Just Before Touch: Manipulating Perceived Haptic Sensations through Proactive Vibrotactile Cues in Virtual Reality

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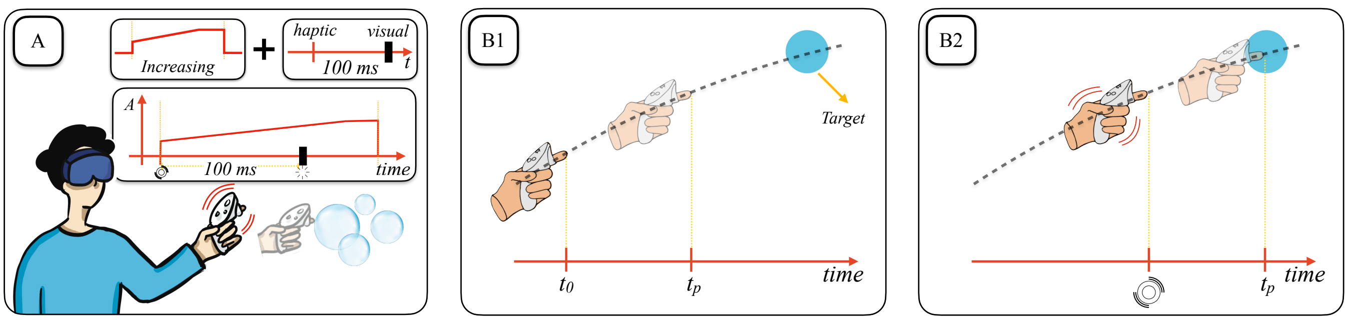

Figure 1: (A) Illustration of a user experiencing *defuse* sensation when interacting with a virtual bubble in VR, achieved through *proactive haptics* provided 100ms before the hand touch the bubble. (B1) shows the current (t_0), predicted (t_p) hand positions, the reaching trajectory. (B2) demonstrates tactile cues triggered proactively before the actual touch event occurs, utilising hand prediction (t_p).

Abstract

Vibrotactile feedback can significantly enhance the user experience in Virtual Reality (VR). In current VR systems, vibrotactile feedback is used reactively, triggered only after a user interaction event is detected. This paper explores a new temporal space of tactile feedback by introducing proactive tactile stimulation that occurs *before* a touch event. We use a motion prediction model to calculate hand trajectory and deliver tactile cues before the virtual hand actually touches virtual objects. We first evaluate the system's effect on realism concerning visual-tactile (a-)synchrony. Subsequently, we conduct an exploratory study to investigate the perceived effects of proactive vibrotactile cues in VR. Our results show that proactive vibrotactile stimulation can evoke a variety of novel pseudo-haptic sensations, including stickiness, elasticity, and diffuseness, depending on the timing and haptic profile.

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AHs 25, March 16 - 20, 2025, Abu Dhabi, UAE
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ACM ISBN 978-1-4503-XXXX-X/18/06
https://doi.org/XXXXXXX.XXXXXXX

CCS Concepts

• **Human-centered computing** → **Haptic devices**; **Virtual reality**.

Keywords

Pseudo Haptic, Sensory Illusions, Virtual Reality

ACM Reference Format:
Yihao Dong, Pamuditha Somarathne, Craig Jin, Juno Kim, Andrea Bianchi, and Anusha Withana. 2025. Just Before Touch: Manipulating Perceived Haptic Sensations through Proactive Vibrotactile Cues in Virtual Reality. In *Proceedings of Augmented Humans International Conference (AHs 25)*. ACM, New York, NY, USA, 13 pages. https://doi.org/XXXXXXX.XXXXXXX

1 Introduction

Virtual reality (VR) is increasingly becoming popular in diverse areas of applications [2, 14, 27, 39, 49]. While commercial VR headsets support multiple input methods such as handheld controllers, hand gestures [42, 50], head movements [24], and eye tracking [5, 33, 34], vibrotactile actuation remains the primary modality for haptic feedback due to its simplicity, cost-effectiveness, and wide availability [29]. Tactile feedback simulates the sense of touch in the virtual environment and, together with audio and visual cues, enhances user experience [15, 22, 38]. Consequently, expanding the design space for haptic experiences through tactile cues has been a major area of interest in the VR community. In particular, pseudo-haptic illusions, where users' perception of haptic feedback is manipulated to create novel experiences [12, 16, 19, 23, 36]. However, current approaches overlook the temporal aspect of touch, which play a crucial role in shaping tactile experiences [10, 37, 46]. For example, the Tau effect demonstrates how haptic timing influences spatial perception [16], and recent research has identified a considerable threshold for the perception of visual haptic asynchrony [6, 51]. These findings suggest an intriguing opportunity to explore haptic experiences within a new temporal space—delivering tactile feedback in advance of visual user interactions, such as just before touching an object. Whereas the current VR systems typically provide tactile feedback reactively [11, 41], activated only after a user has interacted, such as when hands collide with a virtual object.

This paper proposes a novel concept of *proactive haptics*, an approach that delivers vibrotactile cues before the visual interaction occurs, to create new pseudo-haptic experiences. This concept expands the temporal space for tactile experience design by utilizing the time window *just before touch*. We utilize the user's hand motion characteristics such as time to collision and hand acceleration, calculated using a parametric hand motion prediction model [8]. This introduces a new dimension in tactile experience design, the temporal space before touch and the user activities during this period. To the best of our knowledge, this is the first attempt at utilizing this temporal space to create pseudo-haptic sensations. By carefully designing the timing and patterns of haptic cues, we hypothesize that developers can simulate diverse haptic experiences such as softness, elasticity, etc. expanding the haptic vocabulary of VR systems. We demonstrate the effectiveness of *proactive haptics* using a user study involving 15 participants, and six proactive haptic profiles, revealing that a range of pseudo-haptic sensations can be created in VR settings without additional hardware. For instance, Figure 1A, shows a user experiencing *diffuse* bubble on their hands by rendering vibrotactile feedback proactively. Similarly, applications can use the design space to create virtual sensations such as, softness, elasticity, diffuse, localized, etc. that are hard to create with reactive tactile feedback. In summary, the paper contributes:

- A novel concept *proactive haptics*, that provides in-advance haptic cues in VR to create pseudo-haptic sensations by controlling the timing and amplitude of the tactile feedback, resulting *proactive haptic profiles*.
- Through an exploratory user study, we demonstrate that *proactive haptic* cues can simulate a wide range of pseudo-haptic sensations.
- Based on our observations, we provide directions for designing proactive haptics in VR systems, including a sample set of *haptic profiles*, and an open-source software package for designers to explore other profiles[1].

