

# Gaze-based Kinaesthetic Interaction for Virtual Reality

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Kinaesthetic interaction using force-feedback devices is promising in virtual reality. However, the devices are currently not suitable for interactions within large virtual spaces because of their limited workspace. We developed a novel gaze-based kinaesthetic interface that employs the user's gaze to relocate the device workspace. The workspace switches to a new location when the user pulls the mechanical arm of the device to its reset position and gazes at the new target. This design enables the robust relocating of device workspace, thus achieving an infinite interaction space, and simultaneously maintains a flexible hand-based kinaesthetic exploration. We compared the new interface with the scaling-based traditional interface in an experiment involving softness and smoothness discrimination. Our results showed that the gaze-based interface performs better than the traditional interface, in terms of efficiency and kinaesthetic perception. It improves the user experience for kinaesthetic interaction in virtual reality without increasing eye strain.

*Author Keywords: Kinaesthetic interaction, gaze tracking, force-feedback device, virtual reality, workspace, fatigue.*

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## 1. INTRODUCTION

Virtual reality (VR) is becoming increasingly popular in applications such as entertainment (Bates, 1992), professional training (Aggarwal et al., 2006), telepresence, product design, manufacturing (Mujber et al., 2004), and e-commerce. The existing interactions in VR primarily rely on our visual and auditory senses. One of the fundamental ways in which we perceive our physical world is by touch. However, the ability to touch virtual objects, to perceive their geometry, texture, and softness, is still difficult in the virtual world.

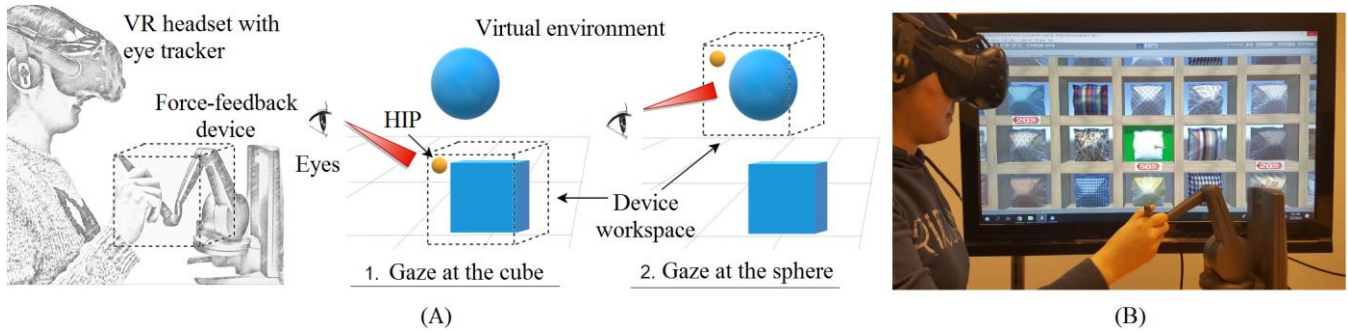
Kinaesthetic interaction as a form of human-computer interaction (HCI) enables realistic bidirectional touch behaviours. It enables natural hand motions as the kinaesthetic input and simultaneously allows users to perceive touch feeling (Saddik et al., 2011). Multiple existing devices can be used for implementing kinaesthetic interaction in the virtual world, namely, ungrounded kinaesthetic pens (Kamuro et al., 2011), wearable haptic gloves (HaptX, 2019; CyberGlove, 2019), and grounded force-feedback devices such as Geomagic Touch (3D Systems, 2019) and Novint Falcon (NOVINT, 2019).

Using grounded force-feedback devices is a promising kinaesthetic interaction setup, because these devices can enable a realistic touch interaction without the need for complex body augmentation. Force-feedback devices (e.g., Geomagic Touch) typically have a mechanical arm with three or six degrees of freedom (Massie and Salisbury, 1994). By holding the arm, the user can use hand motions as the kinaesthetic input for haptic exploration. Further, the device transfers the generated force as the kinaesthetic output to the hand for simulating the feeling of touch.

Using grounded force-feedback devices in VR has two challenges. First, the length of the mechanical arm in these devices limits the interaction space, making it difficult to explore a large VR environment. The common method to avoid this challenge is to use scaling of movement, also called control-display gain (Argelaguet and Andújar, 2013), where a small movement of the mechanical arm results in a large movement of the touch point in the virtual space. This solution helps to explore a large virtual space at the cost of reduced user control (Conti and Khatib, 2005; Dominjon et al., 2005). Second, prolonged interaction can lead to hand fatigue (Hamam and Saddik, 2015). Hand fatigue negatively affects user performance and experience for kinaesthetic interaction (Allen and Proske, 2006; Cortes et al., 2013).

Eye tracking is an emerging hands-free input mechanism for HCI. Numerous studies have demonstrated the feasibility of gaze as an input in various HCI scenarios. For example, gaze can enable easy object pointing and selection (Zhai et al., 1999; Pfeuffer et al., 2017; Nukarinen et al., 2018). Further, the gaze input can assist the interaction with a desktop computer (Kumar et al., 2007), mobile devices (Rantala et al., 2017) and wearables, such as smart glasses (Akkil et al., 2016) and smartwatches (Akkil et al., 2015). Currently, gaze tracking is gaining mainstream significance, and numerous augmented reality and VR devices, such as HTC Vive Pro eye (HTC Vive, 2019), Microsoft HoloLens 2 (Microsoft, 2019), and Magic Leap (MagicLeap, 2019), include built-in sensors that can track the user's gaze.

Using the gaze as a complementary input mechanism has been proposed to improve the current kinaesthetic interfaces. Tracking the user's gaze has been shown to be a reliable way to determine the touch position in a virtual environment (Cheng et al., 2017). Li et al. (2019) directly used the gaze



**Figure 1. (A) Indicative diagram of the gaze-switching workspace (GSW) kinaesthetic interaction: In the physical environment, the user wears a VR headset with an integrated eye tracker and holds the mechanical arm of the force-feedback device. In the virtual environment, when the user looks at a virtual object, the workspace of the force-feedback device automatically switches to that object, enabling an efficient and effortless kinaesthetic interaction with the virtual object by moving the mechanical arm. (B) An online shopping application using the GSW interface: The online store has a variety of pillows on a large showcase. When the user looks at a specific pillow, the workspace of the force-feedback device locks to that pillow. The user can quickly reach for the pillow and freely feel and compare the texture and softness by moving the mechanical arm.**

point to determine the point of interaction, and the touch operation was performed by moving the mechanical arm of the force-feedback device along the z-axis. The proposed interface, *HandGazeTouch*, enables fast point-and-touch interactions on a 2D computer screen.

The approach of directly using the gaze point as the point of interaction has several limitations. First, many of our everyday kinaesthetic explorations involve various hand motions other than the simple point-and-touch interactions. For example, when we want to identify the texture and geometry of an object, we commonly slide our fingers back and forth on the surface or along the edges of the object. These behaviours are difficult to perform using the *HandGazeTouch*. Second, this interface requires a consistent use of gaze as the input during kinaesthetic exploration, thus limiting the user’s freedom of allocation of visual attention when interacting with an object. Third, as this interaction technique requires an explicit intentional use of gaze for pointing, prolonged interactions can lead to eye strain (Li et al., 2019).

In this study, we present *gaze-switching workspace* (GSW), a new kinaesthetic interface combining the eye gaze with hand motions as the input to address the challenges of using force-feedback devices for VR interactions. The GSW interface uses gaze as a complementary modality to switch the device workspace. When the user pulls the mechanical arm of the device to its reset position (i.e., no longer in contact with any virtual object) and gazes at a new target for a predefined duration of time, the device workspace is relocated and locked to the target object. The user can then employ hand motions along the x-, y- and z-axes to control the haptic interaction point (HIP) within the workspace to explore the target. Figure 1 shows the GSW interaction and an example application.

