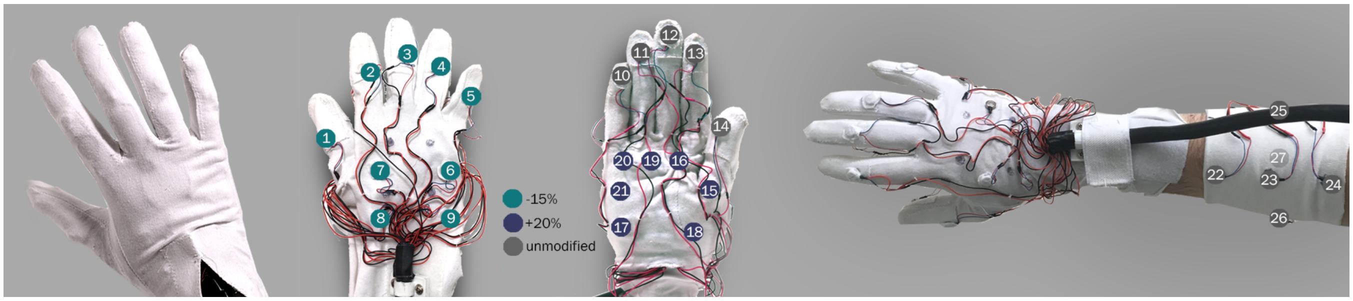

Figure 2: Tactor IDs and balancing of TactaGuide glove, based on pilot study results. The tactors at the arm sleeve were unmodified.

activating tactors in a specific region in a specific sequence – using a specific vibration mode (Fig. 1 and 4). Previous work indicates that such patterns are well interpretable by the user, while cue location and directionality inform the user about the specific body part or joint that should be actuated [31]. These cues can be triggered independent of contact events, i.e., events that relate to touching an object. For example, stimulating three tactors in a serial manner from hand palm to fingertip may indicate to the user that they should stretch that finger (Fig. 1C). Similarly, a forward pattern over the arm may indicate the arm needs to be moved forward (Fig. 1D). Further details on the patterns are discussed in Section 4.2. By focusing on motion and pose adjustment for selection and manipulation, which requires finer control over hand and fingers, we extend previous work [13, 49], that focused only on arm or wrist rotation. Our target actions are closer to EMS-based work [50], though without their aforementioned limitations.

We looked closely at the different actions undertaken by the hand during 3D selection and manipulation. Each of these actions is generally associated with a specific hand or arm region. The different posture/motion actions refer to fundamental hand movements (Fig. 1) and thus to biomechanical actions that involve various joint/muscle activations:

- Radial/ulnar deviation: turning of the hand (yaw).
- Pronation/supination: rotation of the hand (roll).
- Move: arm movement to move the hand in the scene, including abduction and adduction (moving arm up and down), forward/backward and left/right motion afforded by the arm lever system.
- Finger flexion/extension: straightening of fingers to pinch or grasp an object.

While flexion and extension can also refer to orienting the hand around the wrist (pitch), we did not support this motion in our work, as it is used infrequently in the frame of selection and manipulation tasks. For fingers, we use different patterns for closing (palm to fingertip vibration) and opening gestures (fingertip to palm vibration), while hand rotations simply involve directional patterns. With respect to arm movement, the arm is a biomechanical lever system as bones and muscles form levers in the body to create human movement – joints form the axes, and the muscles crossing the joints apply the force to move the arm.

Based on ease of detection of location, direction, and guidance interpretation (which hand motion or pose change does the pattern depict?), we implemented three different vibration modes, which we then assessed in our user studies. The location of a stimulus guides the biomechanical action. E.g., when a finger needs to be bent, the vibration pattern is provided at the finger [47]. The three modes were continuous (a continuous vibration stimuli), stutter (a pulsed vibration stimuli), and mixed (a mixture of both). We assumed that the stutter at the end of the mixed mode pattern could indicate direction. Prior to the studies, we performed a pilot study, where we verified stimuli with 5 users and fine-tuned the system.