2 Related Works

In this section, we explore the potential of time as a critical dimension for controlling these illusions and highlight pseudo-haptic illusions as a means to maximize the utility of the limited output modalities available in VR systems. Additionally, we review prior efforts to incorporate predictive mechanisms into pseudo-haptics and underscore how recent advancements in hand motion modeling have expanded their applications within VR environments.

2.1 Effect of Temporal Mismatch Between Visual and Haptic Perception in VR

Visual-haptic asynchrony in interactive devices plays a significant role in shaping user experience [7]. Consequently, the perceptual thresholds of such asynchrony have been investigated across various contexts, including joysticks [45], texture displays [32], touchscreens [20], and more recently, virtual reality systems [6, 9, 51]. Di Luca et al. found that when haptic feedback was delayed by more than 50 ms relative to visual feedback, the delay was generally noticeable. However, 75% of participants did not detect asynchrony when haptic feedback occurred 55ms before visual cues, indicating a notable tolerance for temporally advanced haptic feedback [6]. Similarly, Zoltanski et al. investigated asynchrony detection, showing that most participants identified asynchrony when haptic feedback preceded visual cues by 100ms [51]. Interestingly, their findings demonstrated that early haptic feedback in a dodging game did not negatively impact user experience, whereas delayed feedback did. Both studies used questions focused on whether the participant noticed an asynchrony, directing their attention towards the asynchrony [51]. This could influence their focus on the perceived haptic sensations and may not fully reflect how users perceive the asynchrony while engaging in a task, highlighting the importance of understanding how asynchrony affects perceived sensations, particularly when users are not explicitly focused on detecting it.

2.2 Pseudo-Haptics for Enhancing Vibrotactile Feedback in Virtual Reality

Pseudo-haptic techniques exploit sensory mismatches to alter the perception of physical properties without modifying the actual stimuli, thereby enhancing user interactions in VR. Visual manipulations, such as visual-proprioception mismatches [26, 36] and temporal delays [19], have been extensively used to induce sensations of stiffness, texture, and mass. These mismatches are commonly utilized in haptic retargeting methods [1, 3, 12], which guide the user's hands towards a limited number of physical props by leveraging the dominance of visual information in sensory conflicts to maintain immersion and enhance the user experience. Additionally, visual-audio feedback has demonstrated its ability to create pseudo-haptic illusions, such as virtual texture manipulation through exaggerated visual deformations, auditory-driven stiffness perception, and effects like the parchment skin illusion [4]. Similarly, visual-vibrotactile methods have shown the potential to induce pulling

[1] https://github.com/aid-lab-org/JustBeforeTouch-ProactiveHaptics

force illusions using asymmetric vibrations [21]. Combining pulling illusions induced by asymmetric fingertip vibrations with kinesthetic illusions generated from wrist tendon vibrations has been shown to enhance the perceived intensity of force while maintaining directional accuracy, thereby expanding the capabilities of small, lightweight force feedback devices [30]. Precise vibrotactile feedback can be used to simulate object deformation, such as stretching, bending, or twisting, without the need for mechanical moving parts [17]. Recent work has also focused on reducing unnaturalness and individual variability in pseudo-haptic experiences by employing non-isomorphic manipulations, which decouple actual and virtual body movements. For instance, analog stick manipulation, as opposed to physical gestures, has been shown to reduce variability and discomfort in pseudo-haptic tasks like pulling virtual objects, even when strong pseudo-haptic effects are applied [18]. The existing studies highlight the potential of pseudo-haptics and controlled temporal offsets in further enhancing vibrotactile feedback for VR applications. Despite these advancements, the interplay between the timing of vibrotactile feedback and the nature of actuation in relation to visual-haptic offsets remains an underexplored area.

2.3 Hand Motion Prediction for Controlling Haptic Delivery Time

Integrating predictive algorithms into haptic systems enhances interaction fluidity and sensory coherence. Clarence et al. [3] utilized a prediction model to optimize haptic feedback for unscripted movements, particularly within the framework of haptic retargeting techniques [1]. While innovative machine learning models, such as the efficient MLP-based motion prediction proposed by Guo et al. [13], demonstrate significant potential, their application is limited by the computational constraints of standalone VR devices.

Gamage et al. [8] developed a generalized continuous hand trajectory prediction model for ballistic movements in VR, demonstrating efficiency suitable for standalone hardware. Their model achieved a Root Mean Square Error of 0.80 cm for 100 ms predictions and an average accuracy of 4 deg at the midpoint of pointing tasks—well below the perceptual threshold for noticeable hand offset [48]. Unlike computationally intensive alternatives, this lightweight model can operates directly on the device, minimizing latency associated with cloud-based processing. Building on this foundation, we propose the proactive haptic concept as a way of utilizing predictive models to enhance the pseudo-haptic vocabulary for VR designers.

3 *Proactive Haptics*

This section introduces the concept of *proactive haptics* and details our approach of implementation. We begin by explaining the core principles of *proactive haptics*, followed by a description of the hand motion prediction model we employed. We then explain the design of haptic profiles. Finally, we present our implementation of *proactive haptics* in an off-the-shelf VR headset.

3.1 The concept

The concept of *proactive haptics* is to provide in advance tactile cues before the actual hand collides with the virtual object. It provides a new temporal space between the detection and collision as shown in Figure 1B, the design space can be expanded with haptic profiles.