This gaze-based design infinitely increases the interaction space using the force-feedback devices, potentially relieves hand fatigue, reduces the intentional use of eye gaze, and

enables natural hand motions for complex kinaesthetic tasks (e.g., for perceiving the shape, texture and material of the virtual object).

To evaluate the usability of the GSW interface, we conducted an experimental study comparing the new interface with the traditional interface that employs scaling of hand motions as the baseline. The focus of the study was to understand how the GSW interface compares against the traditional kinaesthetic interface in two different types of kinaesthetic tasks (softness and smoothness discrimination) that inherently involve distinct hand movement patterns. We evaluated the two interfaces based on interaction efficiency, accuracy of kinaesthetic perception and user experience.

This study is novel in the following ways. We present a new gaze-enhanced kinaesthetic interface that addresses the problems of using the force-feedback device without the limitations existed in the previous work (Li et al., 2019). To our knowledge, this study is the first on the gaze-based kinaesthetic interaction for VR. Moreover, the evaluation is based on an experiment involving both softness and smoothness perception. Softness and smoothness are two important material properties that highly affect our daily kinaesthetic tasks.

The rest of the paper is organized as follows. We first present the relevant previous works. We then describe the design of the gaze-based kinaesthetic interface and the experimental method, followed by the results and discussion.

## 2. BACKGROUND

### 2.1 Existing Kinaesthetic Interfaces for HCI

To provide kinaesthetic feedback to the user, different kinaesthetic hardware have been developed in the past few decades. The kinaesthetic pen (Kamuro et al., 2011) is an ungrounded device that can provide sensations on the user’s fingers for simulating the touch feeling with 3D models. However, the force feedback generated by the built-in

springs and motors is limited. Haptic gloves use an exoskeleton to provide kinaesthetic feedback on the palmar surface of the hand based on, for example, hydraulic systems (Zubrycki and Granosik, 2017; HaptX, 2019) or electro-mechanical systems (Hinchet et al., 2018; CyberGlove, 2019). They normally provide a limited force or require complex and often bulky hardware.

One of the most popular kinaesthetic interfaces is the grounded force-feedback devices. These devices enable natural hand motions as the kinaesthetic input, and thus, provide a flexible desktop-based kinaesthetic user interface for different application scenarios. More importantly, they can generate realistic forces with a high resolution (up to 1 kHz) (Massie and Salisbury, 1994). This study employed a force-feedback device as the kinaesthetic interface and augmented it with eye gaze to interact with virtual objects.

## 2.2 Limitations of Grounded Force-Feedback Devices

Kinaesthetically exploring a large virtual environment using the current force-feedback devices is challenging because of the small device workspace (Fischer and Vance, 2003; Conti and Khatib, 2005; Dominjon et al., 2005). A manual clutching technique (Johnsen and Corliss, 1971) was first proposed to address this issue. The user employs the device button on the mechanical arm to declutch the HIP and manually moves the mechanical arm back to the centre position of the device workspace when the workspace limit has been reached. However, this manual method is not practical for kinaesthetic interaction within a large virtual space because of the multiple re-clutching process required to reach a distant target.

Currently, the common solution is to use scaling: to translate a small movement of the mechanical arm to cause a large movement of the HIP in the virtual space (Fischer and Vance, 2003; Argelaguet and Andújar, 2013).

For example, Conti and Khatib (2005) proposed the *Workspace Drift Controller*, which adopts a similar principle of clutching. The technique progressively centres the device workspace during the interaction and uses the scaling method in the movement across the large virtual space. The *Bubble*, proposed by Dominjon et al. (2005), utilizes a sphere around the HIP and adjusts the movement speed by scaling based on the relative positions of the HIP and the sphere.

Although scaling the hand motions is practical and easy to implement, it introduces new limitations. First, using the scaling method leads to the mismatch between hand motions and HIP movements, which may negatively affect the user control of the HIP and thus the kinaesthetic task performance.

Another limitation of the current kinaesthetic interfaces is hand fatigue. Previous studies have noted that using the current-generation force-feedback device is usually uncomfortable and could cause hand fatigue, because of the repeated hand movements involved (Ott et al., 2005; Hamam and Saddik, 2015). Hand fatigue not only affects the user

experience but also negatively affects user performance in spatial positioning and haptic manipulation (Allen and Proske, 2006; Cortes et al., 2013). Therefore, reducing user fatigue is necessary in the design of kinaesthetic interfaces.

In this study, we present a novel approach to extend the interaction space by using eye gaze to select the location of the workspace instead of relying on scaling hand motions. The new interface has the potential to reduce the hand fatigue associated with kinaesthetic interaction.

## 2.3 Gaze Interaction in HCI

Gaze modality has been used previously as an input channel in numerous HCI scenarios. For example, Zhai et al. (1999) combined gaze with the mouse input to improve the efficiency of pointing and to reduce physical effort and fatigue. Majaranta and Riih  (2002) proposed the use of eye gaze to type words on the screen instead of using a physical keyboard. Kumar et al. (2007) developed *EyePoint*, an interaction technique that uses the eyes to point and keypress to select for everyday computer usage.

The VR environment provides a large and even infinite interaction space, and gaze has been considered as an efficient input for selecting objects (Tanriverdi and Jacob, 2000; Pfeuffer et al., 2017; Nukarinen et al., 2018). Tanriverdi and Jacob (2000) examined the use of eye gaze to point at objects in a VR environment. Their results showed the strengths of gaze-based selection in terms of interaction efficiency, especially for distant objects. Pfeuffer et al. (2017) developed *Gaze+pinch*, an interaction method for manipulating objects in a VR environment, by using gaze to select the object and hand gestures to manipulate it. Nukarinen et al. (2018) investigated the combination of gaze and button press from a handheld controller to select objects in VR. The participants perceived the interaction technique as fast, natural and hands-free.

Previous studies have demonstrated the feasibility and value of eye gaze as an input mechanism in VR. In this study, we extend the use of gaze input to the context of VR kinaesthetic interaction.

## 2.4 Haptic Interaction with Gaze as the Input Modality

Haptic interaction in HCI can be categorized into tactile interaction and kinaesthetic interaction (Saddik et al., 2011). Tactile interaction focuses on cutaneous sensation, whereas kinaesthetic interaction focuses on movement-based sensations originating from the muscles, tendons and joints.

For tactile interaction with tactile input devices, Stellmach and Dachsel (2012) proposed *Look and Touch*, which combines gaze with hand motions on the touchscreen as the input. Eye gaze was used for coarse pointing at the target, and fine selection was done by hand touching. The *Gaze-touch* developed by Pfeuffer et al. (2014) adopts gaze to control the movement of the cursor and combines it with hand motions on touchscreen for object manipulation. Their subsequent work, *Gaze-shifting* (Pfeuffer et al., 2015),

achieved a natural switching mechanism for the functions of gaze for *Gaze-touch*. In terms of tactile output, studies have noted that vibrotactile feedback is feasible and beneficial for the gaze-based interaction (e.g., Rantala et al., 2017).

For kinaesthetic interaction using the grounded force-feedback devices, previous studies have explored the use of gaze to augment kinaesthetic interaction, for example, to enhance safety in robotic surgery (Mylonas et al., 2010) or foster a remote haptic collaboration (Leff et al., 2015). Li et al. (2019) designed a gaze-based kinaesthetic interface to address the limited workspace. In their design, the HIP movement is controlled simultaneously by eye gaze (along the x- and y-axes) and hand movement (along the z-axis). The proposed interface supports fast point (using the gaze) and touch (using the hand-based input) interactions for softness detection. Other touch behaviours, such as feeling the texture and shape of an object, requires a complex HIP movement along the x- and y-axes and thus the accurate control of eye gaze. However, the human eye is primarily a perceptual organ. The fine control of eye movement is physiologically difficult and even impossible to perform.