4 EXPERIMENT

Pose and motion guidance was examined in three studies, 1, 2 and 3, which investigated how well different vibration patterns and modes trigger hand pose and motion changes, to potentially guide the design of haptic selection and manipulation techniques. These studies were designed to show if hand pose and motion guidance is principally possible, and to investigate its potential and limitations. As noted before, we deliberately did so independently of visual cues, to avoid confounds or constraints imposed by such cues.

Different user samples were recruited for each study. In each study users wore the complete TactaGuide glove and arm sleeve setup. Post-hoc questionnaires for each study were composed of 7-point Likert items (0 = "fully disagree" to 6 = "fully agree"), related to mental demand, comfort, usability, and also task-specific perceptual issues. Users were seated at a desk and could rest their elbow on the armrest of a chair in study 1 and 2, while vibrotactor locations (IDs) were shown on a 27" desktop screen. In study 1 we examined if and to what extent our glove enables users to accurately localize tactile feedback and their ability to discriminate between different tactors. Study 2 focused on the user's interpretation of vibration patterns into assuming hand poses and performing motions. In study 3, the user's hand pose and motion were guided through vibration patterns that were chosen on the basis of the previous studies. Study 3 deployed a Wizard-of-Oz methodology to overcome finger tracking limitations associated with the LeapMotion, which cannot reliably detect the hand once it is rotated vertically. Yet, this pose is required for many grasping actions.

4.1 Study 1 - Tactor localization and differentiation

This study focused at the ability of users to locate and differentiate between tactors to ensure that users can detect the actual region that receives biomechanical actuation. As higher-resolution tactile gloves are scarce, there is no information in the literature about the detectability of individual tactor locations (stimuli), especially with respect to our particular locations at the TactaGuide glove. Also, while sensitivity is well studied for the inside of the hand, sensitivity at the back of the hand has hardly been studied [23].

In task 1, participants were asked to locate a single actuated tactor. A within subjects 2 x 2 factorial design was employed to study the effect of factor feedback mode (stutter, continuous) and hand pose (straight, fist) on feedback localization performance (mean hits per trial). Vibration feedback was provided at all 21 different hand locations of the TactaGuide glove, resulting in 84 trials. Two feedback modes were also compared at 6 locations on the wrist, resulting in 12 additional trials. The total of 96 trials were randomly presented. Participants were informed that only a single tactor provided feedback at any given time. In each trial feedback was provided for 2 seconds, after which the participant selected a tactor (ID) from the overview shown on a desktop monitor showing the hand with tactor locations.

In task 2, combinations of two or three actuated tactors had to be located and differentiated. A 2 x 4 x 7 factorial design was used to study the localization of tactors depending on their number (two or three tactors), feedback mode (simultaneous, continuous; simultaneous, stutter; serial, continuous; serial, stutter) and zone (thumb, index, pinkie, palm, back of the hand, from the back to the inner hand, wrist). Each factor combination was repeated, resulting in 112 trials, presented in randomized order. Before starting the task, participants were informed that either two or three tactors would be actuated. Feedback was always provided for 2 seconds. As in the first task, participants responded with tactor ID displayed at the screen. Together, both tasks took around 45 minutes to complete.

4.1.1 Results. Eight right-handed persons (2 females, mean age 39 (SD 15.7), with a range of 25–65 years) volunteered. Six wore glasses or contact lenses and two had normal vision. Within subjects repeated-measures analysis was used to study task specific main and interaction effects of factors on dependent measures.

In task 1, a total of 768 trials were analysed. For each trial the actually activated tactor and the participant's choice were compared, to record a hit as the correct tactor was chosen (1) or a miss if not (0). As expected, the hand pose but not the mode affected hit rate (hits/trials), which was significantly higher with a straight hand pose (M = 0.82, SE = 0.02) than with a fist (M = 0.69, SE = 0.4), F(1 ,7) = 13.44, p = .008, η^2 = .66. With a fist, tactors are closer together, making it more difficult to localize a stimulus. In a secondary analysis, tactors were grouped into six zones across which we compared hit rates (thumb; middle fingers:[index,middle,ring]; pinkie; back of the hand; palm; wrist). The zone affected the hit rate, F(5,35) = 6.48, p < .001, η^2 = .48. Post-hoc comparisons showed that only the pinkie with the lowest hit rate (M = 0.61, SE = 0.05) differed significantly from the back of the hand, which had a high hit rate (M = 0.85, SE = 0.03), p = .015.