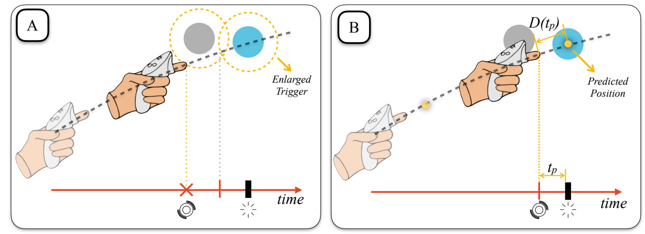

Figure 2: (A) Enlarging the haptic collider to provide early haptic cues led to false triggers from adjacent non-target objects. (B) Details of the proactive haptic system: haptic cues are delivered when the predicted position (yellow dot) collides with the object, with a predetermined prediction time t_p and the predicted displacement based on t_p ($D(t_p)$).

We hypothesize that the combination of the in advance time (t_p) and the tactile amplitudes could potentially influence the user's perception of the interaction, distinguishing it from instantaneous reactive feedback. Furthermore, we speculate that these perceived differences might be interpreted by users in a manner analogous to different haptic experiences in the real world. For instance, a shorter in advance time might be perceived by users as interacting with a rigid material, like metal or stone. Conversely, a longer in advance time might evoke sensations akin to touching more elastic materials, such as rubber or gel, that gives elongated haptic experience.

Given the design space of *proactive haptics*, different parameters, such as time to collision and user's hand movement characteristics (e.g. velocity, acceleration), can be used to create tactile feedback variations, which can lead to different perceived experiences.

3.2 Hand Motion Prediction Model

A naive way to provide haptic cues in advance would be to enlarge the haptic collider of the virtual object, thereby making the collision detection happen earlier. However, this static approach does not accommodate variations in reaching speed, and more importantly, as shown in Figure 2A, can falsely trigger tactile cues when passing by non-target objects. Conversely, predicting the future position of the user's hand, as shown in Figure 2B, to dynamically adjust the tactile cues based on the future hand trajectory offers a more flexible and movement-sensitive solution.

Our hand motion prediction model based on [8] utilizes historical hand movement data to forecast upcoming positions. This prediction model was chosen due to its trade-off between accuracy and resource requirements that match the resources of the VR device. The model predicts continuous ballistic hand trajectories by employing the initial five derivatives of motion: *v*elocity (v), *a*cceleration (a), *j*erk (j), *s*nap (s), and *c*rackle (c). These derivatives are fundamental components of motion kinematics, capturing the

$$D(t_p) = \begin{bmatrix} vt_p & at_p^2 & jt_p^3 & st_p^4 & ct_p^5 \end{bmatrix} \begin{bmatrix} 1.0000 + 0.1693t_p \\ 0.5000 + 0.1837t_p \\ 0.1667 + 0.1151t_p \\ 0.0417 - 0.0343t_p \\ 0.0083 - 0.0064t_p \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v & a & j & s & c \end{bmatrix}^T = \alpha([t_{-1}, t_{-2}, ..., t_{-n}])^{-1} \begin{bmatrix} D(t_{-1}) & D(t_{-2}) & \dots & D(t_{-n}) \end{bmatrix}^T \quad (2)$$

where,

$$\alpha([t]) = \begin{bmatrix} t_{-1} + 0.169t_{-1}^2 & 0.5t_{-1}^2 + 0.183t_{-1}^3 & 0.167t_{-1}^3 + 0.115t_{-1}^4 & 0.042t_{-1}^4 - 0.034t_{-1}^5 & 0.008t_{-1}^5 - 0.006t_{-1}^6 \\ t_{-2} + 0.169t_{-2}^2 & 0.5t_{-2}^2 + 0.183t_{-2}^3 & 0.167t_{-2}^3 + 0.115t_{-2}^4 & 0.042t_{-2}^4 - 0.034t_{-2}^5 & 0.008t_{-2}^5 - 0.006t_{-2}^6 \\ & & \vdots & & \\ t_{-n} + 0.169t_{-n}^2 & 0.5t_{-n}^2 + 0.183t_{-n}^3 & 0.167t_{-n}^3 + 0.115t_{-n}^4 & 0.042t_{-n}^4 - 0.034t_{-n}^5 & 0.008t_{-n}^5 - 0.006t_{-n}^6 \end{bmatrix} \quad (3)$$

rates of change in motion and providing a nuanced understanding of movement dynamics. The model uses these derivatives alongside a time-sensitive regression approach to accurately determine displacement over time. In contrast to steered hand trajectories, ballistic hand trajectories follow the natural movement after an initial force is applied. Object selection tasks in virtual reality can be considered ballistic movements and, thereby, can be modelled with kinematics instead of kinetics of motion. The model reported an average root mean square error (RMSE) of 0.80 cm for predicting hand positions 100ms in future. We combine the Equation (2) and $t < 0.16$ s version of Equation (5) from [8] for building our version of the prediction model as Equation 1 to calculate the displacement vector ($D(.)$ m) at time t_p s in future.

The motion smoothing method used by [8] before calculating the derivatives requires the use of a Gaussian filter which is not a causal filter, i.e. it requires future motion data. While this is not an issue when using recorded data, using the model in a real-time setting requires a causal system that doesn't require knowing future motion in advance. To achieve this, we use the inverse form of Equation 1 from [8] to calculate the derivatives directly from the historical data according to Equation 2.