The present work can be considered an extension of Li et al.'s (2019) study. We propose a new design for gaze-based kinaesthetic interaction that uses eye gaze for switching the device workspace and maintains the hand motions as the input for flexible kinaesthetic explorations.

### 3. METHOD

#### 3.1 Design of the Prototype System

In the development of the prototype system for the GSW kinaesthetic interface, an eye tracker is used to detect the

user's current point of gaze. When the user needs to touch a distant object, he simply pulls the mechanical arm backward to its reset position, and gaze at the target area for 500 ms (i.e., as the time interval between two continuous gaze points is fixed, the 500 ms dwell duration was implemented by judging whether there is enough number of gaze points continuously located on the model with an accumulated time of 500 ms.). The centre of the workspace then switches to the centre of the target object and remains locked at the target until the user repeats this process. This two-step approach allows for the fast relocating of the device workspace and ensures that no accidental switches will occur during the kinaesthetic exploration due to wandering eyes. Thus, the user has visual freedom to gaze at other objects while interacting with an object.

When the workspace switches to a new object, the position of the user's viewpoint and the size of the workspace, 16 cm × 12 cm × 12 cm (3D Systems, 2019), remain unchanged. The user notices the workspace switch by observing that the HIP has moved to the object. Then, the user can control the HIP along the x-, y- and z-axes by hand motions to explore the object.

The implementation of the traditional kinaesthetic interface adopts the scaling method to increase the size of the workspace. The selected scaling factor is 4, that is, a 1 cm physical movement of the mechanical arm results in a 4 cm movement of the HIP along the x-, y- and z- axes, thus increasing the size of the device workspace in the virtual environment by 4 times (i.e., 64 cm × 48 cm × 48 cm). The scaling function is available in the haptic plugin of Unity, the development software used in the study. The interaction

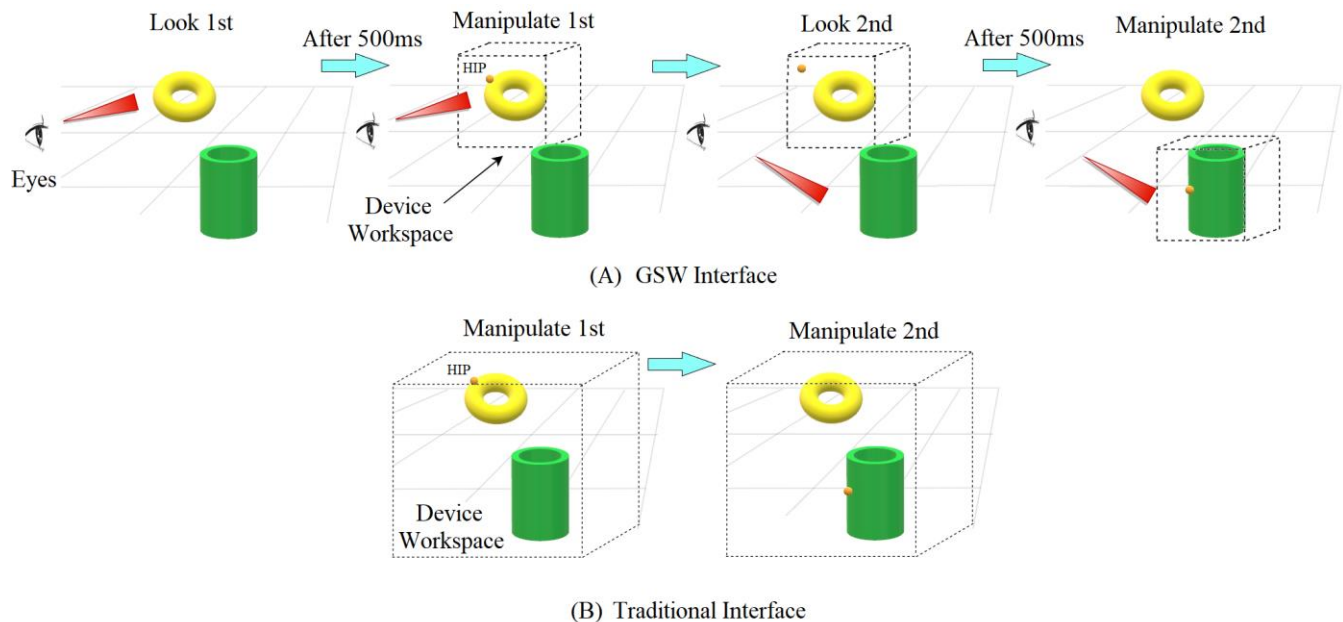


Figure 2. (A) Interaction process of the gaze-based GSW interface that uses gaze to locate the workspace of the force-feedback device. (B) Interaction process of the traditional interface with an extended device workspace using the scaling method.

processes using two kinaesthetic interfaces are shown in Figure 2.

For both interfaces, the VR headset is used as the visual display, and the kinaesthetic feedback is transferred to the hand through the mechanical arm of the force-feedback device.

### 3.2 Design of the experiment

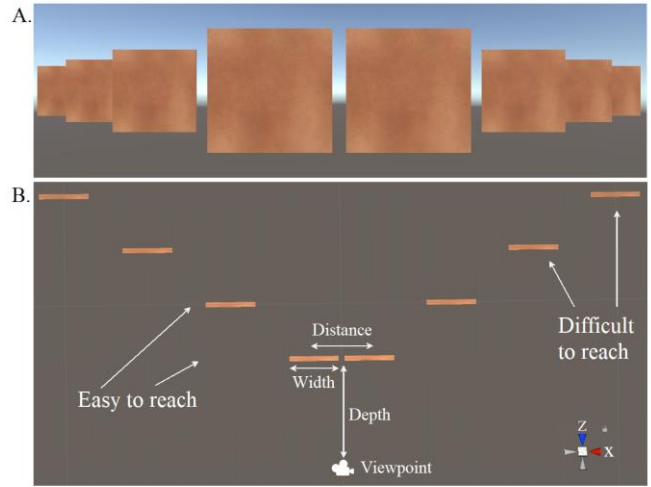
We designed a within-subject experiment in a controlled laboratory setting to compare the two kinaesthetic interfaces. The experimental task for the participant was to touch and compare two square models with different softness or smoothness characteristics. The widths of the models were the same (8 cm × 8 cm, without considering the thickness). After comparing the material properties, the participants were required to decide which one was harder or rougher and to communicate the answer by pressing the corresponding key on the keyboard (left model: A; right model: D). The participants had no visual feedback for the interaction (i.e., no visual deformation occurred when touching and the same material image was used for all models), because the different visual feedback could influence users' kinaesthetic perception (Samad et al., 2019) and therefore their task performance.

To complete the tasks, the participants had to move the HIP from its resting position to reach the target and to alternately touch the two models to estimate the difference in the material properties. The difficulty to reach the objects was based on the spatial positions of the models. Targets that were far from each other (i.e., their positions along the x- and y-axes) and at a greater depth (i.e., their positions along the z-axis) were likely to be more difficult to reach than those that were close together and at a lower depth. Further, when the difference in material properties was not evident, the participants had to alternate between the targets multiple times to gauge which object was harder or rougher.

The difficulty in reaching the target and in perceiving the difference in the material properties could influence the task performance. Thus, we manipulated the difficulty of reach and the difficulty of perception as the experimental variables.