In task 2, a total of 896 trials were analysed. In this task activated tactors were compared to participants' responses. Depending on their perception, participants could either name three tactor IDs or they could name less than three and state there were no more activated tactors. We scored a hit for each correctly named tactor and also for correctly stating that no more tactor was activated. That is, the maximum number of hits per trial was always three. Mean hits depended significantly on the stimulated zone F(6,42) = 2.62, p = .03, η^2 = .27 (see Fig. 3 for mean values and standard errors), the feedback mode F(3,21) = 10.81, p < .001, η^2 = .61 and its interaction with the number of activated tactors F(3,21) = 22.98, p < .001, η^2 = .77 (see Table 1 for mean values and standard errors). A post-hoc test showed that the mean number of hits was higher when feedback was provided at the back of the hand compared to the thumb, the pinkie, and the palm. Performance on the back of the hand was also marginally better than feedback transitioning from the back to the inner hand (p = .058). There were also more hits when feedback was provided at the index finger than at the palm (p = .048). In trials with two activated tactors and for both simultaneous feedback modes, participants got more hits compared to both serial activations (p < .01). When three tactors were activated differences became non-significant.

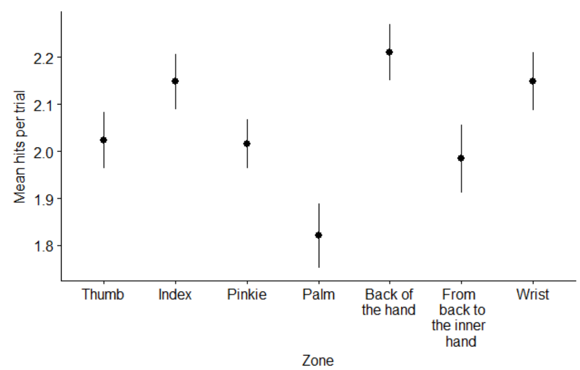

Figure 3: Study 1, task 2 (tactor localization and differentiation): Mean number of hits per trial by stimulated zone with standard errors (SE) hits per trial, hit range = [0;3].

Table 1: Study 1, task 2 (tactor localization and differentiation): Mean hits per trial by number of activated tactors and feedback mode with standard errors (SE), hit range = [0;3].

Number of tactors	Feedback mode	Mean (SE)
Two	Si-C	2.33 (0.09)*
	Si-S	2.45 (0.09)*
	Se-C	1.72 (0.08)
	Se-S	1.87 (0.09)
Three	Si-C	1.89 (0.08)
	Si-S	1.94 (0.09)
	Se-C	2.15 (0.16)
	Se-S	2.05 (0.14)

Si = Simultaneous, Se = Serial, C = Continuous, S = Stutter

Reflection. Performance was best at the index finger and the back of the hand. While the mean differences between zones were statistically significant, they were relatively small (up to 0.23 = 8% of the maximum score). This outcome might be related to the distribution and sensitivity of mechanoreceptors of glabrous skin [23], where the density of low threshold mechanoreceptive units at the fingers is principally higher than in the palm. Therefore, vibrations are in general harder to differentiate inside the palm, especially in case of adjacent, nearby located tactors. Simultaneous activations led to better performance compared to serial continuous activation when two tactors vibrated. Mean differences ranged from 0.46 to 0.72 (=15% to 24% of the maximum score). However, when three tactors were activated, participants generally achieved a good hit rate for serial feedback, as they correctly identified two out of three tactors on average. There was no interaction effect between feedback mode and stimulated region, that is, the optimum feedback mode was not region specific.