3.3 Haptic Profiles

We explore 6 haptic profiles to augment the vibrotactile cues given according to the prediction. Each haptic profile describes the level and changes in the amplitude of the vibrotactile cues based on time or the acceleration of hand movement. The selection of these profiles was made to cover the varying effects of haptic profiles in combination with *proactive haptics* within the scope of the project and to keep each study session under a reasonable time frame. The 6 profiles are named *constant*, *pulse*, *positive-a*, *negative-a*, *increasing*, and *decreasing*. The *constant* profile provides a baseline and is the simplest with no change in amplitude over the interaction time. In contrast, the *pulse* profile delivers a fixed duration haptic cue. The *increasing* and *decreasing* profiles introduce changes in amplitude at a fixed rate. The *positive-a* and *negative-a* profiles dynamically adjust the amplitude change rate based on hand motion, offering more complex and dynamic feedback. These profiles were chosen to represent a broad spectrum of possible haptic experiences, from stable and predictable to dynamic and context-sensitive, thereby allowing us to investigate their distinct impacts on user perception in combination with the *proactive haptics*. We use the variables; prediction time of the prediction model (T), dwell time (i.e. the time hand spends inside the object - D_t), hand velocity (v), and maximum vibrotactile amplitude (A) to define the profiles. We also consider the time at which the hand actually collides with the object as time $t = 0$. As a result, prediction occurs during ($t < 0$).

3.3.1 Constant. This haptic profile is the most basic profile where we use a constant amplitude level from the point of detecting the collision to the hand leaving the object. Here, only the prediction time (T) affects the duration of the vibrotactile feedback, as shown in Figure 3a and Equation 4.

$$f_{constant}(t) = \begin{cases} 0.5A, & if -T \le t \le D_t \\ 0, & otherwise \end{cases} \quad (4)$$

3.3.2 Pulse. Comparing to the *constant*, the *pulse* profile provided a fixed duration of vibrotactile pulse T_{pulse}, when the collision between the hand and the object is detected as described in Equation 5 and shown in Figure 3b.

$$f_{pulse}(t) = \begin{cases} 0.5A, & if -T \le t \le -T + T_{pulse} \\ 0, & otherwise \end{cases} \quad (5)$$

3.3.3 Increasing and decreasing. The *increasing* and *decreasing* haptic profiles introduce amplitude changes at a fixed rate compared to the constant haptic profile. Both haptic profiles start from $0.5A$ until the amplitude reaches the maximum A for *increasing* or minimum 0 for *decreasing* at a rate C. Similar to *constant*, the haptics stop when the hand leaves the object. The haptic profiles can be described as shown in Equation 6 and 7; and shown in Figure 3c and 3d.

$$f_{increasing}(t) = \begin{cases} min(A, 0.5A + C(t+T), & if -T \le t \le D_t \\ 0, & otherwise \end{cases} \quad (6)$$

$$f_{decreasing}(t) = \begin{cases} min(A, 0.5A - C(t+T), & if -T \le t \le D_t \\ 0, & otherwise \end{cases} \quad (7)$$

3.3.4 Positive-a and negative-a. The two profiles introduce dynamic amplitude changes based on hand moment to the *constant* profile. Once the prediction model detects the collision, the vibrotactile cues is given with a positive (or negative) proportion (coefficient $C_a > 0$) to the acceleration (a) of the hand until the hand leaves the object. This results in a variation of the amplitude with the user's motion, which follows a decreasing and then increasing trend for the *positive - a* and follows an increasing and then decreasing trend for the *negative - a*. The amplitude change rate becomes 0 as the user's hand changes movement direction. It can be described by Equation 8 and 9; and generally follows the shape shown in Figure 3e and 3f.

$$f_{positive-a}(t) = \begin{cases} min(A, 0.5A + C_a a), & if -T \le t \le D_t \\ 0, & otherwise \end{cases} \quad (8)$$

$$f_{negative-a}(t) = \begin{cases} min(A, 0.5A - C_a a), & if -T \le t \le D_t \\ 0, & otherwise \end{cases} \quad (9)$$

3.4 Implementation

The *proactive haptics* system comprises three main components: the device, the software, and the prediction model. We use the Meta Quest 3 headset along with its Meta Quest Touch Plus controllers as the device as they are the most recent version of a commercially available and generally accessible VR platform. The software has been developed using Unity Editor (2022.3.18f1) along with the Meta XR Interaction SDK (60.0.0), which handles the virtual environment, provides data to the prediction model as input, and uses the output of the prediction model to provide the haptic cues. The prediction model is responsible for forecasting the future hand position.

3.4.1 Implementation on the Meta Quest 3. The proposed system first captures the controller positions and provides them to the prediction model. It uses the output of the prediction model as the trigger position (shown as the yellow dot in Figure 2 B) for the haptic feedback. Each virtual object in the virtual environment has a collider (i.e., a boundary) used to decide if any other object collides with it. Generally, these colliders trigger visual effects when two objects collide. The haptic cue is generated once the haptic trigger is detected inside a virtual object's collider. The system can use the same colliders for visual and haptic cues, thereby reducing the colliders and collision calculations needed. Additionally, the system logs actual position, predicted position, and haptic trigger signals for evaluation purposes.

We made several improvements to the prediction model and ran the entire system at $80Hz$ ($12.5ms$ period) to achieve smooth and stable synchronized operation. This includes the screen refresh rate, input tracking rate, data logging rate, prediction model's parameters (refer to section 3.4.2), and haptic cues generation rate. While the headset supports a higher refresh rate, those options cannot provide a consistent refresh interval for the prediction model, leading to worse performance. Our tests confirmed there was no difference when comparing the on-device setup with a desktop streaming setup at $80Hz$. The system was then deployed on the standalone headset to provide a cable-free experience.

3.4.2 Adjustments to the Prediction Model. A streamlined version of the model was developed to match the device's resource constraints and the real-time calculation requirement of this application. This included adjustments in the sampling rate and sample size of historical data, calculation of derivatives, and available prediction times. This was implemented as a matrix operation, further increasing the calculation speed of the prediction model.