The difficulty of reaching had two levels: easy and difficult (Figure 3). The targets that were close to each other (distance: 9 cm and 24 cm distance measured from centre to centre) and close to the viewpoint (depth: 18 cm and 27 cm) were classified as easy to reach. The targets that were farther away from each other (distance: 39 cm and 54 cm) and farther away from the viewpoint (depth: 36 cm and 45 cm) were classified as difficult to reach. Thus, based on the distance and depth values as well as the size of the models, the required size of the experimental space was at least 62 cm × 45 cm × 45 cm.

Similarly, the difficulty of perception had two levels: easy and difficult. For the easy level, the softness or smoothness differences between the two models was large and was thus relatively easy for the participants to identify. By contrast,



**Figure 3. (A) All possible groups of models for the reaching difficulty from the viewpoint of the participant in the VR environment. (B) Top view of all possible groups based on the difficult and easy reaching difficulty levels. Each trial randomly selected one possible group.**

for the difficult level, the differences were small, and identifying the harder or rougher model was more difficult.

The softness and smoothness of each model were implemented separately by the linear spring law ( $F = kx$ ), where  $k$  is the stiffness coefficient and  $x$  is the penetration depth of the HIP, and by the kinetic friction ( $F' = \mu F_n$ ), where  $\mu$  is the friction coefficient and  $F_n = mg$ , the normal force value. Two haptic features were integrated in the haptic plugin of Unity.

We manipulated the softness and smoothness degrees by changing the stiffness coefficient ( $k$ ) within the range of (0.175 – 0.235) and the friction coefficient ( $\mu$ ) within the range of (0.11 – 0.18). The difference in the stiffness coefficient ( $\Delta k$ ) and the difference in the friction coefficient ( $\Delta \mu$ ) between two models had six possible values ( $\Delta k$ : 0.01 – 0.06 in steps of 0.01;  $\Delta \mu$ : 0.02 – 0.07 in steps of 0.01).

**Table 1. Difficulty of perception for the softness and smoothness tasks.**

	Softness task		Smoothness task	
<b>Difficult to Perceive</b>	$\Delta k$ : 0.01	$k_1$ : 0.20 $k_2$ : 0.21	$\Delta \mu$ : 0.02	$\mu_1$ : 0.135 $\mu_2$ : 0.155
	$\Delta k$ : 0.02	$k_1$ : 0.195 $k_2$ : 0.215	$\Delta \mu$ : 0.03	$\mu_1$ : 0.13 $\mu_2$ : 0.16
	$\Delta k$ : 0.03	$k_1$ : 0.19 $k_2$ : 0.22	$\Delta \mu$ : 0.04	$\mu_1$ : 0.125 $\mu_2$ : 0.165
<b>Easy to Perceive</b>	$\Delta k$ : 0.04	$k_1$ : 0.185 $k_2$ : 0.225	$\Delta \mu$ : 0.05	$\mu_1$ : 0.12 $\mu_2$ : 0.17
	$\Delta k$ : 0.05	$k_1$ : 0.18 $k_2$ : 0.23	$\Delta \mu$ : 0.06	$\mu_1$ : 0.115 $\mu_2$ : 0.175
	$\Delta k$ : 0.06	$k_1$ : 0.175 $k_2$ : 0.235	$\Delta \mu$ : 0.07	$\mu_1$ : 0.11 $\mu_2$ : 0.18

**Table 2. Statements in the questionnaire.**

Statements	Description
S1	This interaction technique is mentally easy to use.
S2	This interaction technique does not make my hand tired.
S3	This interaction technique does not make my eyes tired.
S4	This interaction technique is natural to use.
S5	This interaction technique is pleasant.

Table 1 presents the details of the difficulty levels of perception.

There were 24 trials for each task using each kinaesthetic interface. The reaching levels were repeated six times in the experiment ( $4 \text{ levels} \times 6 \text{ times} = 24 \text{ trials}$ ), and the perception difficulty levels were repeated 4 times ( $6 \text{ levels} \times 4 \text{ times} = 24 \text{ trials}$ ). For each trial, the reaching and perception levels were independent and randomly selected from a list of possible values (the selected values were removed from the lists after each selection). Each participant was asked to perform the softness and smoothness tasks using the two interfaces. Thus, each participant completed four rounds of the task ( $2 \text{ tasks} \times 2 \text{ interfaces} = 4 \text{ task groups}$ ), resulting in a total of 96 trials in the experiment.

The prototype system recorded the task completion time and the users' answer for each trial as the objective data. Further, we used a seven-point Likert scale questionnaire to record the perceived mental effort, the hand and eye fatigue, and the naturalness and pleasantness of using the interfaces as the subjective data. The questionnaire was motivated by the NASA task load index questions (Hart and Staveland, 1988) to assess the users' subjective feelings. Table 2 presents the statements in the questionnaire.

### 3.3 Pilot Study

Before the experiment, a pilot study was conducted with four participants who had previous experience in gaze or haptic interaction. The purpose of the pilot study was to identify the suitable parameters for the system.

- The size of the models ( $8 \text{ cm} \times 8 \text{ cm}$ ) was chosen, so that the users could smoothly perform the touch activities. The selected size was also large enough for the robust model selection by gaze, without the accuracy and precision of gaze tracking affecting the interaction, especially for the tasks in which the model was at a large depth.
- The distance and depth values for the two levels of the reaching difficulty were also chosen. As the spatial positions of objects could be various, we simply placed the two models at the same depth and manipulated their depth and the distance between them to design the variable of the reaching difficulty. Two levels (easy and difficult) could sufficiently represent the increasing difficulty in reaching distant objects.



**Figure 4. Experimental environment. The additional 2D display shows one experimental trial with the group of models.**

- The values for the softness and smoothness differences between the models were selected based on human touch perception and the sensitivity of the force-feedback device. The high difficulty levels were selected to make them perceivable by the participants but with a more focused comparison.
- The scaling factor (4) for the traditional interface was chosen based on the original workspace size of the force-feedback device and the required virtual space size for the experimental tasks. Thus, the device workspace of the traditional interface ( $64 \text{ cm} \times 48 \text{ cm} \times 48 \text{ cm}$ ) could cover the experimental virtual space ( $62 \text{ cm} \times 45 \text{ cm} \times 45 \text{ cm}$ ), allowing the users to reach any spatial points required by the experimental tasks.
- We used the raw gaze data returned by the tracker without any additional filtering. Further, the dwell time for the workspace switching was selected as 500 ms. As the interaction involved two steps (i.e., moving the mechanical arm to its reset position and then dwelling), it was robust against unintentional activation. Thus, a short dwell time was selected to increase the feeling of responsiveness of the system and to avoid unnatural long staring while still enabling user control of the gaze-based activations.

## 4. EXPERIMENT

### 4.1 Apparatus

We used an MSI GS63VR 7RF Stealth Pro Windows 10 laptop with an Intel i7-7700HQ processor, GeForce GTX 1060 graphics card, and 16GB of RAM as the host computer. A Geomagic Touch X (3D Systems, 2019) was utilized as the force-feedback device, and an HTC Vive VR headset (HTC Vive, 2019) with an integrated Tobii eye tracker (Tobii, 2019) was used as the display. The headphones on the VR headset were utilized to block out noise, and a keyboard was employed for the participants to record their answers. The test environment is illustrated in Figure 4.

The experimental development software was Unity with SteamVR, Tobii SDK and haptic plugin for Geomagic OpenHaptics. The haptic plugin was used to connect the force-feedback device with Unity and to control the haptic properties of the virtual objects. The Tobii SDK was used for eye tracking.

## 4.2 Participants

We recruited 32 participants (21 women and 11 men) from the local university community aged between 19 and 40 years ( $M = 24.6$ ,  $SD = 4.30$ ). Thirteen participants had normal vision, and the others had corrected vision. Four participants reported they were left-handed, and the others were right-handed. Nine participants had used a similar VR headset one to two times, but none had previous eye-tracking experience. Two participants had used a similar force-feedback device on a 2D display once as a part of coursework. According to the self-reports, all participants had normal touch sensitivity.

