# Generating Haptic Sensations over Spherical Surface*

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**Abstract.** Haptic imagery, the imagining of haptic sensations in the mind, makes use of and extends human vision. Thus, enabling a better understanding of multi-dimensional sensorimotor information by strengthening space exploration with "seeing by touch." Testing this concept was performed on a spherical surface to optimize the way of generating localized haptic signals and their propagation across the curved surface to generate dynamic movements of perceivable peak vibrations. Through testing of several spherical structure prototypes, it was found that offset actuations can dynamically amplify vibrations at specific locations. A pilot study was followed to understand the impact of haptic stimulation on viewers of video content in a passive VR environment. Results showed a correlation between heart rate and the presented content; complimenting the technical data recorded.

**Keywords:** High-Definition Haptics, Tangible Mental Images, Virtual Tactile Actuation, Interference Maximum, Actuation Plate.

## 1 INTRODUCTION

Human intellectual and creative potential, as well as the development of perceptual and motor abilities, are all influenced by our visual-based culture [68]. As technology progresses, more advanced features become available for computer users. Great achievements have been made in processing visual information and communication technology. Different types and formats of digital video are becoming more common; emotional components and precise patterns in video, pictures, and audio messages may readily enhance the perceiver's experience. When emotionally rich information is unavailable, blind and visually impaired children often experience severe emotional distress, which can lead to depression and an inhibition in cognitive development. [3, 7].

Immersion, interactivity, and imagination have been the focus of Virtual Reality (VR) since 1965, when Ivan Sutherland first proposed the technology

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[73]. Progress in computer graphics and sound synthesis over the last 50 years has enabled VR systems to achieve fairly realistic rendering and stimulation of the human imagination. That said, the natural empathic ties of humans to other humans and to the world also contributed to their imaginative powers [70]. Moreover, sighted people are eager to live richer interactive experiences through other senses; visual exploration being the easiest way to achieve "theoretical imagination" (for example, Neo learning Kung Fu (haptic imagery) in the Matrix (through vision) [76, 77]). Despite these advances in the visual realm, haptic imagery falls far short of what users expect. Most VR systems' haptic sensations pale in comparison to the vast array of haptic qualities that humans can truly detect in the real world [19, 15]. From desktop haptics, surface haptics, and wearable haptics to more powerful haptic devices, haptic technology will continue to advance to the point that they are able to simulate physical properties in a natural way and in more details allowing the integration of spatially and temporally discrete sensory inputs [82].

Despite the apparent relevance of haptics in human perception development, spatial visual representations of distance, size, shape, and motion often prevail over haptic perception [62]. As a result, there is a great challenge to propose new ways to induce tactile sensations of spatial objects through dynamical haptic stimulation or modify the visual experience of the user through the use of new haptic technology and materials. Multiple tech companies such as Apple [59] focused on improving of the haptic feedback in their products attesting in an increasing demand for improved tactile feedback.

From curved edges to flexible displays, more innovative and interesting device shape factors are continuously explored [34].As interfaces and screens become more sophisticated and nonstandard in design, adaptive tactile output will be required for further haptics improvements in consumer products. Tactile click buttons, which could formerly be felt, were quickly phased out in favor of capacitive touchscreen displays, which were also featured in the prototypes detailed in this paper. Our present study focuses on localized haptics on a spherical surface, with the goal of developing haptics with various geometries. Understanding how enhanced haptic signals may be used to introduce high quality haptics is equally important as form factors develop and we move away from standard flat displays.

We utilized a simpler method over previous studies to produce localized points of actuation in our study. Although the employment of a large number of actuators is useful, it is impractical due to the added complexity and cost. Furthermore, any system that requires constant surface monitoring may be challenging to execute outside of a laboratory context. We want to address the aforementioned concerns by lowering the number of actuators necessary to generate a localized point of vibration while determining the offsets required for a specific material.

When engaging with graphical objects via physical actions, humans mix the visual information prompted by the tangible interface, such as keystrokes on a keyboard, mouse buttons, or another haptic device. Force feedback in a personal space, in direct contact with the surface [14], is often used to verify and predict visual inputs, to prevent a collision, or present more specific physical information about the external object subject to the interaction. Nonetheless, force feedback parameters can only change within a restricted range of magnitude gradient and duration (length of tactile stimuli). Furthermore, force feedback is referred to as shared forces in most haptic interfaces that are based on direct finger contact (those tangential to the skin). When skin travels laterally across a sensitive surface, the pressure generated (65-100g) provides a contact force that causes orthogonal skin deformation (normal to the surface). The human sense of touch, on the other hand, is a more complex analyser of processing dynamic arrays of force vectors (e.g., when distinguishing the concave and convex components of surfaces). This is evident when haptic textures and objects are reproduced using 3D haptic instruments [13], but it is not yet commonly applicable to surface haptics on touchscreens [41], when ordinary haptic exciters are employed. As a result, dynamically actuated virtual vibration, sources of vector force traveling across the display surface, can be used to convey a higher bandwidth of information to the user in order to display more complex vector graphic haptic images than primitive down sampling based reliefs [21, 22, 47, 48, 40, 56, 69, 44].

Actively explored touch surfaces provide a rich haptic experience to users by giving kinesthetic, proprioceptive, and cutaneous information. To control each "tactile pixel" (or taxel) spread out in a two-dimensional array, the approach often employed for tactile modeling of objects and their surfaces was adopted [75]. Taxels have been utilized for sparse low-resolution approximation of interactive surfaces and virtual stages rather than high-definition haptic simulation of items [13, 48, 44]. However, using visual perception concepts [71, 69] to replicate the most sophisticated tactile display technology [79] may not work for haptic visualization since a surface can be defined by multiple physical qualities. These must be perceived, identified, and understood as a static, dynamic, or virtual (cross-section) array of identical pieces using haptic imagination. When investigating and engaging directly or indirectly with virtual surfaces, a range of technical techniques have been investigated for surface modeling and control of attributes (mechanical and acoustic) [22, 20], simulating shapes [21, 20, 27], texture [69] properties such as stiffness, curvedness [27, 35], friction [55], and compliance/elasticity [51].

It has already been shown that without curvature, the properties of vibrotactile interference can be achieved on a flat surface [42]. Taking advantage of the properties of wave interference it may be possible to create feelable precise high definition tactile points traveling across a surface with variable curvature leading to an apparent tactile motion [60, 6]. This indicates that a high definition vibrotactile display would require fewer actuators (Fig. 2). This might be accomplished by accurately offsetting any number of provided actuations in sync from exciters attached to the actuation surface of contact, of which can also be curved. At the exact point of contact, the ensuing point of constructive wave interference would considerably magnify the amount of vibration signal over the ambient noise (Fig. 4). If the actuation offsets required to dynamically produce a point of maximum constructive wave interference at every point traveling over the surface are known, a matrix of values may be recorded and utilized to stimulate apparent tactile motion through inducing haptic imagination.

A music instructor encouraging a student to play the piano on their desk is an example of haptic imagination. Without manipulating the piano keys, the learner may picture and feel the music composition to be played. "The hands-on tactile exploration is the gateway to haptic imagination," as said by R. Schwaen. [66].

We may augment this notion, for example, by enabling virtual moveable haptic vibrations that can be felt traveling over the surface by consecutively activating the appropriate offsets that produce a feelable moving point of maximum interference. This vibration interference position might be dynamically positioned in order to show information to a user in an unusual manner. Tactile data may be moved around a user's hand, or the user could be told to focus on or follow a moving virtual actuator.