- Sampling Rate: The sampling rate refers to the number of historical data samples taken in a second. The FixedUpdate()[2] function of Unity was used to maintain consistency in this interval across all samples. The sampling rate was adjusted to $80Hz$ to match the overall refresh rate for smooth operation, resulting in $12.5ms$ time intervals between each sample.
- Sample Size: The sample size is the number of historical hand positions utilized for making predictions. To minimize noise and improve prediction accuracy, the sample size was set to 50, i.e. $612.5ms$ of historical data.
- Prediction Time (t_p): Prediction time represents how far into the future the model forecasts. The prediction time was adjusted to be multiples of $12.5ms$ to match the device refresh rate. This highlighted an advantage of using [8] model as it can predict the motion of different future times without any retraining process.

[2]https://docs.unity3d.com/ScriptReference/MonoBehaviour.FixedUpdate.html

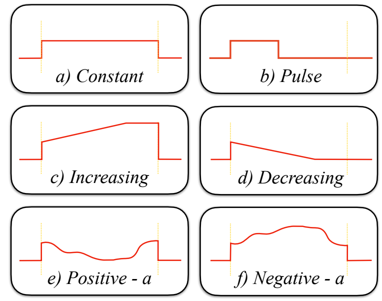

Figure 3: Illustration of the six haptic profiles used in augmenting *proactive haptics.* The first yellow dotted line indicates when the haptic trigger enters the target, and the second yellow dotted line indicates when the visual trigger exits the target.

The authors of [8] reported that their model achieved an average RMSE of $0.80cm$ when predicting hand positions $100ms$ into the future. We validated and evaluated our final implementation in a validation study, as shown in section 4.4. Our results show that when predicting hand positions $62.5ms$ and $100ms$ into the future, our implemented model achieved an average RMSE of $1.44cm$ (SD : $0.56cm$) and $1.92cm$ (SD : $1.09cm$) respectively. This slight drop in accuracy could be due to the reduced accuracy of the sensing system (OptiTrack for [8] vs. VR controller's built-in location) and the difference in actions performed.

4 Evaluations

The implementation was validated in the study setup by assessing the system's visual-haptic delay and ensuring that precisely timed proactive haptic cues are delivered before the visual events. Two user studies were conducted to explore the effect of *proactive haptic* cues on the interaction experience and the perception of object characteristics. In this section, we describe the setup of the studies, present results from the System Validation (Section 4.3) and Preliminary Study (Section 4.4), and outline the procedure of the Perception Study (Section 4.5).

4.1 Study Setup and Environment

A mid-air target acquisition task inspired by [25, 43, 47] was designed. There are a total of 33 possible spawn positions for the target, arranged into three layers (L1, L2, L3), each with an ISO

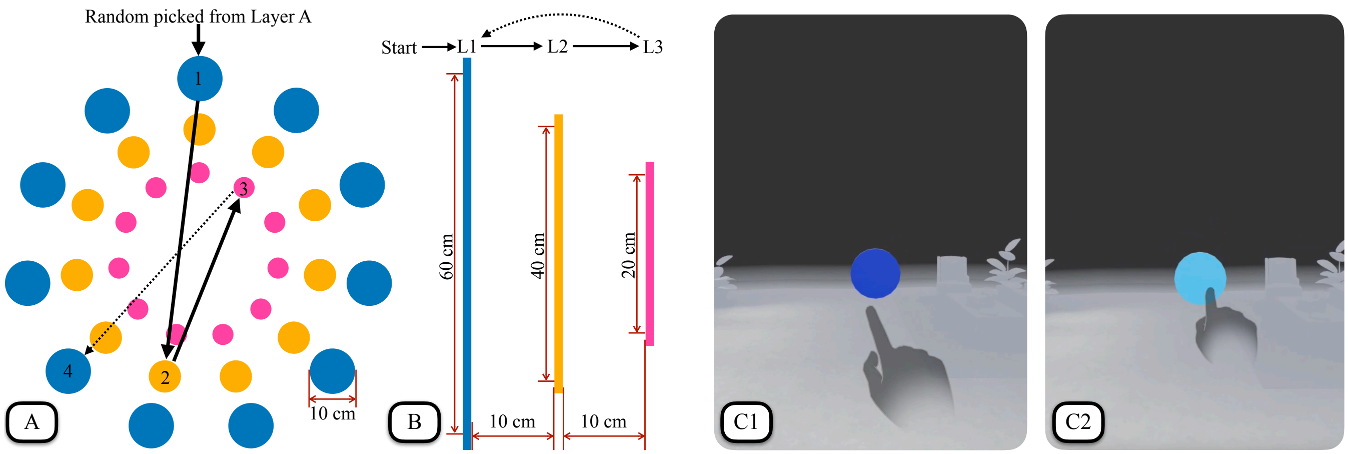

Figure 4: (A) All possible spawn positions of the target, with three layers of positions colour-coded in the diagram. (B) Dimensions of the three layers. (C1) Screenshot of a participant during a trial, attempting to interact with the target using the visual index finger. (C2) Screenshot of a participant during a trial, with their hand reaching the target.

9241 standard 11 target ring, as shown in Fig 4 A and Fig 4 B. Each target is a 10 cm diameter cylindrical object. Layers L1, L2 and L3 are positioned at $40cm$, $50cm$, and $60cm$ along the z-axis, away from the centre of the two eyes. And the ring radius for layers L1, L2, and L3 are $30cm$, $20cm$, and $10cm$ respectively. The introduction of three layers and different ring radius aim to eliminate the effect of the approaching direction and depth. Meanwhile the reaching difficultly for each of the target across trials remaining consistent according to the Fitts' Law [28].

Minimal visual cues are provided to eliminate the effect of visuals on the perceived sensations. The colour change indicates successful interaction. When the virtual hand's visual enters the target, the target turns from blue to light blue, as shown in Fig 4 C1 and C2, and when the virtual hand exits, the target changes its position to the next pre-determined location.

In each trial, the participant must interact with six targets sequentially. The target randomly appears at one of the possible positions in Layer L1 and moves to the position opposite of the next layer, following the order L1 → L2 → L3 → L1 → L2 → L3.