## 4.3 Procedure

We first introduced the study and the equipment to the participants. All the participants signed an informed consent form and filled out the background questionnaire.

Each participant was assigned four task groups, and the order of the task groups was counterbalanced. For each task group, the participants were informed about the task type and introduced to the kinaesthetic interface. They had up to 5 min to familiarize themselves with use of the interface.

Before the experiment started, the eye tracker was calibrated using a five-point calibration system integrated with the Tobii SDK. For both interfaces, the participants used their dominant hand to hold the mechanical arm of the force-feedback device. The mechanical arm was positioned at its maximum distance from the device at the beginning. The participants sat comfortably on the chair and could rest their arm on the table while holding the force-feedback device.

The participants were instructed to complete each experimental trial as accurately and quickly as they could. We did not provide any feedback regarding the task performance. During the experiment, the participants could alternate between touching the two models as many times as they wanted, to identify the difference in softness or smoothness. After the comparison, they moved the mechanical arm back to the start position and used their non-dominant hand to press the corresponding key on the keyboard to record their answer. The prototype system then automatically moved to the next trial. After completing one task group with 24 trials, the participants had a 5 minutes break before the start of the next task group.

As the level of sound produced by the force-feedback device could indicate the amplitude of the force, constant white noise (fuzzy sound) was played to the participants through the headphones of the VR headset.

**Table 3. Tests of within-subject effects for the softness task. All significant  $p$  values are in bold.**

Sources	Time			Errors		
	Df	F	Sig.	df	F	Sig.
Interfaces (I)	1, 31	10.595	<b>0.003</b>	1, 31	21.68	<b>&lt;0.001</b>
Reaching (R)	1, 31	13.44	<b>0.001</b>	1, 31	13.841	<b>0.001</b>
Perception (P)	1, 31	8.235	<b>0.007</b>	1, 31	60.662	<b>&lt;0.001</b>
I and R	1, 31	10.317	<b>0.003</b>	1, 31	12.339	<b>0.001</b>
I and P	1, 31	0.001	0.972	1, 31	0.818	0.373
R and P	1, 31	2.044	0.163	1, 31	0.067	0.797
I, R, and P	1, 31	1.530	0.225	1, 31	2.201	0.148

## 5. RESULTS

For simplicity, the results of the softness and smoothness discrimination tasks were analysed separately. We first conducted the Shapiro-Wilk normality test for the data. In each experimental task, the result showed that the task completion times and the task errors were not normally distributed (all  $p < .001$ ). Therefore, we analysed the completion times and task errors separately using a  $2 \times 2 \times 2$  (interfaces  $\times$  difficulty levels of reaching  $\times$  difficulty levels of perception) aligned rank transform (ART) repeated-measures non-parametric analysis of variance (ANOVA) (Wobbrock et al., 2011) for the softness and smoothness tasks, respectively. The post hoc analysis relied on the Wilcoxon signed-rank test. We used the Holm-modified Bonferroni correction (Holm, 1979) to control the family-wise type-1 error for interaction effects.

In the experiment, each participant was given 24 trials in each task group. We used the mean time to evaluate the interaction efficiency and the total number of errors of each task group to analyse the perception accuracy.

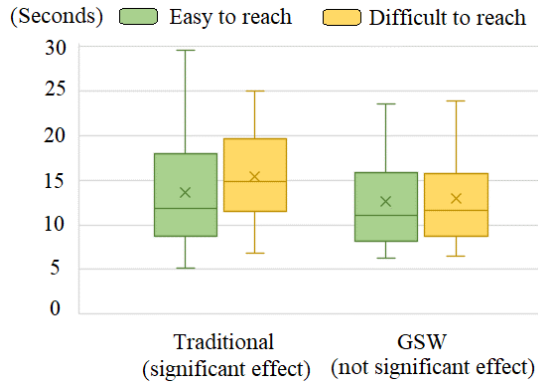
### 5.1 Softness Discrimination Task

Table 3 shows the results of the ART ANOVA on the task completion times and the errors for the softness task. As expected, the reaching difficulty and the perception difficulty statistically significantly influenced the task completion times and errors. In the following sections, we focus only on the main effect of the interfaces and the more interesting interaction effects.

#### *Interaction efficiency*

For the main effect of interfaces, the post hoc analysis using the Wilcoxon signed-rank test showed that the task completion time when using the GSW interface ( $M = 12.68$ ,  $SD = 5.41$ ) was statistically significantly shorter than the time when using the traditional interface ( $M = 14.5$ ,  $SD = 5.05$ ;  $Z = -2.749$ ,  $p = .006$ ).

In addition, a statistically significant interaction effect was found between the interface and the reaching difficulty. Figure 5 shows the task completion time for the two interfaces based on the reaching difficulty.



**Figure 5. Task completion time based on the reaching difficulty for the softness task. (The cross mark is the mean value, and the line is the medium value.)**

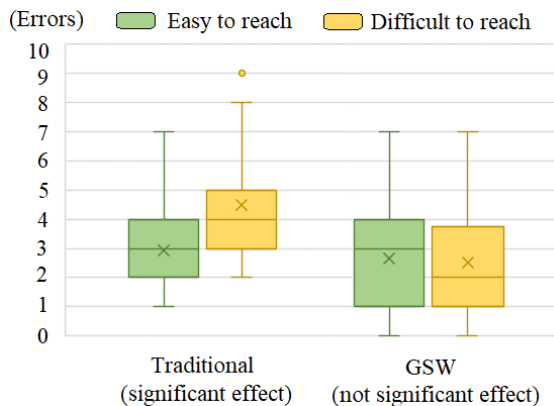
For the traditional interface, the post hoc analysis showed that the participants spent less time completing the task when the reaching difficulty was low ( $M = 13.64$ ,  $SD = 5.89$ ) than when it was high ( $M = 15.37$ ,  $SD = 5.02$ ;  $Z = -2.637$ ,  $p = .016$ ). By contrast, for the GSW interface, the reach difficulty did not affect the task completion times ( $M = 12.64$ ,  $SD = 5.83$  for the low difficulty compared with  $M = 12.93$ ,  $SD = 5.34$  for the high difficulty;  $Z = -1.272$ ;  $p = .204$ ).

#### Kinaesthetic perception accuracy

During the experiment, the participants committed different numbers of errors in judging the difference in softness while using the two kinaesthetic interfaces. Overall, 402 errors out of the 1536 trials (32 participants  $\times$  48 softness trials = 1536 trials), which yielded an overall error rate of 26.2%, were committed.

For the main effect of the interfaces, the post hoc analysis demonstrated that the participants using the GSW interface ( $M = 5.16$ ,  $SD = 3.02$ ) made statistically significantly fewer errors than those using the traditional interface ( $M = 7.41$ ,  $SD = 2.33$ ) for the softness task ( $Z = -3.52$ ,  $p < .001$ ).