Previous work in this area of haptic research has demonstrated a similar strategy of induce locations of virtual actuation across a given surface by utilizing wave characteristics. Enferad and others [17], for example, who worked on establishing a controlled localized point of stimulation utilizing voltage modulated signals to activate piezoelectric patches over an aluminum beam. They accomplished superposition mostly through voltage phase modulation. Charles Hudin and his colleagues used time-reversal wave focusing to solve a similar challenge [33]. During the focusing step, a vibrometer calibrated the time-reversal wave, which was then followed by an actuation signal from an array of 32 actuators glued to the bottom perimeter of a glass plate. This worked well in terms of producing a precise, localized point of haptic stimulation. However, the usage of a closed loop control system creates substantial issues since it limits its practical application when a touch point in a consumer product is masked or repressed by a finger.

## 2 Concept & Design of the Spherical Haptic Display

To put the previously described design concept to the test (Figure 1 [11]), we created a mockup of a spherical haptic display (Figures 2-6 [11]). This preliminary design is designed to investigate the viability of virtual force actuation, as well as various methods of optimizing the configuration of actuator assembly in relation to these forces. The architecture and quantity of actuators, the characteristics of the virtual sources of vector force, and the arrangement of elementary haptic signals may all be changed to optimize the system. The prototype will also be used to assess the propagation of constructive wave interference across the curved display surface. Measurements from similar research have shown that by controlling the offset of several signals, it is feasible to obtain precise localization of enhanced vibration at a chosen point of contact [9, 12].

We employed a special combination of strong unidirectional voice coil actuators to produce a virtual vibration source at a spot on the curved touch display

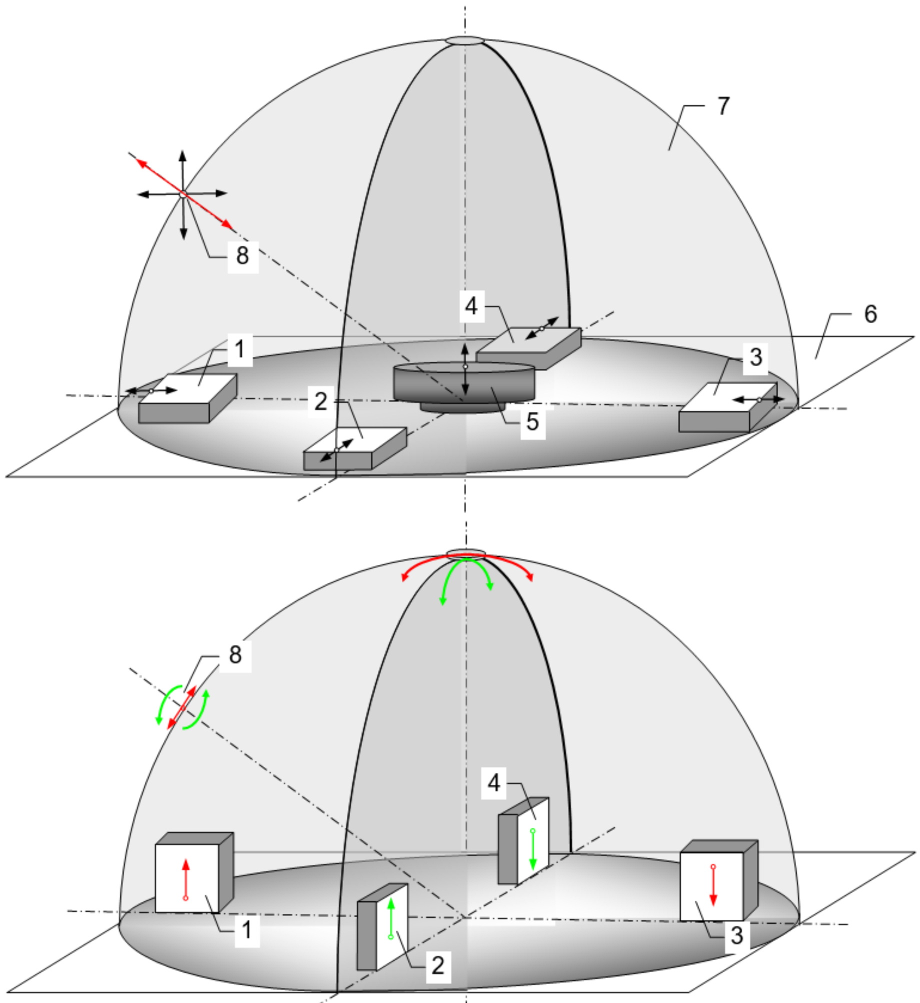


**Fig. 1.** The variants of haptic actuators assembly affixed to the actuation plane. 1-5 - Lofelt L5 (1-4) actuators and Tectonic exciter TEAX25C10-8HS (5). Red arrows indicate linear motion, while green arrows indicate angular motion. Black arrows indicate actuator movement. 8 - Represents a targeted point of increased magnitude or vibration; 6 - an actuation plate; 7 - a spherical haptic surface. [11]

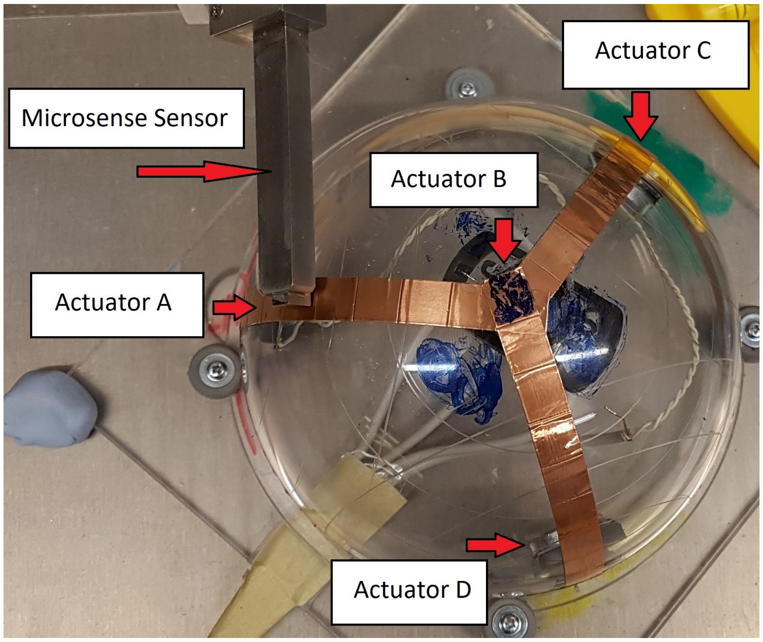


**Fig. 2.** Top view of the first spherical prototype, with centimeter lines on copper tape for sensor placement. [11]

surface (Tectonics and Lofelt). Figure 1 [11] depicts a concept known as the Volumetric Tactile Display (VTD). It is made up of constructive wave interference that propagates sequentially to the places of contact with the skin. By combining geographically and temporally distinct sensory inputs, the resultant point of localized vibration is capable of correctly mediating haptic signals.

We created two dome-shaped prototypes to collect preliminary data. The goal of each prototype was to study several ways of localisation that all aimed at the same goal. The first sphere was concerned with wave interference, while the second was concerned with vector force concepts. Before attempting to merge both approaches, each prototype was successfully tested independently. Both prototypes were made within a 116mm diameter polycarbonate dome. Wires were routed from the inside of both domes to an external motor controller (L298). The motor controller uses an Arduino DUE, which was chosen for its high speed of 84Mhz, allowing for high accuracy outputs and data collecting at 5.3 µm intervals. A copper strip was utilized for exact calibration of vector forces propagating over the Spherical Haptic Surface (SHS) from the configuration of unidirectional actuators (where micro-displacements over touch surface are sensed with the MicroSense sensor).