We utilise the six haptic profiles described in Section 3.3 along with three prediction time (T) levels. We implement the reactive haptic condition as $T = 0$ without using the prediction model to provide haptic cues. Di Luca and Mahnan has reported $68ms$ and $100ms$ respectively as threshold limits for 50% and 65% of the population being able to identify haptic-before-visual interactions [6]. We select the nearest multiples of our sampling rate, $T = 62.5ms$ and $T = 100ms$, for the *proactive haptics* system to be in the boundary of visual-haptic-asynchrony. For these two conditions, the prediction model is used to anticipate the collision between the hand and target $62.5ms$ and $100ms$ in advance, respectively.

4.2 Procedure

All user study sessions followed a specific protocol to ensure consistency. The study procedure have been approved by the HREC of the University of Sydney 2019/553. Each study session lasted approximately 30 to 40 minutes.

The session began with an introduction, where participants were provided with an overview of the study. The 18 sensation terms were presented to the participants, accompanied by definitions in simple English. Participants were required to read and comprehend the terms and definitions, ensuring they fully understood their meanings. Following the introduction, participants completed a pre-study questionnaire. This questionnaire collected demographic data, information about past VR experience, and English proficiency. The sensation terms were shown again in the questionnaire to double-check participants' confidence in understanding those terms. A tutorial scene was then presented, allowing participants to complete one sample trial. This familiarized them with the interaction and the sensation term selection UI in VR.

The main study consisted of 18 trials, one for each unique combination of prediction time and haptic profile. For each trial, participants selected the target six times at different locations described in Section 4.1. To understand the perceived sensations of the proactive vibrotactile stimulation, we followed the method used by [35]. After each trial, we provided a list of terms in the VR and asked the participant to "Select terms which describe the sensations." The order of terms was randomized for each trial.

Participants could spend as much time as needed on the questionnaire and select any number of terms (refer to Table 1 for the sensation terms used in the Perception Study). The effect of trial order was counterbalanced by first randomizing the sequence of six haptic profiles, followed by randomizing the prediction time within each haptic profile.

The session concluded with a semi-structured interview, conducted after participants completed all trials. This interview aimed to gain more insights about their perceived sensation of the proactive vibrotactile cues. Participants were encouraged to describe their sensations in more detail and comment on the overall study. The audio recording of the interview was transcribed and used for further analysis.

Absorbing	Diffuse	Elastic	Flowing	Localized
Pulling	Pulsing	Pushing	Radiating	Rigid
Rough	Slippery	Smooth	Soft	Static
	Sticky	Strong	Weak	

Table 1: List of Sensation Terms

4.3 System Validation

To validate our implemented system, we assessed the visual-to-haptic asynchrony for each prediction time setting, verifying the system's ability to deliver precisely timed in advance haptic cues.

4.3.1 Methodology: Using a modified study setup, we performed the target acquisition task in which the headset screen turned white when the virtual hand (visual trigger) made contact with the target. Meanwhile, the haptic cue was triggered separately by the haptic trigger, applied in combination with one of three prediction times: $0ms$, $62.5ms$, or $100ms$, using a *constant* haptic profile. We employed a photodiode on the headset's left screen and a microphone (Adafruit MAX9814) on the controller to capture light and vibration data, respectively, using a FireBeetle ESP32-E Microcontroller. The recording system sampled at $2.5kHz$.

4.3.2 Results: Analysis of 30 target selections per prediction time revealed that haptic cues consistently preceded visual cues. The average lead times were $13.32ms$ (SD: $21.87ms$) for $0ms$, $89.26ms$ (SD: $22.71ms$) for $62.5ms$, and $123.30ms$ (SD: $9.37ms$) for $100ms$ conditions. This consistent lead of approximately one frame plus the prediction time is attributed to the instant activation of haptic motors compared to frame-based visual updates. Notably, the asynchrony in the $0ms$ condition falls below the detection threshold reported by [6], validating the system's accuracy in delivering proactive haptic cues.

4.4 Preliminary Study

This study served as a pilot before the formal Perception Study, assessing the impact of proactive haptics on perceived realism and validating the sensation terms selected for the study. Additionally, the actual and predicted hand positions collected from participants were used to evaluate the performance of the implemented prediction algorithm presented in Section 3.4.2.

4.4.1 Methodology: A total of 13 participants (4 female, 9 male, aged 18-34) were recruited. After each trial, the participant was asked to rate the statement "The virtual object felt real to me" on a 7-point Likert scale (1=strongly disagree, 7=strongly agree). We chose to focus on realism rather than explicitly measuring visual-haptic asynchrony, as our goal was to observe whether users would naturally detect any discrepancies in timing during the task. We further employed the 21 terms describing tactile sensations from the [31] and [35] and asked the participants to pick descriptive words for each trials in the study.

4.4.2 Results: Although the *proactive haptics* conditions exceed the visual-haptic asynchrony threshold reported by [6], our results did not show statistically significant differences in realism, which aligns with the findings from [51]. The mean and standard errors of the realism rating $0ms$, $62.5ms$ and $100ms$ are $5.27(0.129)$, $5.15(0.188)$ and $4.95(0.130)$. The data was normally distributed and a two-way ANOVA was performed to analyze the effect of prediction time and haptic profile on realism. Results showed no significant difference on the main effects prediction time ($F(10, 216) = 1.602$, $p = 0.204$) and on haptic profile ($F(10, 216) = 0.540$, $p = 0.746$), also no significant on the interaction effect ($F(10, 216) = 0.590$, $p = 0.821$). This suggests that it is possible to manipulate pseudo-haptic sensations by delivering vibrotactile cues in advance without affecting the realism.

4.5 Perception Study

4.5.1 Changes to Procedure: Based on term frequency analysis and interview responses from the *Preliminary Study*, we refined the sensation term list to 18 terms for the Perception Study, as shown in Table 1. Most common haptic descriptions such as "vibration" and "tapping" were removed, as they directly described the vibrotactile effect and may influence the perception and sensation of other terms. Additionally, since we did not find significant differences, we eliminated the realism questionnaire from the formal study to enable participants to focus solely on the sensations evoked by the vibrotactile cues.