4.2 Study 2 - Pattern interpretation and preference

We explored motion interpretation and preferences in this observational study in two different tasks. In task 1 we focused at how users would interpret a certain trigger (pattern + mode) by adjusting their hand pose or motion, while task 2 investigated which vibration mode was preferred for a stated hand pose or motion change.

For task 1 of study 2, feedback was provided at the same six hand zones as in the second task of study 1 (localization and differentiation), as well as at the wrist and at an additional hand zone that includes the thumb and index. A specific feedback pattern with varying numbers of involved tactors depending on the zone, see Table 2. We actuated the tactor-vibrations serially in three modes: Stutter, continuous and a mixed mode (see Fig. 4).

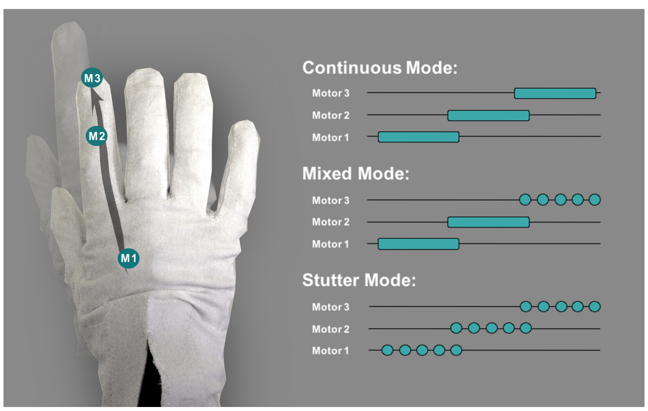

Figure 4: Activation sequence of different feedback modes using the example of finger pointing motion (index finger) with three involved tactors.

In mixed mode, the first tactor(s) was in continuous mode, while the last one was stuttering. Unlike study 1, simultaneous feedback modes were not used in study 2, as we provided directional feedback cues through serial activation. Feedback patterns at each zone were provided using zone-specific vectors in two opposite directions (forward/clockwise and backwards/counterclockwise), except for the wrist at which three vectors with opposite directions were provided (forward/backwards; up/down; left/right). Feedback was provided and randomized blockwise. Participants completed one block of 36 trials with feedback at six hand zones first (6 regions x 3 modes x 2 directions), followed by 18 trials for the wrist (3 modes x 3 vectors x 2 directions) and finally 6 trials involving the thumb and index at the same time (3 modes x 2 directions), for a total of 60 trials per participant. Participants were told to change their hand pose in a way that they felt matched the provided pattern best. The starting pose for each trial was resting the elbow on the armrest of a chair while the hand was hanging down in a relaxed manner (i.e., a pose between a fist and fully stretched hand gesture). No further instructions were given and users could choose their movements and gestures freely. The experimenter recorded the resulting motions.

For task 2, the zone-specific feedback patterns and directions were the same as in task 1. We pre-defined specific hand poses for each zone-specific feedback pattern and direction, see Table 2. In each trial, the experimenter first demonstrated which movement or hand pose should be initiated by the feedback that followed. Then the corresponding feedback was provided in three different modes (continuous, stutter, mixed mode), presented in randomized order. The modes were not examined as factor but functioned as response options: that is, the user had to choose which cue was most suitable for initiating the previously shown movement or pose. The suitability of the feedback for the respective movement/pose was also rated on a 7-point Likert scale (6 being "totally suitable"). As in task 1, six hand zones, the wrist, and the zone including thumb and index were tested and randomized blockwise. With one repetition 24 trials were presented for the six hand zones (6 zones x 2 directions x 2 repetitions), 18 trials for the wrist (2 repetitions x 3 vectors x 3 directions) and 4 trials for thumb and index zone (2 repetitions x 2 directions), resulting in 46 trials. The experimenter recorded the choice of mode and suitability rating for each trial. Eight participants (7 right-handed, 2 females, mean age 29.6, SD 5.3, with a range of 23–40 years) volunteered. Three wore glasses or contact lenses and five had normal vision.