The first dome was used to investigate the possibility of wave interference between seismic signals generated by actuators directly attached to a spherical haptic surface. It was made up of four Tectonic actuators (TEAX1402-8) that

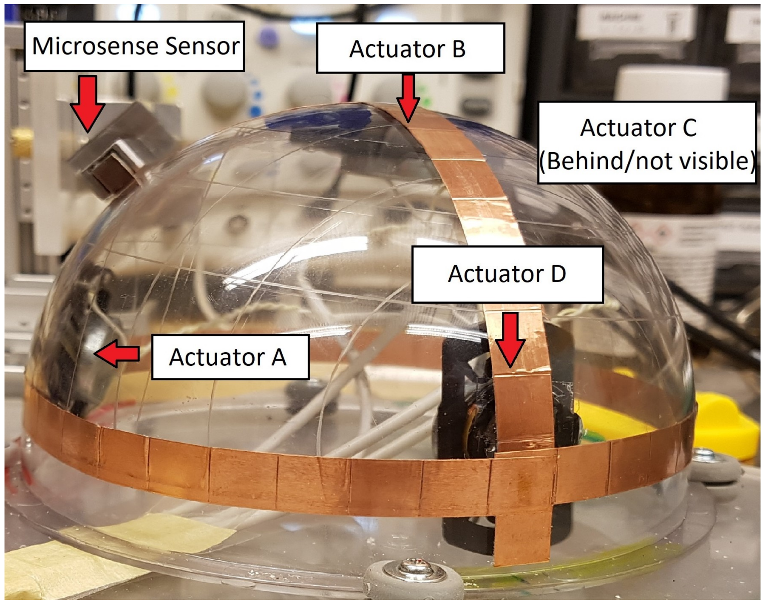


**Fig. 3.** A side view of the first spherical prototype with centimeter lines on copper tape for sensor placement. [11]

were joined from the inside and put at the vertices of the tetrahedron (Figure 3 and 2 [11]). The controlled offset of several actuation impulses was to be used to localize the vector force at the appropriate point of contact over SHS. The controlled offset actuation intended to move the point at which constructive wave interference occurred over the hemisphere's surface.

In the second dome (Figure 5 and 4 [11]), we concentrated on putting the ideas of a shifting magnitude to the test. These effects were achieved by altering the magnitudes of lateral and vertical motions. The installed more powerful next-generation Lofelt technology L5 actuators were attached to the actuation plate along the X and Y axes, while a strong Tectonic exciter was utilized to actuate vertically in the Z-axis direction. We intended to use this design to increase the resultant force of seismic signals that initially interfered in orthogonal directions across from an actuation plate by applying various magnitudes of actuation in the vertical and horizontal axes. Nonetheless, as shown in Figure 1 [11], unidirectional haptic actuators may be combined in a variety of ways to provide both linear (red) and angular (green) force momentum (torques).

It was discovered during the creation of the actuation plate that hydrophobic materials (such as Gorilla-glass, Teflon, and silicone) might impact the perception of convexity vs. concavity at the point of finger contact. The thickness of a material, such as glass, has an effect on the vibration that is perceived [80]. The outcome is promising for further validation via a user study. This paves the way for new methods of modeling volumetric forms in virtual and augmented reality.

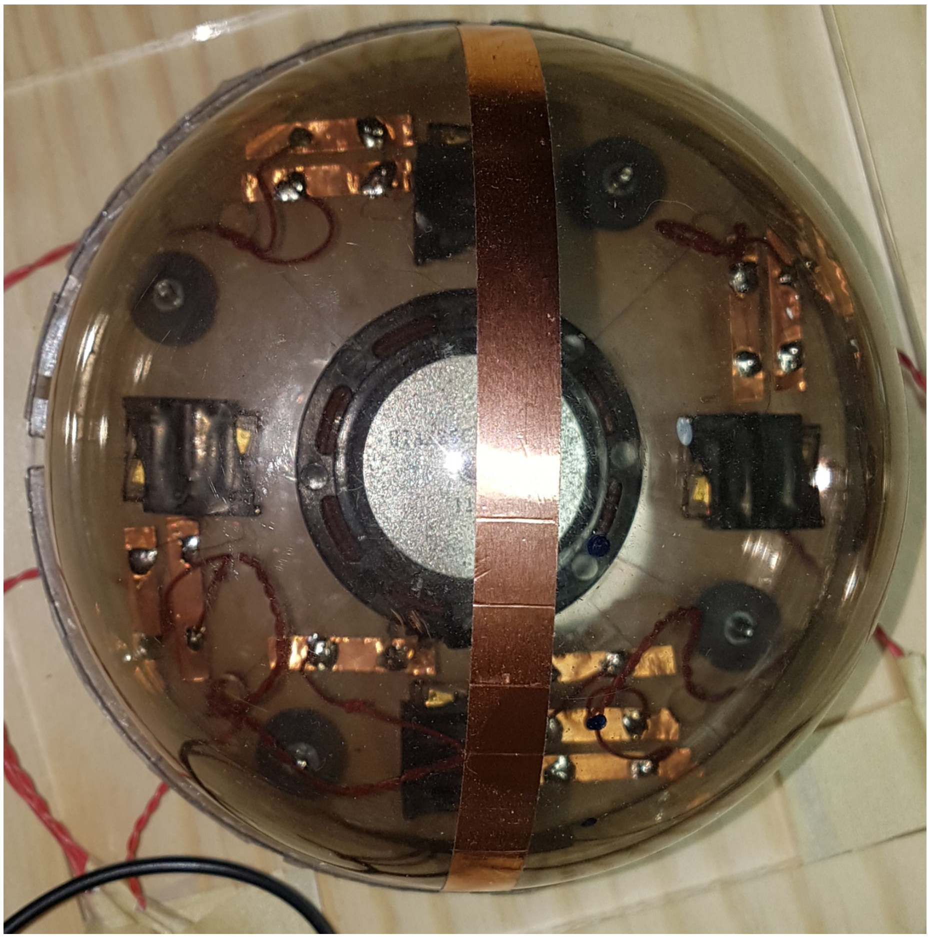

**Fig. 4.** Top view of the second spherical prototype, showing centimeter markings for sensor location. This structure is made up of four Lofelt L5 actuators and a single Tectonic exciter TEAX25C10-8HS attached to a Haptic Actuation Plate (HAP) that transfers seismic waves over a spherical surface. [11]

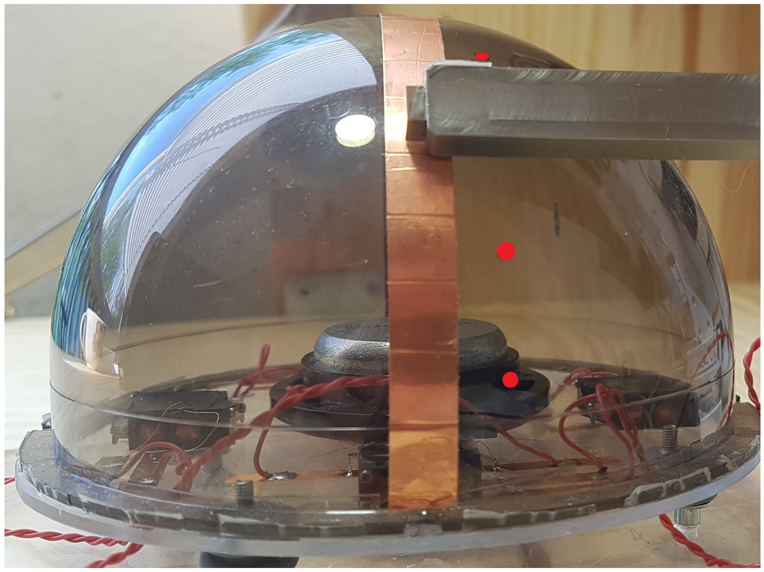

**Fig. 5.** View of the second spherical prototype from the side, with red markings every two cm for measurement placement. [11]

As a result of the combination of novel material characteristics and actuation technologies, we can produce complex haptic sensations that are required for developing haptic imagination in both healthy persons and those with perceptual difficulties.