4.5.2 Participants: A total of $N = 16$ participants were recruited for the study. However, one participant did not complete the entire study due to their lack of confidence in understanding the English terms. Therefore, their data was excluded from the analysis of valid responses. The remaining $N = 15$ participants, including 6 females and all between 18 and 34 years of age, completed 270 trials. Notably, two participants had never used VR devices before this study. Among those with prior VR experience ($n = 13$), three reported using VR devices weekly, one reported using them monthly, and the remaining 9 rarely used them. The 15 valid participants selected a total of 1,061 terms, averaging 70.6 terms per participant and 3.92 terms per trial. Participants spent an average of 30.6 seconds per trial on the sensation questionnaire ($SD = 18.0s$).

5 Results

In this section, we present and interpret the results of term selections from trials of the perception user study. First, we compare responses of the reactive haptic condition against the two proactive haptic conditions to validate that users are able to perceive the proactive haptic conditions differently from the reactive haptic condition. Then, we analyse and interpret the term frequency trends observed for the proactive haptic conditions. We primarily consider the opposing trends in antonymous word pairs and the users' qualitative descriptions of those conditions. We also highlight some minor trends we observed about the terms that are less pronounced than the antonymous relationships.

We analyzed system logs to validate that haptic cues were delivered as intended in the perception study. Across 540 target selections from 15 participants, we measured the time difference between the haptic and visual triggers, ensuring alignment with the predefined advance times. The system operated at 80 Hz, matching the screen refresh rate and prediction algorithm frequency. Results showed that haptic cues preceded visual feedback by an average of 59.66 ms ($SE : 1.16$) in the 62.5 ms condition and 93.00

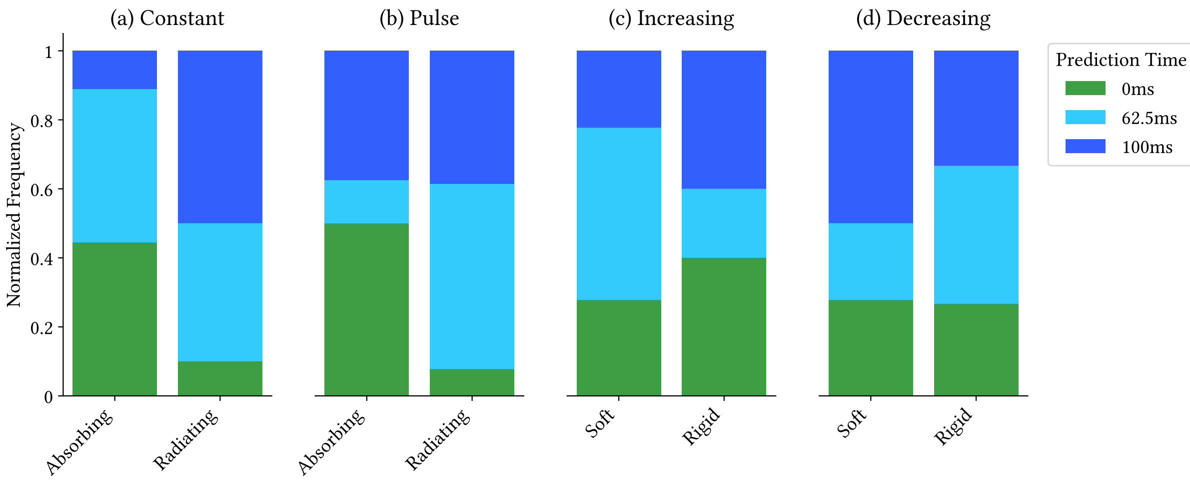

Figure 5: The effect of prediction time (T) on sensation pairs (a,b) Absorbing-Radiating and (c,d) Soft-Rigid.

ms (SE : 1.91) in the 100 ms condition, confirming that the system reliably executed proactive haptic cues with minimal deviations.

5.1 The Effect of Prediction Time on Sensations

We investigate the effect of proactive haptics on participants' sensory perceptions across all haptic profiles by comparing reactive ($0ms$) and proactive ($62.5ms$ and $100ms$ prediction times) haptic conditions. Wald chi-square tests were conducted for each sensation term to determine statistically significant differences. The results of the Wald chi-square tests shows the 9 out of 18 sensation terms have statistically significant differences between the reactive and proactive haptic conditions, which are *weak*, *soft*, *localized*, *pulling*, *pulsing*, *elastic*, *smooth*, *slippery*, and *sticky*. The results are shown in Appendix A.

5.2 The Combined Effect of Prediction Time and Haptic Profiles on Sensations

We analyse the term frequency as pairs of antonymous terms for the two proactive haptic conditions. As the antonumous term pairs represent opposing concepts linguistically, an inverse relationship is hypothesised. Unsurprisingly, most term pairs demonstrated opposite trends; for instance, the terms *strong* and *weak* showed inverse relationships. Here, we highlight some of the most contrasting relationships when comparing the effect of prediction time and haptic profiles on the term selection frequency. All combinations of the prediction time and haptic profiles for each term can be found in Appendix B. The post-study interview recordings were transcribed and then authors carried out a general inductive analysis [44] with the transcripts and handwritten notes.

5.2.1 Absorption and Radiation Sensation. Specifically, the *constant* and *pulse* haptic profiles exhibited the most significant effects, as shown in Figure 5 (a) and (b). As the prediction time (T) increased, the *constant* haptic profile elicited a stronger sensation of *radiating*, while the sensation of *absorbing* decreased. We define *radiating* as the sensation of energy or force spreading outward from a source, akin to the feeling of heat dissipating. A higher prediction time aligns with this definition, as the vibrotactile cue begins before contact, enhancing the perception of radiating sensations. Conversely, the *pulse* haptic profile was associated with a higher frequency of *absorbing* sensations and a lower frequency of *radiating* sensations as prediction time increased. We hypothesize this is due to the vibrotactile duration remain unchanged for the *pulse* profile regardless of the prediction time. [P10] remarked that they experienced radiating when they felt they did not touch the virtual object, but tactile feedback had already begun. [P04] and [P08] described *absorbing* sensation as "absorbing is a little bit of pulling" and "absorbing is kinda like reduction", respectively.