Table 2: Study 2, task 1 (pattern interpretation) and 2 (preference): Pre-defined hand movements depending on zone, activated tactors and feedback direction. The + symbol indicates simultaneous activation of concatenated numbers.

Zone	IDs of activated tactors (see Fig. 2) and order of activation	Movement for tactor activation → from left to right, ← from right to left
Thumb	7, 1, 14	→ stretch ← bend
Pinkie	6, 5, 10	
Index	7, 2, 13	
Thumb and Index	7, 1 + 2, 13 + 14	→ pinch ← release
Hand inner	18, 16, 20, 17	→ ulnar deviation ← radial deviation
Back of the hand	8, 7, 6, 9	
From back to inner hand	7, 6, 20, 16	→ supination ← pronation
Wrist	24, 23, 22	→ forward ← backward
	26, 23, 25	→ right ← left
	27, 23	→ up ← down

4.2.1 Results. For task 1, 480 trials were analysed. All feedback-dependent interpretations were listed and counted if they occurred sufficiently often, that is, were used by at least three of the participants. When feedback was provided at the thumb, the back of the hand, palm, or wrist, resulting movements were diverse for each feedback direction and mode and no coherent movement/gesture could be observed. Feedback provided once at the index, pinkie and at thumb and index, or repeatedly from the back to the inner hand resulted in "successful" movements/gestures, which correspond to our interpretation of the respective feedback. That is, forward/backward feedback at the index and pinkie resulted in stretching/bending respective fingers, simultaneous feedback at the thumb and index was interpreted as pinch movement and feedback provided from the back to the inner hand resulted in supinations.

For task 2, 384 trials were analyzed. Mode preferences for hand and wrist were analyzed separately, as three instead of two directional vectors were used for the wrist. For each participant and factor combination we calculated how many times each mode was preferred. With one repetition each mode could maximally be preferred two times for a given combination. Generally, the continuous mode was preferred at the hand, M = 1.21, SE = 0.1, over the stutter, M = 0.2, SE = 0.06, p = .001, and mixed mode, M = 0.6, SE = 0.06, p = 0.18, F(1.15,8.03) = 30.09, p < .001, η^2 = .81. Nevertheless, this preference was not consistent across zones as, especially at the back of the hand and the palm, the mixed mode was chosen more often than the continuous mode, but not significantly so. At the wrist the continuous mode was also preferred, F(2,14) = 8.71, p = .003, η^2 = .56. Post-hoc comparisons showed that the continuous mode, M = 1.27, SE = 0.19, was significantly superior to stutter vibration, M = 0.25, SE = 0.1, p = .02. Mode preferences in percent by zone are listed in Figure 5.

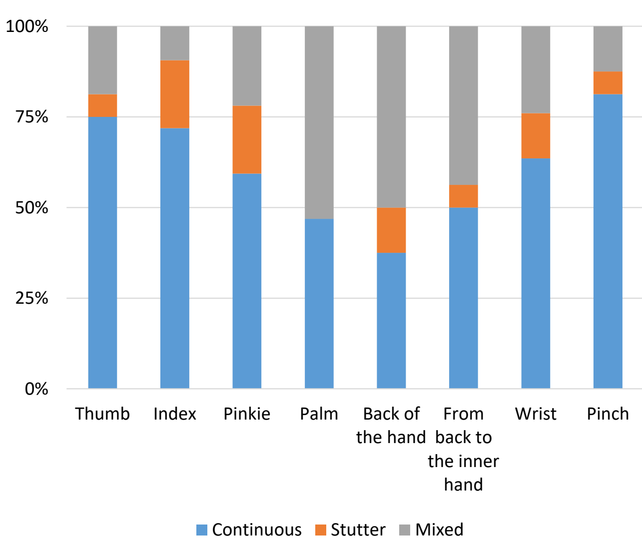

Figure 5: Task 2: Vibration feedback mode preferences by zone in percent.

The direction (at hand zones and wrist) and the vector (at the wrist) did not affect mode preference. Suitability ratings were generally slightly positive, while feedback patterns that were provided on the wrist to trigger up/down and left/right movements got more neutral ratings.