Aside from physical dimensions, personal exploratory behavioral characteristics will have an influence on interpreting numerous tactile information obtained while interacting with SHS during the perception of mental representations of the items shown. As a result, a user-centered approach will be employed to illustrate the issues and limits of the suggested interaction strategies (Figure 6 [11]). The spherical surface, as depicted, compliments the hand's form. Tactile feedback may now spread over the palm and fingers.

We concentrated on the impact of varied magnitudes of lateral and vertical motions while designing the second dome. Wave interference existed and happened moving across the surface due to its form, however the entire structure was moved by the vertical and horizontal movement created by connected actuators. As a result, distinct magnitudes of actuation in the vertical and horizontal axes might be used to amplify a point of maximal vibration. These magnitude maxima might potentially be used with wave interference maximum to enhance tactile signals and focus given vibration received on the surface.

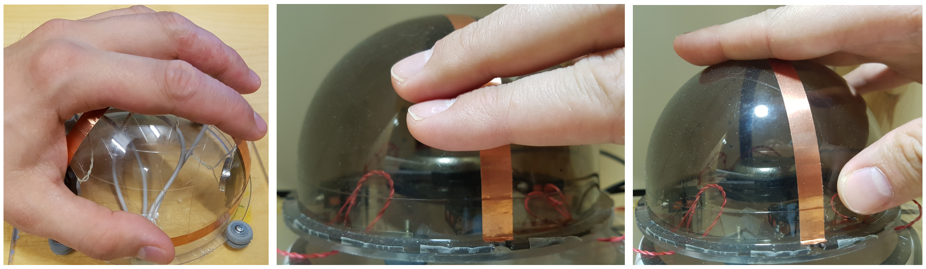

**Fig. 6.** Top: A relaxed hand is put over a spherical prototype to demonstrate a comfortable position. Middle: Exploratory behavior displayed by just touching the finger pads. Bottom: Four fingers extended straight ahead, as if attempting to feel the smooth edge of a surface. [11]

## 3 Methods

We investigated two ways for determining the ideal offset in establishing a point of peak magnitude vibration approximately five centimeters from the hemisphere's base. This was determined by going vertically over the sphere's surface from the first actuator (A, Figure 2 and 3 [11]). The first approach involved evaluating a variety of offset vibrations on the sphere between a starting pair of actuators (AB). After determining the offset necessary to achieve maximum vibration interference between these two actuators, we tested a third actuator by offsetting it against the existing offset pulse of the first two actuators (ABC). This procedure was repeated for the fourth actuator, offsetting it against the prior three actuators' offset pulses (ABCD).

MicroSense sensors were used to collect data (Model 5622-LR Probe, with 0.5 mm x 2.5 mm sensor). Because it is a capacitive sensor, a copper strip was needed to be put across the surface of the sphere in order for measurements to be taken. The sensor has an accuracy of 0-200 µm and noise of 3.44 µm-rms at 5kHz, and it has been amplified using Gauging Electronics up to 10V and attenuated to a range of 0 to 5V to be compatible with the Arduino's analogue input. The sensor was positioned to track the curvature of the sphere.

## 4 Results

### 4.1 Constructive Wave Interference

Figure 7 indicates that the addition of the third actuator (C) greatly increased displacement while the addition of the fourth actuator (D) introduced just a little rise. A probable constructive wave interference occurred between the first two actuators A and B, with actuator A triggering 2ms before actuator B, resulting in a displacement of 183 µm. The vibration was raised to 257 µm by triggering the third actuator 3ms after actuator B. However, activating the fourth actuator resulted in a very little increase in peak vibration. Before actuator A raised the vibration to 276 µm, the fourth actuator (D) engaged for 24ms. Nonetheless, actuator (D) can have a good effect on the total vibration. The vibration was decreased to 203 µm by delivering a deconstructive pulse 19ms before actuator A.

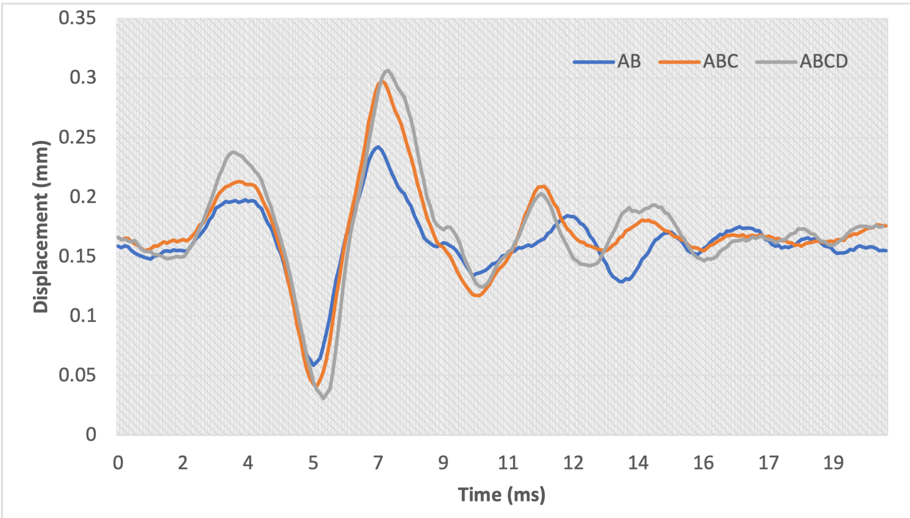


**Fig. 7.** Measured maximum displacement using offsets for two (AB), three (ABC) and four (ABCD) actuators.

We conducted more extensive testing because we were unsure whether the actuators in a spherical setup would interact with each other in the same way as those in a flat actuation plane. We tried out every possible combination of offsets between each of the four actuators for 15ms before and after each other. This process's optimum offset resulted in a maximum displacement of 276 µm, which is equal to the prior result when all four actuators were triggered.

Figure 8 displays the maximum displacement when the full range offset sweep test is used to determine the offsets needed to achieve a maximum displacement. The discovered offsets varied, showing that there are numerous ways to obtain a peak vibration maximum. We also discovered that the offset is the consequence of actuators (B) and (C) being triggered 5ms after actuator (A), and actuator (D) being triggered 9ms after actuator (C). Although we consider the data gained by cycling through every conceivable combination offers highly precise offsets, the approach is hampered by the length of time necessary to measure all combinations as well as the volume of data that must be collected.

Based on this information, we predict that, while some waves will most likely pass over the surface, the semi-flexible connection to the base implies that actuators would most likely pull the entire object. We must consider not just the delay of wave propagation, but also the movement of the entire dome. We must

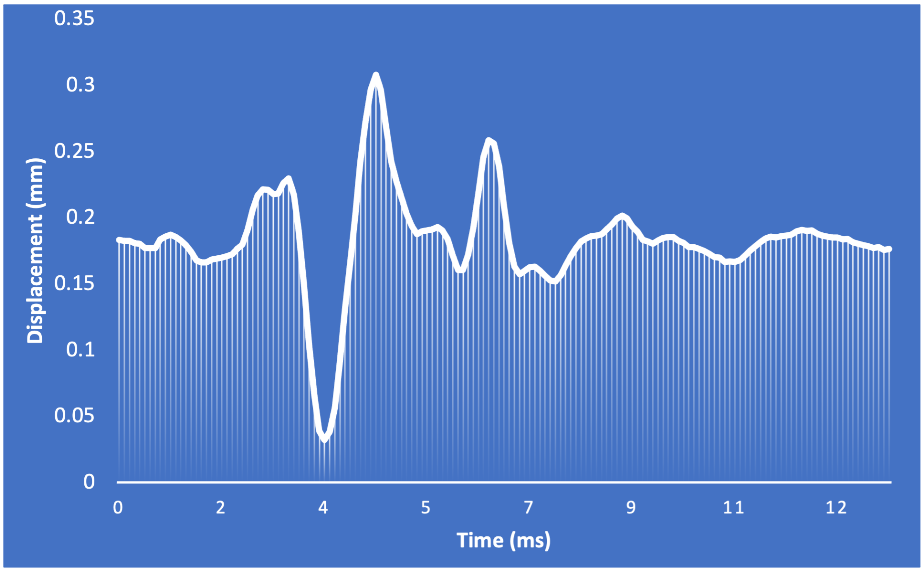


**Fig. 8.** Measured maximum displacement using offsets when scanning through all four actuators simultaneously.

test the optimal magnitudes and phases of each signal applied to each actuator in addition to determining the needed offset delays.