The interaction effect between the interfaces and the reaching difficulty was statistically significant. The boxplot is shown in Figure 6. The post hoc analysis demonstrated that



**Figure 6. Task errors based on the reaching difficulty for the softness task.**

**Table 4. Tests of within-subject effects for the smoothness task.**

Sources	Time			Errors		
	df	F	Sig.	df	F	Sig.
Interfaces (C)	1, 31	7.359	<b>0.011</b>	1, 31	62.309	<b>&lt;0.001</b>
Reaching (R)	1, 31	27.597	<b>&lt;0.001</b>	1, 31	34.586	<b>&lt;0.001</b>
Perception (P)	1, 31	31.39	<b>&lt;0.001</b>	1, 31	86.856	<b>&lt;0.001</b>
I and R	1, 31	0.3	0.588	1, 31	32.809	<b>&lt;0.001</b>
I and P	1, 31	7.466	<b>0.01</b>	1, 31	4.645	<b>0.039</b>
R and P	1, 31	0.978	0.33	1, 31	3.052	0.091
I, R, and P	1, 31	0.521	0.476	1, 31	1.341	0.256

the participants using the traditional interface committed fewer errors when the reaching difficulty was low ( $M = 2.94$ ,  $SD = 1.50$ ) than it was high ( $M = 4.47$ ,  $SD = 1.67$ ;  $Z = -3.325$ ,  $p = .002$ ). However, when using the GSW interface, the difference in the errors based on the reaching difficulty was not statistically significant ( $M = 2.5$ ,  $SD = 1.8$  for the high reaching difficulty compared with  $M = 2.66$ ,  $SD = 1.66$  for the low reaching difficulty;  $Z = -0.65$ ,  $p = .516$ ).

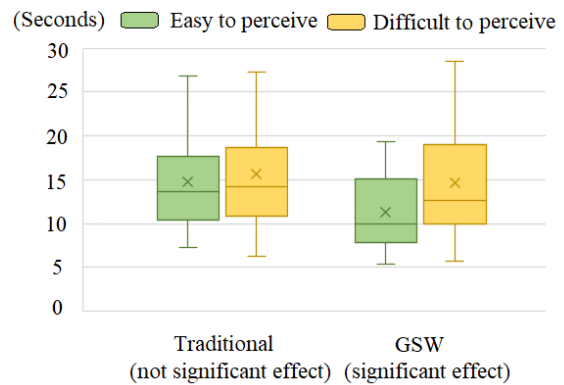
#### 5.2 Smoothness Discrimination Task

Table 4 shows all the  $p$  values for the task completion times and the errors in the smoothness task based on the interfaces, the reaching and the perception difficulties. We focus on the main effect of the interfaces and the interaction effects in the following sections.

#### Interaction efficiency

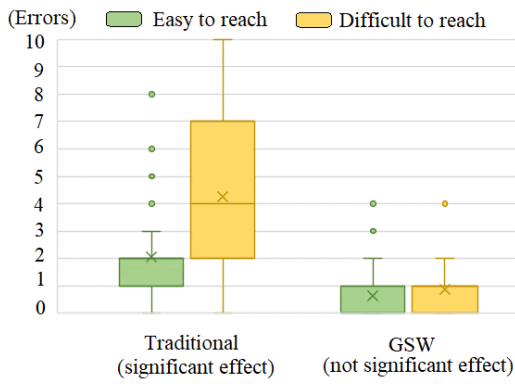
For the main effect of the interfaces, the post hoc analysis demonstrated that using the GSW interface ( $M = 12.78$ ,  $SD = 5.28$ ) led to a statistically significantly shorter task completion time than using the traditional interface ( $M = 14.98$ ,  $SD = 5.50$ ;  $Z = -2.898$ ,  $p = .004$ ).

Figure 7 shows the boxplot of the task completion times for the statistically significant interaction effect between the interfaces and the perception difficulty. For the traditional interface, no statistically significant difference was found in the task completion time when the smoothness



**Figure 7. Task completion time based on the perception difficulty for the smoothness task.**





**Figure 8. Task errors based on the reaching difficulty for the smoothness task.**

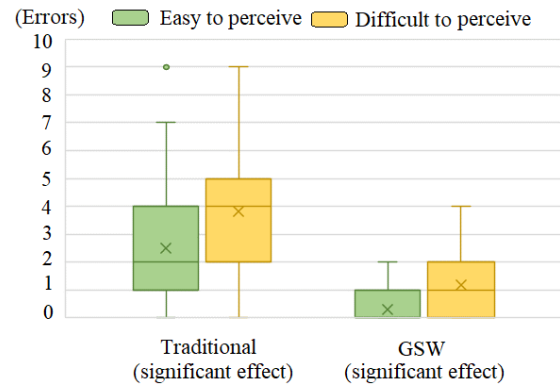
discrimination was easy or difficult ( $M = 14.73$ ,  $SD = 5.36$  compared with  $M = 15.69$ ,  $SD = 6.43$ ;  $Z = -1.589$ ,  $p = .112$ ). By contrast, using the GSW interface led to a statistically significantly shorter task completion time when the perception difficulty was low ( $M = 11.29$ ,  $SD = 4.08$ ) than when it was high ( $M = 14.63$ ,  $SD = 6.07$ ;  $Z = -4.394$ ,  $p < .001$ ).

#### *Kinaesthetic perception accuracy*

In the smoothness task, 238 errors out of the 1536 trials, which yielded an overall error rate of 15.5%, were committed. For the main effect of the interfaces, the post hoc analysis demonstrated that the number of errors committed when the participants used the GSW interface ( $M = 1.5$ ,  $SD = 1.5$ ) was statistically significantly lower than the one committed when the participants used the traditional interface ( $M = 5.94$ ,  $SD = 3.24$ ;  $Z = -4.743$ ,  $p < .001$ ).

Figure 8 shows the boxplot of the task errors based on the interfaces and the reaching difficulty. Using the traditional interface caused fewer errors when the targets were easy to reach ( $M = 2.06$ ,  $SD = 2.11$ ) than when they were difficult to reach ( $M = 4.25$ ,  $SD = 2.54$ ;  $Z = -3.895$ ,  $p < .001$ ). However, when the participants used the GSW interface, no difference in the task errors was found based on the reaching difficulty (low difficulty:  $M = 0.63$ ,  $SD = 1.01$  compared with high difficulty:  $M = 0.88$ ,  $SD = 1.04$ ;  $Z = -0.989$ ,  $p = .323$ ).

Figure 9 illustrates the boxplot of the task errors based on the interfaces and the perception difficulty. For the traditional interface, the participants committed fewer errors when the perception difficulty was low ( $M = 2.5$ ,  $SD = 2.13$ ) than



**Figure 9. Task errors based on the perception difficulty for the smoothness task.**

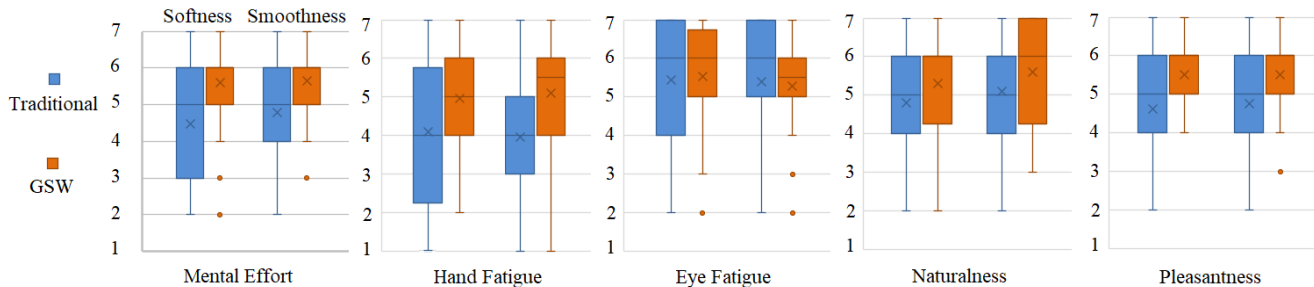
when it was high ( $M = 3.81$ ,  $SD = 2.21$ ;  $Z = -3.347$ ,  $p = .002$ ). The results for the GSW interface followed a similar pattern: the participants committed fewer errors when the perception difficulty was low ( $M = 0.31$ ,  $SD = 0.54$ ) than when it was high ( $M = 1.19$ ,  $SD = 1.33$ ;  $Z = -3.182$ ,  $p = .001$ ).

#### **5.3 Subjective Data**

The subjective data collected from the questionnaire are shown in Figure 10. We analysed the data using the Wilcoxon signed-rank test.