Reflection. Results from task 1 indicate, that in principle patterns can be reasonably well interpreted, i.e., users did perform the intended main action. However, the interpretation of direction was often an issue. Most likely, the generally good detection of the main action can be associated to the biomechanical limitations and prime actions of hand and fingers, e.g., fingers are mainly bent, not rotated. Still, as we did not inform users what kind of action a pattern could potentially trigger, they had little possibility of learning a pattern. For task 2, it is not clear why the mixed mode was preferred for some areas. One possible explanation is that both areas (inner, back of hand) are quite flat, and exhibit different mechanical properties compared to, for example, the fingers. Suitability ratings indicated that feedback patterns used at the hand zones and wrist are generally appropriate for guidance.

4.3 Study 3 - Hand pose and motion guidance

Based on the outcomes of the first two studies (1 and 2), we performed a Wizard-of-Oz [18] study to assess the cues for controlling finer-grained hand selection and manipulation actions. We deliberately chose a Wizard-of-Oz methodology to overcome some of the evident limitations of the hand tracking system we used (Leap Motion), which cannot track fingers precisely when the hand is held vertically, due to the occlusion of the fingers in the camera image. This study investigated user performance in six selection and manipulation tasks that cover hand pose changes and hand motions. Grids were used to control and measure performance on the horizontal and vertical plane with 25 x 16 grid fields on each plane and a grid field size of 2 x 2 cm, see Fig. 6.

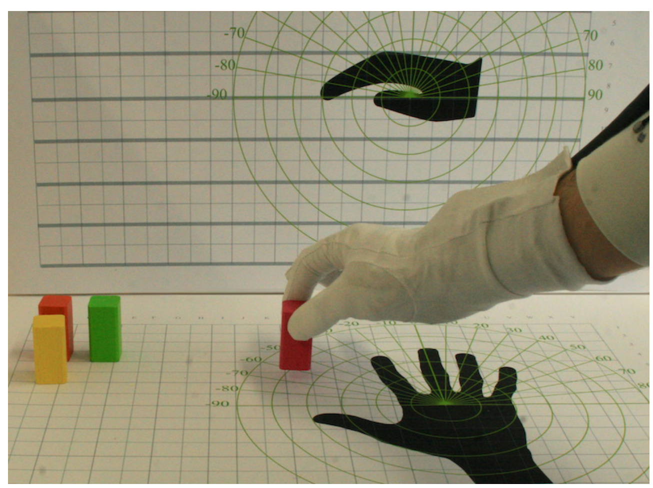

Figure 6: Apparatus for Study 3, showing the measurement grids used for observing performance in the tasks.

The six tasks involved 1) moving the hand to a specific field in straight horizontal directions on the grid and 2) on the vertical plane using the shortest path, 3) performing supination/pronation, 4) radial/ulnar deviation, 5) pointing and 6) grasping one of four wooden blocks that were arranged on the horizontal plane in a 2 x 2 matrix. We included pointing in addition to selection and manipulation, as it is often used for cohesion in training tasks. To trigger actions we applied a pattern that we also used in study 2 and that corresponds to a pre-defined motion, see Table 2: pinching was used to grasp blocks. We decided to use the continuous vibration mode as it was preferred overall in study 2. Before starting the actual experiment, participants received a 5-minute training session to learn the association between vibration feedback patterns and corresponding actions.

Each participant performed the six tasks in random order. The experimenter acted as operator who had an overview about the tasks and the order and "controlled" each action of the participant step by step, using a visual interface to trigger the predefined patterns. The operator started and stopped the specific feedback that was required for the respective task. False movements were not corrected, that is, if the user's hand moved too far, the operator provided feedback, as if the hand was at the correct position. After a task was finished, an observer (assistant of the experimenter) who was not aware of the targeted position and who could only see the participant, recorded the final position of the hand, noted any further observations and took pictures. After having finished all six tasks, the participant started a new trial that required him/her to do the six tasks again in a random order. All tasks were the same for the second time, except for grasping the block. When participants encountered a task for the first time, blocks had a distance of two fields between each other. The second time around the difficulty was raised by reducing the distance to one field. Study 3 was video-recorded with permission of the users. After having completed the study, participants rated feedback perception, task easiness, needed concentration, ease of remembering movements/gestures that correspond to a respective feedback, suitability of feedback and their performance. Eight right-handed participants (2 females, mean age 35.8 (SD 16.4), with a range of 23–65 years volunteered.