### 4.2 Combination of peak displacement magnitudes

To remedy the earlier issue with wave propagation, we conducted additional testing by mixing different actuation magnitudes with offset triggering. We utilized the second prototype for this test (Figure 4 and 5) featuring Lofelt L5 actuators for X and Y vibrations and a central Tectonic actuator for Z axis movement. In particular, we activated the Lofelt L5 actuators across the X-axis for 10ms and the center actuator for 1ms. This arrangement should minimize the magnitude of the central actuator's actuation in comparison to the Lofelt L5 actuators. We experimented with various offsets to calculate the optimal vibration offset (Figure 10). The data displayed in Figure 9 exhibits a pattern until roughly the third point, when the sphere's angle begins to become more horizontal. The practical effect of this tendency is that we are not only feeling forces attributable to wave interference from vertically positioned actuators, but also vertical displacement of the whole hemisphere caused by horizontally placed actuators. We would need to measure distinct magnitudes for a fixed offset rather than a changing offset in the future. Magnitude may be changed by modifying the size of the pulse or the voltage applied to a certain actuator. Additional testing should be performed to determine the range of these modifications and their impact on the resultant vibration.

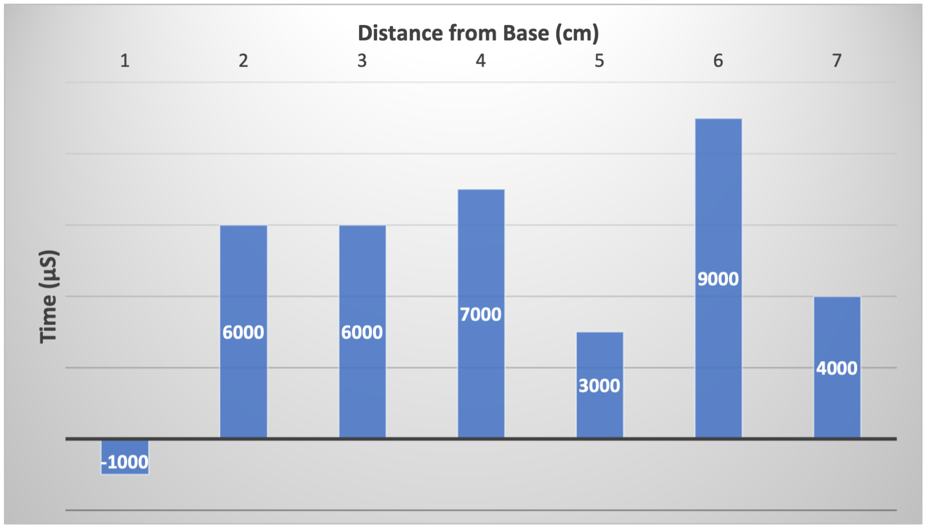


**Fig. 9.** Offset required for maximum peak vibrations for Lofelt L5 actuators with and without Tectonic actuator (center coil).

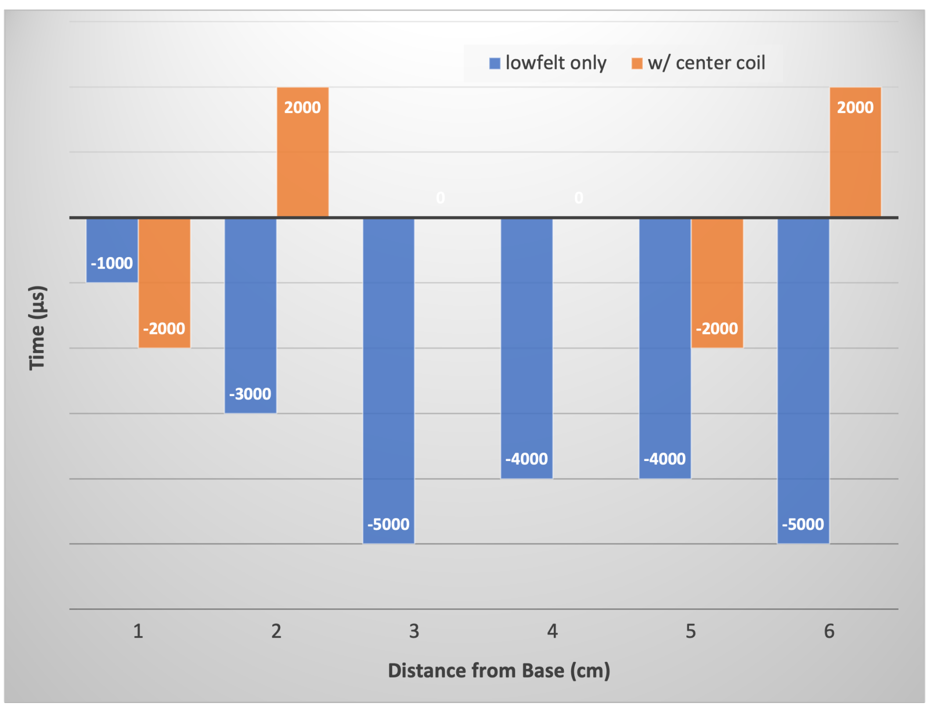


**Fig. 10.** Time offset required for maximum peak vibrations while activating Lofelt L5 actuator (1) for 10ms and tectonic actuator (5) for 1ms.

## 5 Providing Enhanced Immersion to Video Content – Application Pilot Study

An initial pilot study has been implemented to understand the initial effectiveness of the spherical display. Haptic sequences were induced over a tactile spherical surface which supported the hands. Participants watched a 1-minute video tested under two conditions: with and in the absence of accompanying haptic signals. Their heart rate was measured during the experiment. Results revealed a significant difference in heart rate data between the two conditions. Moreover, a heart rate response has allowed to reveal significant difference between viewers with respect to visual content and haptification ($t(119) = 31.4$ vs $t(119) = 11.7$ ($p < .0001$)). This leads us to believe that an enhanced immersion and affective experience can be achieved through the addition of a haptic channel to audio-visual content that already are shared over video streaming platforms and social media.

### 5.1 Pilot Study Background

Haptic theater enhancements, such as D-Box Motion Effect chairs [49] are already in use in multiple locations worldwide to enhance the viewing experience by adding haptic signals to 3D visuals. Being synchronized by the action depicted in the film, the chair's effects range from soft vibration to a hard jolt backwards if, for example, a character is hit. But what about home viewers that stream videos online through platforms such as YouTube or Vimeo? People share their life experience through these tools; yet rich emotional personal experiences cannot be shared in full as other senses such as smell, taste, and touch are missing. Our focus is on the haptic channel, which has been in use already for nearly 200 years [24, 57] to share, communicate, and enhance human sensations.