For the softness and smoothness tasks:

- **Mental effort:** The GSW interface was considered mentally easier to use than the traditional interface (softness:  $Z = -3.224$ ,  $p = .001$  and smoothness:  $Z = -2.909$ ,  $p = .004$ ).
- **Hand fatigue:** The GSW interface caused less hand fatigue than the traditional interface (softness:  $Z = -3.137$ ,  $p = .002$  and smoothness:  $Z = -3.166$ ,  $p = .002$ ).
- **Eye fatigue:** No difference was found between the two kinaesthetic interfaces (softness:  $Z = -0.33$ ,  $p = .741$  and smoothness:  $Z = -0.502$ ,  $p = .615$ ).
- **Naturalness:** The GSW interface was considered more natural than the traditional interface for the softness task (softness:  $Z = -2.062$ ,  $p = .039$ ), and no difference was found in terms of naturalness for the smoothness task, but the difference approached statistical significance ( $Z = -1.952$ ,  $p = .051$ ).



**Figure 10. Subjective data of the study.**

- Pleasantness: The GSW interface was considered more pleasant than the traditional interface (softness:  $Z = -3.256, p = .001$  and smoothness:  $Z = -3.095, p = .002$ ).

## 6. DISCUSSION

This study explored the use of eye gaze as an input modality to relocate the workspace of the force-feedback device for VR kinaesthetic interaction. This new design enabled a flexible and robust kinaesthetic exploration within a large virtual space. There were two types of kinaesthetic interaction tasks in the experiment: softness and smoothness discrimination. Softness and smoothness discrimination inherently involve different patterns and complexities of the HIP movement. The study results showed that the GSW interface has benefits for both kinaesthetic tasks. In this section, we discuss our results related to the state of art.

### 6.1 Softness Discrimination Task

The softness discrimination task was characterized by multiple point-and-tap interactions with the objects, by alternating between them several times. Our results showed that the GSW interface generally enabled a shorter task completion time and a better kinaesthetic perception compared with the traditional interface.

#### *Interaction efficiency*

The interaction efficiency of two kinaesthetic interfaces was highly influenced by the efficiency to reach the targets because of the type of kinaesthetic interaction the participants performed for softness discrimination. For the traditional interface, the participants took more time to complete the task when the targets were further apart. This was not the case while using the GSW interface.

Using the traditional interface, the participants had to use their hand along the x-, y- and z-axes to reach the targets which required more time when the distances were larger (Sallnäs and Zhai, 2003). Further, researchers have noted that the visual size of an object affects the motor speed in reaching the object (Berthier et al., 1996). In VR interactions, the visual size of the target object (the size along the x- and y-axes from the viewpoint of the user) is directly related to its position along the z-axis. For example, when the reaching difficulty was high, the targets were further away from the viewpoint of the participant and thus, appeared smaller. The small visual size of the object could have negatively affected the reaching speed by the hand motions. Our results support the previous results of Sallnäs and Zhai (2003) and Berthier et al. (1996) regarding the effects of the distances to the objects and their visual sizes on the reaching speed, which led to the lower efficiency while using the traditional interface.

Conversely, using the GSW interface, participants traversed the virtual space by employing saccadic eye movements that typically last 30–120 ms (Jacob, 1995). This approach eliminated the need for explicit hand motions to reach targets. Eye gaze has been found to be a fast input

mechanism for reaching an object in different HCI contexts (Zhai et al., 1999; Majaranta and Riih , 2002; Kumar et al., 2007), including kinaesthetic interaction (Li et al., 2019) which uses the gaze point as the touch point.

In this study, we used the gaze to select the object for relocating the device workspace. Schuetz et al. (2019) noted that gaze as a selection method is less influenced by the distance between the targets and more influenced by the size of the targets. They suggested that a visual size of above 3 degrees for gaze-based selection could ensure a near-constant selection time, regardless of the distance between the targets. In our case, the smallest visual size of the target (real size: 8 cm) at the highest depth (45 cm) appeared approximately 10 degrees ( $2 \times \arctan(8/(45 \times 2)) \approx 10$ ) in the visual angle. This likely explains why the reach difficulty had no influence on the task completion times and thus the increased interaction efficiency using the GSW interface.

#### *Kinaesthetic perception accuracy*

In the experiment, the participants were asked to identify the harder model after comparing the two models. The difference in the number of errors committed by the participants indicates the difference in kinaesthetic perception by our somatosensory system enabled by the two interfaces. The results suggest that the kinaesthetic cues generated from the GSW interface are easier or clearer to interpret with the somatosensory system than those from the traditional interface.

Interestingly, the reaching difficulty differentially influenced the perception accuracy using two interfaces (Figure 6). The reaching difficulty did not have a statistically significant effect on the number of errors for the GSW interface. However, for the traditional interface, the participants committed more errors when the objects were difficult to reach than when they were easy to reach.

This phenomenon while using the traditional interface has two potential explanations. First, when the objects were difficult to reach, participants had to perform a strenuous hand motion to control the HIP during the exploration (especially with the scaling on the hand motions). This strenuous hand motion could have interfered with hand ability to perceive subtle differences in the material properties, a phenomenon that is widely known as *tactile suppression* (Williams and Chapman, 2002; Chapman and Tremblay, 2015; Juravle et al., 2017). *Tactile suppression* indicates that our somatosensory system naturally suppresses haptic perceptual sensitivity under motor commands (Chapman and Tremblay, 2015). It could explain the higher number of errors committed using the traditional interface when the targets were difficult to reach. A second plausible, although unlikely, explanation could be the effect of haptic memory. When the material properties of two objects are sequentially compared, an increased amount of time between the comparisons could lead to the fading of the haptic representation of the first stimulus in the memory. Previous studies showed that the memory of the haptic representation

of an object is short-lived, up to 2 s (Shih et al., 2009) or even 5 s (Metzger and Drewing, 2019). However, in the present case, the time to alternate between targets was much smaller (<1 s) and was unlikely to have had a significant effect.

In comparison, our results showed that the kinaesthetic perception accuracy was not affected by the reaching difficulty while using the GSW interface. Using the GSW interface enabled participants to quickly switch between the target objects without the need for strenuous hand motions, and to easily control the HIP for fine point-and-tap interactions. Similar to the *HandGazeTouch* (Li et al., 2019), the GSW interface maintained a high accuracy in softness perception.

In sum, our results indicate that the GSW interface is a better interaction technique than the traditional interface for VR applications involving perceiving softness in terms of both efficiency and accuracy of perception.

## 6.2 Smoothness Discrimination Task

The smoothness discrimination tasks required the participants to switch between the target objects and was characterized by long kinaesthetic interactions with the objects using complex gestures (e.g., sliding back and forth or making a circular motion with the HIP). These touch behaviours are physiologically difficult to perform by eye gaze using the *HandGazeTouch* (Li et al., 2019). However, our results showed that the GSW interface is suitable for the smoothness discrimination task. In the following, we discuss the results of the smoothness task using the GSW interface and the traditional interface.

### *Interaction efficiency*

For the smoothness discrimination task, the GSW interface was also faster than the traditional interface. However, this improved efficiency cannot be fully attributed to the faster reaching of the target enabled by gaze. In fact, the effect of the reaching difficulty did not differentially affect the task completion times for the two interfaces, shown in our results (i.e., no statistically significant interaction effect). Perceiving the smoothness of an object requires complex kinaesthetic interactions on the models, in contrast to the simple point-and-tap style interaction required to detect softness. Thus, the time required to reach the object is likely only a small part of the overall task completion time for the smoothness task.