4.3.1 Results. For study 3, we analysed 48 trials. The comparison of the targeted and the actually reached grid field showed that participants could be guided quite precisely to a specific grid field on the horizontal plane. In the first trial, the reached field had only an average deviation of M = 1.88, SD = 1.36 fields from the targeted one, and M = 2.25, SD = 2.05 in the second trial. Deviations on the vertical plane were even smaller: M = 0.88, SD = 0.35 in the first and M = 0.63, SD = 1.06 in the second trial. Pointing and grasping the bricks at the two difficulty levels was always successful. Nevertheless, sometimes participants confused radial/ulnar deviation with supination/pronation, radial with ulnar deviation and up/down with left/right feedback. Participants' ratings were compared between different tasks. Generally, all ratings were positive, especially concerning pointing and grasping. While ratings for the tasks that targeted supination/pronation, radial/ulnar deviation and moving the arm around received slightly positive feedback, ratings for pointing and grasping were strongly positive. Suitability ratings for moving the arm up/down and left/right were also slightly positive and higher than in study 1b. Grasping and pointing required even less concentration than the other tasks and the assignment of the vibration feedback to the movement/gesture seems to have been easier to remember. Participants thought they performed better in pointing and grasping than in the other tasks and that the pattern initiating pointing and grasping fitted "better" compared to other patterns. Overall comfort and usability ratings are listed in Table 3. In general ratings are rather positive, only the cable seemed to have disrupted users slightly, which could be due to the weight of the cable as users also felt somewhat exhausted after wearing the glove for some time.

Table 3: Overall comfort and usability ratings for Study 3.

Statement	Mean (SD)
Glove wearing comfort	5 (1.2)
Sitting comfort	5.13 (2.03)
No disruption through the cable	3.88 (2.17)
Noticeability of vibrations	4.5 (0.93)
Not exhausted	3.75 (2.38)
Ease of learning the system	5.5 (0.03)
Ease of using the system	4.88 (1.13)
Expected improvement through exercise	6.5 (0.54)

Reflection. While results are generally encouraging, hand rotation guidance was not followed reliably. As noted below in the discussion section, based on previous work [6], we can assume that the combination of tactile and (non-ambiguous) visual cues could address this and further improve performance.

5 DISCUSSION

Here, we will discuss findings with regards to the research questions.

RQ1. How well can tactors be localized and differentiated across the hand and lower arm?

We showed that users can reasonably well localize and differentiate cues. Especially interesting is the good performance of cues at the back of the hand, which performed about as well as the index finger (which is highly sensitive, in contrast to the back of the hand). This result is useful as the back of the hand can also be used for other purposes, like the provision of touch-driven events that can be coupled to guidance, e.g., touching a wall with the back of the hand while moving a grasped object.

RQ2. How do users interpret tactile pose and motion patterns and what are their preferences?

While tactors could be localized well, the interpretation of more complex stimuli – in particular direction – was not without errors. For several reasons, this is not surprising. First, a previous study also found that users interpret some patterns as either push or pull motions [47]. That is, the direction a pattern refers to may be interpreted differently by different users. While recognition of the dominant biomechanical action (e.g., flexion of the finger, or rotation of the hand) was reasonably high, we assume that personalizing patterns will result in a higher percentage of correct motions. In our study we observed that the efficiency of our system likely improves with learning. This means that over time, users will likely be able to interpret the patterns more easily and reliably. Previous work already noted that the level of abstraction likely influences learning rates [37], with lower abstraction resulting in quicker learning. Here, we assume that our guidance patterns are at a medium to low abstraction level, as patterns are (a) easily localizable and (b) have good directional information that can be associated with a dominant biomechanical action. Learning will likely also be required to separate different types of feedback. Currently, we did not focus on touch cues, which would involve vibration at specific contact points. Depending on the context of operation, such vibration could be misunderstood, especially in cases where the user touches an object while receiving a pose change guidance pattern. While we could use different vibration modes to encode different events, the ability of users to actually differentiate among them requires further study, especially if we want to integrate pose and motion guidance methods with haptically supported selection and manipulation techniques.