Haptic signals directly connected with kinesthetic sense and motor imagination are strong enough to provoke premotor or ideomotor actions (the cognitive representation of an action) [32]. Additionally, to induce or initiate haptic apprehension in observed visual actions, haptic information has to be personally and emotionally significant and linked to previous human experience.

Human vision is not only limited to visual feedback but also helps with navigation and locomotion, contributing to human proprioception. As in hunter-gatherers, human vision has been developed to predict behavior of any items, including motion, through the total control of the personal space [28]. Proprioception is the main component of the afferent flow that integrate information from different modalities to support adequate human response and behavior. Cross-modal information transfer help to more efficiently perceive and interact with an external space surrounding the body [23].

In this work, we would like to explore haptification of visual content supposed to enhance emotional effects in relation to the activity of an actor in the dramatic situation of an activity that is able to elicit fear, anxiety, or general sympathetic activation [50]. More specifically, we asked participants to watch a video clip of down-hill biking as the dramatic competition scenario while interacting with a spherical haptic surface (SHS) [11].

There are different systems for haptic effects based on haptification model [63], plethora of video clips have not been yet investigated sufficiently with respect to such a way of affective visualization. In particular, haptics does not yet integrate with dynamic visualization in multimedia, even though both are naturally and tightly connected in the ontogenesis of perception [39] and development of intermodal perception and imagination [74].

The scenario that we are interested in is users watching video clips, movies, and other dynamic art media. The viewer is a relatively passive observer and cannot directly impact to the digital content. The viewer's state of mind and video content, which are closely intertwined in human imagination, contribute to the immersion and transition of the passive observer into active participant of the visual scene, while the sensory motor activity manifests in the form of emotions and physiological reactions. To induce human imagination, video content is often accompanying with background audio (soundtrack).

### 5.2 Experimental Design

The experiment combined visual content presented through VR headset enhanced with a new haptic concept that combine spherical and planar sensations [12, 11, 10]. We also expect that the haptification [63] of visual content is a natural way to support affective visualization [82].

**Participants** Six people participated in this study. None of the participants reported skin or cardiovascular issues.

**Apparatus** The experiment is designed around a Microsoft Surface Go tablet (Fig. 11) that was used as a Haptic Actuation Plate (HAP) and was chosen for its ease of software and hardware implementation. The Spherical Haptic Surface (SHS) consists of a 116 mm diameter polycarbonate dome (Fig. 11) attached to the surface of the tablet. Parameters for local interference maximum (LIM) of seismic signals over the touchscreen tablet and propagating across SHS were determined in previous studies [11, 10].

The TEAX1402-8 actuators attached to the top of the tablet display, as well as TEAX25C10-8/HS affixed to the base of the SHS [11], are designed to strike the surface at a predetermined offset from each other. The offset creates a point of increased vibration where the seismic shear waves interfere. This allows us to create discernable, feelable, and dynamic haptic LIM signals moving over either touchscreen or other surfaces properly affixed to and being in mechanical contact with HAP. The method described can be explored in further detail in previous works. [12].

An Arduino Due was used to store the predetermined offset locations as well as the output sequence created for this experiment. Output signals were sent to an external MX1508 motor drive module driven at 7.5 Volts. Silicone molded

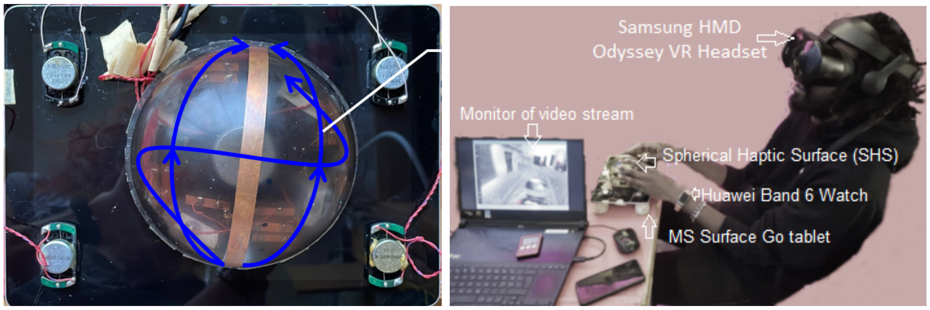


**Fig. 11.** Left: An arrangement of Tectonic actuators and SHS over tablet touchscreen. Blue arrows indicate virtual haptic scanpaths Right: A participant interacting with Spherical haptic surface affixed to MS Surface Go tablet during the experiment.

legs were attached to the bottom of the tablet to provide vibration isolation. A Huawei Band 6 watch was used to track heart rate data with ECG comparable accuracy [67] that are logged in 5-second intervals.

**Video Content and Haptic Actuation** A Samsung head-mounted display (HMD) Odyssey VR headset [64] was used to display the visual content that consisted of one-minute video, created from publicly available online footage and was converted to match the requirements of the display. The output signals of the actuators that generate the haptic cues were synchronized with the actions in the video footage resulting in haptic motion sequences matching the motion presented in the visual scenes. The haptification (vibration sequences) has been manually designed using video footage timings where each second of footage was visually analyzed to associate tactile sense with objects that are in proximity or visual periphery.

## 6 Experimental Procedure

Participants were instructed to first put the Huawei Band 6 watch on their left wrist. They were then asked to put the VR headset on, wear the headphones, and adjust the volume to a comfortable level. To start exploring the video, they were asked to rest both hands on the SHS.

A one-minute clip of down-hill biking was used (Fig. 12). This clip was played 20 times. Ten of these playbacks were with the haptic (WH) signals synchronized with the video content, while the remaining ten playbacks were with no haptification (NH), resulting in two experimental conditions.

After the experiment, participants were asked to complete the NASA-Task Load Index (TLX) questionnaire [31] along with additional questions to help us understand the effectiveness of device. These questions are shown in Table 1

**Fig. 12.** Key dramatic footage at seconds 5, 24, 36, 40, 41, 43, 45, 50, 52

| |
|---|
| Did you perceive a local and/or moving vibration? |
| On a scale from 1-5 how well did you perceive the localized vibration? |
| Are you prone to motion sickness in VR? |
| If yes, did the vibration worsen or alleviate your symptoms? |
| In general, which did you prefer. The experience with or without the vibration? |
| In what devices do you think this would be best suited? Why? |
| What benefit could localized haptification provide to an existing device? |

**Table 1.** Questionnaire questions

## 7 Results

**Objective Results** We can assume participants likely had different experiences biking, ways of thinking, temperaments and possibly even moods during the test. Therefore, we cannot expect the same response from viewers to specific visual content and haptic stimulation. Nevertheless, heart rate scores have been measured 12 times and grouped based on the Pearson correlation coefficient $r > 0.83$ ($p < 0.001$) and $r < 0.8$ ($p < 0.001$) over all (12) presented footage.

The heart rate response has revealed significant difference between viewers with respect to visual content and haptification. In all situations observed over footage, with all participants, we see a significant consistent difference between instances when the haptic signals were enabled (WH) vs. when the haptic signals were disabled (NH) (Fig. 13). Paired Samples 2-tailed t-test revealed significant difference within the group $r = .9023$, $t(59) = -2.98$, $p = .02$, 95% CI(WH/NH)=[82/84, 75/77]. When haptic signals were enabled, we have observed a marked decrease in heart rate for the entire video sequence.

When looking at heartrate data with haptic signals enabled, we see a gradual increase from the start of the sequence up until a peak at the 30 second mark. If we compare this with the data, we have collected when haptics was disabled (NH), we see a far less pronounced synchronization $r = 0.688$ ($p < .05$) in average with the events on screen. That is to say that the data shows an increased correlation when the haptic display is in use (WH) $r = 0.90$ ($p < .0001$) in average.