Another possible reason for the improved overall efficiency of the GSW interface in the smoothness discrimination task could be the improved user control of the HIP. An important difference between the GSW interface and the traditional interface is the different scaling factor applied to the hand motions. As the GSW interface enables effortless relocation of the device workspace using the user's gaze, it overcomes the need for applying scaling on the hand motion to reach distant objects. The HIP movement matches with the hand movement, that is, a 1 cm movement of the mechanical arm moved the HIP by the same amount. By contrast, in the case of the traditional interface, scaling of hand motions must be

applied (gain = 4) because of its inherently limited workspace. Consequently, a 1 cm movement of the mechanical arm resulted in four times the amount of movement of the HIP.

The greater control of the HIP using the GSW interface, compared with the traditional interface, could have enabled a more flexible and finer kinaesthetic exploration. With such a kinaesthetic exploration, a better haptic perception could be achieved (Lederman and Klatzky, 1987). Using the GSW interface, the participants could perform flexible hand motions to efficiently detect smoothness. The benefit in the interaction efficiency was more evident in tasks that were easy to perceive (Figure 7).

### *Kinaesthetic perception accuracy*

Similar to the softness discrimination task, the reaching difficulty modulated the accuracy of the task performance for the traditional interface in the smoothness discrimination task (Figure 8). Again, this could be attributed to the phenomenon of *tactile suppression* (Chapman and Tremblay, 2015). Conversely, the perception accuracy in the smoothness task using the GSW interface was unaffected by the difficulty of reaching the target.

Another difference between the GSW interface and the traditional interface was evident in the tasks in which the smoothness differences were difficult to perceive. Using the traditional interface, the range of the hand motion to detect the smoothness kinaesthetic cues (i.e., by sliding motions along the x- and y-axes) was limited by the size of the object and, more importantly, by the scaling applied. Thus, the traditional interface was practically not conducive for fine-level kinaesthetic explorations that were required for smoothness discrimination. This could have further led to more errors while using the traditional interface for the smoothness task with the high perception difficulty (Figure 9). By contrast, the number of errors committed using the GSW interface was only marginally higher when the perception difficulty was high than when the perception difficulty was low.

## 6.3 User Experience

This study compared two kinaesthetic interfaces in terms of a subset of user experience factors, such as perceived mental effort, hand and eye fatigue, and the naturalness and pleasantness of the interaction. Overall, the GSW interface was perceived to cause less mental effort and hand fatigue and considered to be more natural and pleasant to use (Figure 10).

Multiple factors could have contributed to the improved rating of the GSW interface compared with the traditional interface. The GSW interface reduced the extent of the hand motion required to move between the target objects and thus led to less strain on the hands. Further, the GSW interface enabled the better control of the HIP and allowed a more realistic, natural and fine-level kinaesthetic exploration.

**Table 5. Differences between the HandGazeTouch and GSW.**

Advantages	HandGazeTouch	GSW
Suitable for kinaesthetic tasks involving smoothness perception	No	Yes
Flexible for allocation of visual attention during exploration	No	Yes
Reduced intentional and explicit use of the eyes, thus lowering eye strain and mental effort	No	Yes
Simplified the mechanical design for force-feedback devices	Yes	No

The participants did not report increased eye strain while using the GSW interface. Typically, performing unnatural eye movements, for example, long unnatural staring at objects (Majaranta et al., 2009) or unnatural gaze gestures (Chitty, 2013), can cause eye strain for novice users. The design of the GSW interface leverages the natural hand-eye coordination that exists in everyday physical tasks without the need for explicit unnatural eye movements.

At a general level, it is interesting to compare *HandGazeTouch* (Li et al., 2019) with this current work. Table 5 summarizes the differences between the two gaze-based interfaces. Clearly, both the interaction techniques have their own advantages. *HandGazeTouch* can lead to a simplified mechanical design of the force-feedback device because the physical motion of the mechanical arm is required only along the z-axis. However, the GSW interface is better suited for flexible and user-friendly kinaesthetic explorations.

#### 6.4 Limitations and Future Work

This study has several limitations.

First, the experimental scenario for examining the two kinaesthetic interfaces was simple. The models were large, flat in shape and unblocked in terms of visibility. The relatively large size enabled the easy selection with the eyes, and gaze data quality had little effect on our results. It is likely that when objects are small, placed very deeply or densely distributed, selecting them with the eyes would be highly susceptible to the gaze tracking accuracy and precision. Previous studies have started to address this issue. For example, Mardanbegi et al. (2019) used the depth estimation to resolve target ambiguity (e.g., due to partial occlusion) within a 3D environment and to make gaze selection more robust in complex VR scenarios. Future research is required to understand the use of the GSW interface in complex VR environments and study new methods to make gaze-based selection more robust in such environments.

Second, we examined the GSW interface with relatively small virtual objects compared with the size of the device workspace. For very large objects, the current implementation of the GSW interface may be hindered by

the limits of the workspace because we always relocate the workspace to the centre of the object. Another possible approach for interacting with very large objects is to design multiple workspace relocation points on the same object based on eye gaze. We propose this idea for the future research.

Third, the study experiment focused on the comparison between the GSW interface and the traditional interface with the fundamental scaling technique that applies the scaling factor on the hand motions for reaching and manipulating objects. Future studies can compare the task performances using the GSW interface with those using the interfaces employing other techniques, such as *Workspace Drift Controller* (Conti and Khatib, 2005)) and *Bubble* (Dominjon et al., 2005), which applied the scaling factor on the hand motion only for reaching, within the large virtual environment provided by the VR headset.

Fourth, the participants were predominantly young students. The GSW interface is a novel interaction technique that requires a higher level of hand and eye coordination. Older participants are known to have less hand and eye coordination (Ruff and Parker, 1993) and may perform differently while using the GSW interface. Therefore, further research is required to understand the usability of the GSW interface for different participant groups.

Fifth, the force-feedback device we used supported only single-point interactions. For the softness task, using this device is adequate for an accurate softness discrimination (Lamotte, 2000). For the smoothness task, the participants easily completed the experimental task using this interaction method without any practical problems. However, we normally use multi-point touch (e.g., the palmar surfaces of the fingers) to detect the smoothness difference in the physical world. Conceptually, the GSW interface can be applied to multi-point touch interactions. Future research using an advanced force-feedback device is required to examine the effects of a multi-point interaction on the smoothness task while using the GSW interface.

Sixth, this study mainly focused on the virtual space in front of the user. Conceptually, the GSW interface can be applied to kinaesthetic interactions within the 360 degrees of the virtual space presented by the VR headset. Using the GSW interface, the device workspace is locked at the gazing object, and the direction of kinaesthetic input can be adjusted along with the user's view angle by orienting the workspace. This method makes the kinaesthetic interaction for the extended virtual space around the user possible. Future studies can investigate the performance of the GSW interface for this aspect.

Seventh, the study experiment involved only static objects. Typical VR scenes may have a multitude of moving stimuli (e.g., planets in motion). Interacting with moving objects using the traditional kinaesthetic interface may be particularly difficult. We believe the GSW interface to be well-suited for such interaction tasks because the workspace

can remain locked to the object that has current visual attention. Previous research has shown that gaze is particularly suited for selecting moving targets (Shishkin et al., 2018). However, future research is required to understand the cost and benefits of the GSW interface in such scenarios.

## 7. CONCLUSION

In this study, we presented the GSW interface, a gaze-enhanced kinaesthetic interaction technique for VR. The design of the GSW interface addressed the limited workspace and hand fatigue associated with using a force-feedback device. Eye gaze was used for locating the device workspace while still maintaining hand motions for various kinaesthetic interactions. This design avoided the overuse of the eye gaze and enlarged the applicability of the gaze-based kinaesthetic interface. The experimental results showed that the GSW interface is better than the traditional interface in terms of interaction efficiency, perception accuracy and user experience. It could be a compelling choice of interaction technique for future VR kinaesthetic interactions.

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