RQ3. How does tactile pose and motion guidance perform in a guided selection and manipulation task?

With respect to hand guidance, we showed that our guidance methods can trigger motions and poses that can support finer-grained 3D selection and manipulation, independent of touch cues that may normally drive hand guidance. Our results extend previous tactile methods that only support general motion and pose guidance [13, 49], while our granularity is similar to EMS-based methods [32, 50], but without their disadvantages. Furthermore, while our current patterns only triggered start-to-end motions, e.g., to move the finger from a stretched to a bent configuration, guidance to intermediate stages is possible by running the pattern as long as needed. We might also use the strength of the feedback to provide a further indication about when to stop a motion, e.g., by making the feedback proportional to the error being made [14].

In all studies, we decoupled tactile cues from visual feedback. We deliberately did not use visualization aids to isolate the performance of our tactile guidance method, without interference from any given visualization method. However, related work, e.g., [6], has established that cross-modal feedback, such as the combination of visual and haptic cues, may also reduce error rates. We assume that tactile guidance methods can be visually enhanced to reduce ambiguities, based on visual and haptic stimuli integration theories [15]. The challenge is to do this in an unambiguous manner and to avoid visual conflicts. An example of visualization techniques that can aid to this respect are see-through visualization techniques [3], like transparency or cut-away. While cut-away techniques may limit spatial understanding as inter-object spatial relationships may be more difficult to understand (as objects are not rendered), transparency has been shown to maintain a reasonable level of spatial understanding [3]. Such visualization could be combined with feedback co-located with the hand (instead of embedded in the scene) that provides motion and pose guidance. We assume co-located feedback – for example by overlaying a second hand / finger animation over the virtual hand to provide guidance – will likely have a higher success rate, to avoid ambiguity issues. However, this requires further study. Furthermore, coupling of feedback in multiple modalities may increase cognitive load [54]. In our case, the somatosensory system performs complex processes involving multiple brain areas to interpret the haptic cues, while cognitive load can vary based on different haptic properties [52]. Still, cognitive load likely decreases through learning, [56], an issue we plan to follow up in future work.

6 CONCLUSION

We presented a novel tactile approach to improve hand motor planning and action coordination in complex spatial 3D applications, by guiding hand motion and poses. Such guidance can be highly useful for 3D interaction, especially for applications that suffer from visual occlusions. Extending previous work on tactile cues that only worked on more general body motions, we showed that finer-grained pose and motion adjustments can be triggered. While learning and visual cues are expected to further improve performance, e.g., by reducing some interpretation errors, the results of our user studies already provide a solid basis for implementing tailored 3D selection and manipulation techniques that can be used in the frame of applications that require fine motor control, such as assembly training.

Future work includes full integration of guidance methods into 3D applications and study thereof. An important next step is the coupling of tactile guidance with hand co-located visual cues, which will likely lead to further improvements and a better understanding of the full potential of guidance support methods. We also want to investigate task chain variations to see when and how guidance feedback affects performance in complex situations, including tactile cues for guidance and touch-related events (collision, friction) in combination with visual feedback. For real training applications, guidance methods need to be coupled to behavior and ideal path analysis to dynamically guide users through, for example, training scenarios. To address the finger detection problems with a single sensor, hand tracking must be improved, e.g., via a multi-sensor setup [21]. Finally, we like to point out that due to the independence from visual cues, our system can be used in other domains, such as guiding visually-disabled people [31].

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