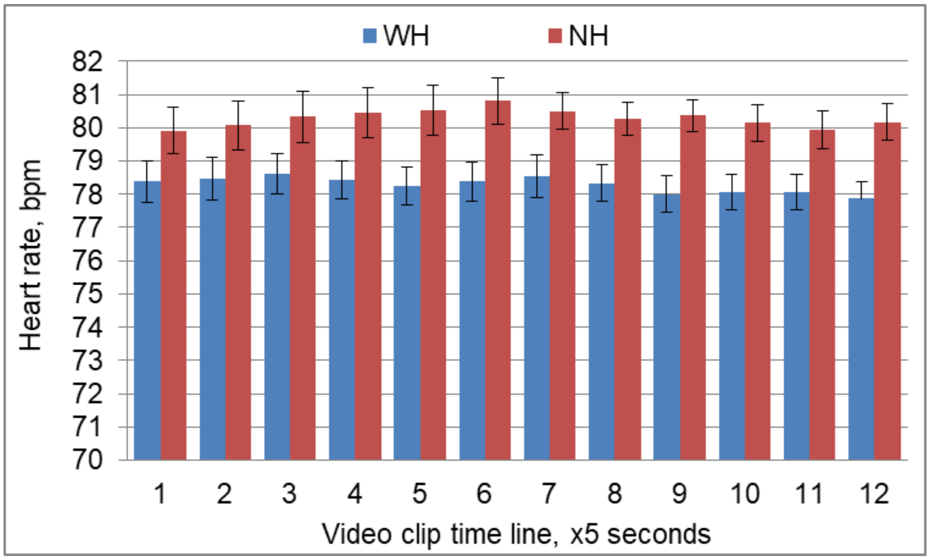


**Fig. 13.** A cardiovascular response in participants.

### Subjective Results

*The NASA-TLX questionnaire* The NASA-TLX questionnaire allows the evaluation of six sub-scales: the mental demand, physical demand, temporal demand, own performance, effort, and frustration the results of the TLX are summarized in Fig. 14.

Participants responded that the workload demand was of concern, with an average response of 50 on the NASA-TLX scale. For several of our participants this was their first experience wearing a VR headset. Otherwise, with an average score of 76, participants felt that they were able to successfully complete the task they were given.

*Post-experiment Questionnaire* When asked if they could feel the presence of localized moving vibrations, all participants confirmed that they could. Their ability to perceive localized vibrations obtained an average score of 3.125 out of 5 (5 being the best). 62.5% of the participants reported that they preferred watching the VR video using the SHS.

Half of our participants answered that they had felt motion sickness during the experiment. Of those who felt motion sickness, half claimed that the use of the SHS alleviated their symptoms.

Open-ended questions revealed that participants think that the SHS can be used for Gamepads to improved games interactivity, for professional training for drivers and pilots, and in-car displays to eliminate distractions.

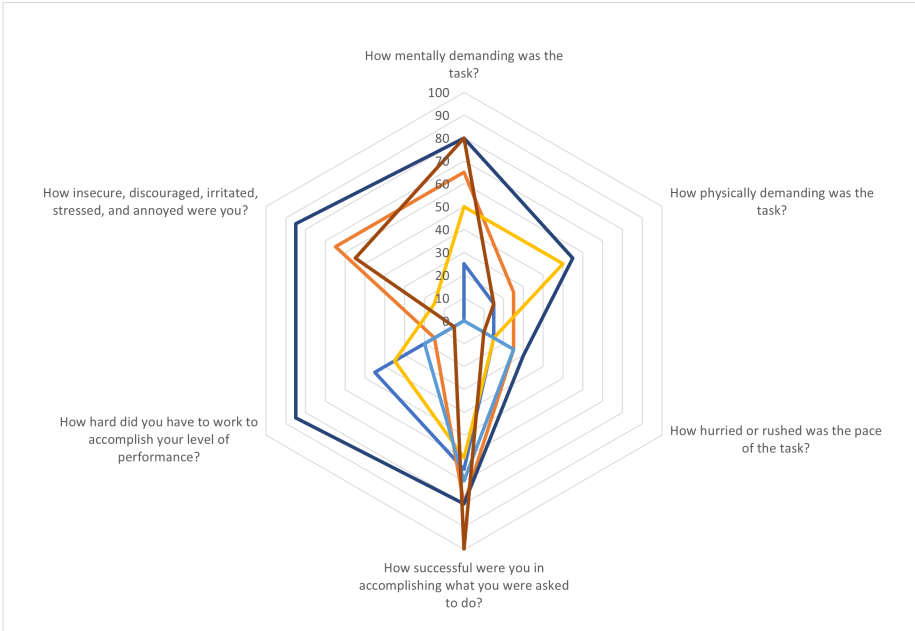


**Fig. 14.** Radar chart of all TLX responses.

### 7.1 Pilot Study Discussion

Artists have been developing the expression of motion in drawings for thousands of years. To illustrate motion, we can refer to the artists of the Lascaux caves who portrayed animals upon the walls with multiple heads, legs, and tails. The superimposition and matching successive images (e.g., juxtaposition of colors) have been used by many artists in a different ways to achieve a similar result. The visualization of dynamic motion is followed by a long tradition of motion visualization throughout the history of visual art [57, 53]. The impression of movement in a still image can bring about an emotional experience. As mentioned by Barry Ackroyd "It can bring you to tears, and take you to places unimaginable" [1]. In modern cinema, it might be thought that we can only assess the meaning of audio in movies when a soundtrack has been interrupted. On the contrary, thanks to imagination, the soundtrack is often able to fully compensate the lack of visual peripheral immersion in scenes.

The collected data showed to us a significant difference between two conditions of the presence or absence the haptic information concerning signals accompanying in sync with visual content viewing with the VR headset. Furthermore, the relative accuracy at which heart rates increased to match the viewed activity on the screen was prominent with the haptic enhancement relying on SHS. This falls in-line with existing research on heart rate variability in virtual reality immersion [50]. The assumption would be that the participants are greater immersed when receiving physical sense of contact in connection with the audio-visual content.

Seeing that the use of the haptic signals subjectively may have reduced symptoms of motion sickness, we can assume that the experience may have been more immersive. Giving participants accurate haptic enhancement may have decreased the cognitive load of what would be an audio-visual only experience. Similarly Liu et al. have also found that the introduction of haptics can be used to reduce virtual reality sickness [46].

A SHS with localized dynamic haptic signals moving in sync with visual events of scenes may be the key to better immersion. While our current study was focused on the use of the SHS to improve the VR experience, the technology involved could be implemented in a wide variety of devices to enhance the user contact experience.

### 7.2 Pilot Study Conclusion

The hypothesis that we set to explore was shown to be valid. Yes, localized dynamic haptic signals can support affective visualization. Participants were eager and excited to try out the Spherical Haptic Surface. Even better, they were able to see and understand possible use cases for this technology in modern devices. The data we collected contained other captured sensor information, including SPO2 levels and stress levels. In the future we would like to further parse this data out so that we can get a better understanding of how this data might support our results.

The next step would be to see how a SHS might aid in the creation of visual experiences without visual data, by inducing imagination by haptic signals. How would the dynamic haptic signals affect our audio only experiences, or haptic symbolic patterns (tactons) only experiences? The use of emerging haptic technologies needs to be studied in depth to understand how they should be implemented to improve our daily interaction through computing devices.

Our contributions are as follows: We investigated the subjective perception of the video content enhanced with haptic signals dynamically presented in motion over spherical haptic surface to the palms; We found that haptic signals moving in sync with video content had a significant effect on the participant's heart rate.

## 8 Discussion and Future Work

A wide spectrum of users would be able to engage with the high-fidelity spherical display. The sphere has a natural shape on which a user may rest their hands for lengthy periods of time. As we continue to have access to a wider range of interactive technology, we will need to investigate new intuitive techniques of feedback and engagement.

Our visual culture has a significant influence on human intellectual and creative capacity, as well as the development of perceptual and motor skills [38].Despite the significance of haptics in the evolution of human perception, visual information tends to prevail over haptic perception after spatial visual representations of distance, size, shape, and motion have been formed [6, 43]. Much of the visual content currently available is often inaccessible to blind and visually impaired people [37]. Learning is frequently found to increase with the help of visual feedback, leaving persons with visual impairment suffering in courses. Fortunately, it has been demonstrated that the use of haptic feedback can help to bridge the gap between visual and tactile learning.

The use of haptics in education may be broadened to help all students who are compelled and linked to a subject, for example, by constructing a bridge between the sciences and physical reality. David Grow's work on educational robots has yielded successful outcomes in this area [29] as well as by Michael Pantelios [58] with input gloves and force-feedback devices. Much research available [30, 25, 8, 54] would imply that incorporating haptics into the educational environment at all levels can boost student learning.A spherical surface, such as the one we're testing, can give a long-lasting polycarbonate surface that can sustain heavy, frequent use. It also gives kids with a unique surface to explore.It is feasible to combine it with a spherical projection [26, 83, 81] over the surface, displaying an interactive picture or video that may be explored via tactile feedback.

Because we do not limit our notion to any size and hope to be able to repeat our findings in larger and smaller spherical shapes, we open up the concept of spherical haptics to a wide range of applications. In place of an analog control stick on a gaming controller, we propose a haptic hemisphere. Feedback, in addition to giving accurate input, may be modified to produce a number of effects. For example, the texture of a game may vary as you go through uneven terrain, or the localization of feedback could reveal the location of an adversary. We may picture a bigger sphere being used to precisely manage heavy machinery in 3D space, such as a crane lifting a concrete slab. A spherical display in the center of a round table might be utilized as an interactive map to assist a team in collaborating with localized feedback offering extra information to prevent visual overload. Localized input might alert a taskforce to the presence of subsurface structures or other areas of interest.

Manufacturing technology are always evolving. We are moving away from the strict constraints of consumer electronics design, as the continued trend of miniaturization, as well as the development of flexible displays and innovative molded integrated circuits, means that products may now assume any imagined shape or form. Many user interfaces, such as a mouse, gamepad, or even a car steering wheel, already include significant portions with substantial curvature. We should be able to enhance the bandwidth accessible to the user by providing vibration that can be localized at any point across these surfaces, allowing us to offer new, more natural engagement cues.

To go further, we are aware that existing virtual reality headsets provide credible visual input but have yet to provide high-fidelity haptic feedback to a large number of consumers. Incorporating this improved realism into present controllers might provide a new degree of immersion to current technology [2].

There is also the possibility of using such a spherical gadget in public places. The extra benefit of accurate tactile feedback might not only make an information kiosk more generally accessible, but also assist users in navigating the device in a loud setting such as a mall [18].

Surprisingly, our recent research discovers that the offsets required to produce localized vibration locations occur within milliseconds of each other. This means that it may be feasible to swiftly and progressively trigger various offsets to generate several focus points that appear to be synchronous. This would open up a new channel for the development of haptic patterns, as well as the development of haptic imagination.

The ultimate objective of this study is to create a perceivable moveable actuation that can be mediated to any position on the spherical surface. What we'd call a virtual haptic actuator. We would need to look into this more to find the best combinations that provide the most effective (and immediately recognizable) numerous afferent flows, increasing in intensity to a specific spot or along edges around the sphere's surface. We would also need to investigate how wave interference can be combined with different magnitude combinations to increase the precision and force of a given vibration across the surface of the sphere, as well as how perceptual interference of other receptive fields can affect fingertip tactile sensation. [45].

Intermediate materials have been shown to improve an object's sensation of touch. Auto body shops, for example, have utilized cellophane film to evaluate polishing on cars [65]. Additionally, the Touch Enhancing Pad [61], a patented instrument consisting of lubricant placed between two thin plastic sheets can help identify malignancies in breast tissue. As a consequence, it would be worthwhile to experiment with various materials in order to improve the perceptible localized input in our haptic environments.

As this study progresses, we will have a greater knowledge of the use cases that this developing approach may bring to users.

## 9 Future Applications

Spherical interfaces do exist [72, 4, 16, 78, 5], nonetheless, they are not widely used. The suggested technology for high-fidelity haptic feedback offers up several options for future touch interaction. Because the sphere's shape adapts to the hand in its natural resting posture [36, 52] it may be utilized as a generic computing interface with rich tangible information that can be used for long periods of time.

Hidden or veiled entities and deeper structures of a palpated substance, whether biological (tumor) or physical (defect inspection), can be increased with localized haptic input while investigating medical images. Similarly, the basic user interface might be improved, such as allowing a user to feel and pick icons on a desktop that are beneath a document they are working on without having to minimize or switch windows.

The spherical surface needs a significantly reduced range of motion to engage with, which might be advantageous for anyone suffering from a movement-impairing injury or sickness. High-fidelity feedback can also assist persons with little or no eyesight in navigating an operating system by employing detailed haptic images.

We don't consider the spherical interface as being restricted in size. A bigger child-sized spherical interface might enable children to study instructional content in a more engaging manner. An adult-sized spherical display may serve as a kiosk at a mall, presenting information that, on a visual-only flat display, can be confounding, such as orientation or direction. A big sphere might serve as an interface in the center of a circular meeting table, allowing people to collaborate. Meetings are frequently stopped to address minor matters, such as informing a coworker that a file has been sent or that they need to slip out. This information might be transmitted utilizing high-definition haptics, which would eliminate unwanted interruptions.

A haptic spherical interface also opens up intriguing new possibilities for enabling secure entrance into a gadget. A passcode, for example, predicated on recognizing localized light-pressure patterns, may be actively moved around the surface while still being identified by localization. Although the input pattern would stay constant, the constant change of the physical location would make capturing the passcode by a third party challenging. From the outside, each physical entry of the passcode would appear to be unique.

Overall, we envision a broad range of applications that can benefit from the usage of a high-fidelity spherical haptic interface. Unlike many consumer interfaces already on the market, we see the spherical haptic interface as extremely customizable and open to a wide range of design use cases.

## 10 Conclusions

We discovered that offset actuations may be employed to enhance vibrations at specified spots on a spherical surface based on objective measurements of constructive interference of spherical structure prototypes. These magnifications can be achieved through a combination of two methods: first, through wave interference, in which we can use the properties of constructive wave interference to create an amplified point on the surface, and second, through the combination of peak displacement magnitudes, in which different forces are applied to an object's X, Y, and Z axes to increase forces felt at a specific point across the surface. The current study shows that a localized vibration effect may be reproduced over a curved surface. Second, using magnitude combinations, we acquired preliminary data indicating that increased amplitude has an impact at a given position over the surface.

In this study, we discovered that once offsets are located and set, the subsequent output is very constant. Localization offsets should only need to be collected once for a particular actuator setup, which is critical for sustainability. It has also been established that the usage of numerous installed actuators compensates for observed losses owing to attenuation of individual actuators.

When compared to existing global non-localized vibrations that generate a muddled sensation, the amount of localization exhibited has the potential to boost consumers' immersion in XR settings. This field of dispersed haptic resolution can be likened to the fields of optical and auditory propagation. Improvements in haptic fidelity, like improvements in other sensory modalities, aim to improve the user experience.

The utilization of a virtual vibration point over three-dimensional curved constructions is demonstrated in this paper. When producing high-fidelity haptics, this may enable the use of fewer actuators in a variety of feedback interfaces.

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