5.2.2 Rigidity Sensation. The *increasing* and *decreasing* haptic profiles exhibited opposing trends in perceived rigidity and softness (Figure 5 (c) and (d)), with peak effects at the $62.5ms$ condition. The *increasing* profile was associated with the highest *soft* sensation counts, while the *decreasing* profile peaked for *rigid* sensations. This may be due to the duration of touch sensation and the discrepancy between visual and haptic timing. *Soft* objects typically provide a sustained touch, while *rigid* objects create an immediate response. At shorter prediction times, asynchrony is less noticeable, whereas at longer times, it can be perceived as motion resistance, enhancing rigidity perception. We noticed that the participants could not distinguish vibrotactile amplitude from duration, suggesting they interpreted them interchangeably. Thus, a *decreasing* intensity over time reinforced the feeling of a soft, sustained touch, while an *increasing* amplitude was perceived as rigidity.

5.2.3 Pulling and Pushing Sensations. When examining the sensations of *pushing* and *pulling* (Figure 6 (a) and (b)), we found that *decreasing* and *positive-a* haptic profiles showed similar trends. The sensation could be shifted from *pushing* to *pulling* by increasing the prediction time. The similarity between these profiles could be attributed to them having similar haptic profiles (Figure 3), especially when the hand is decelerating. Interestingly, participant P09 selected both terms in a trial. They later reiterated in the interview

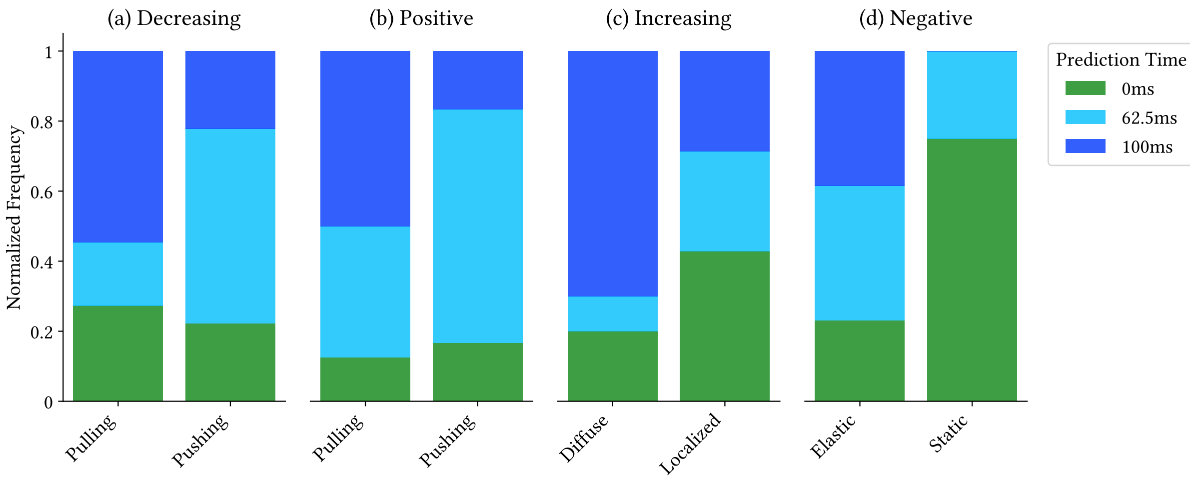

Figure 6: The effect of prediction time (T) on sensation pairs (a,b) Pulling-Pushing, (c) Diffuse-Localized, and (d) Elastic-Static.

that they indeed felt both sensations: *pushing* when the hand was reaching forward and *pulling* when the hand was retracting. Additionally, there was an ambiguity in the direction of *pushing*/*pulling* where several participants were unsure whether *pushing* referred to the hand pushing the object or the object pushing the hand.

5.2.4 Diffuse and Localized Sensations. The sensation of locality shifted from *localized* to *diffused* when increasing the prediction time on *increasing* haptic profile (Figure 6 (c)). This suggests that the localization of the vibrotactile cue becomes harder with higher prediction times. All of prediction time, motion trajectory, and the accuracy of the prediction model could have an effect on this trend. As the reactive haptic is consistently triggered when the hand is on the object, it could lead to a *localised* feeling whereas the haptic triggered in 100*ms* in advance occurs at different locations in space. The prediction error of the model could enhance this effect and add a randomness to the position at which the haptic is delivered. Altogether, this could lead to a *diffused* or fuzzy sensation. One participant [P03] described the *localised* sensation as "I can feel the physical [target]." [P08] described the sensation of *diffuse* as "the increasing intensity of the vibration". Furthermore, [P02] commented "so some vibrations I could almost feel it in my wrist while some were only just the fingers so the ones that I felt like the vibration only stayed in the fingers would be soft and stronger ones would be where I can feel it almost in my wrist."

5.2.5 Elastic and Static Sensations. Increasing the prediction time shifted the sensation from *static* to *elastic* for the *negative-a* haptic profile, as shown in Figure 6 (d). The higher prediction times allow a sustained vibration while the *negative-a* haptic profile provides increased resistance during the deceleration, giving an overall rubbery effect. Participant [P07] described the elastic sensation as "pushing into it" while [P11] noted it by "as I was pulling away, I still felt the sensation." These comments suggest that the elastic sensation was experienced in different directions, one from pushing and the other from pulling. Contrary to pushing and pulling sensations, the elastic sensation doesn't require a specific direction, thereby not being affected by subjective interpretations of direction.

6 Discussion

6.1 Interpretations of the Studies

The implementation and optimization of the hand prediction model, as proposed by Gamage et al. [8], has been pivotal in achieving efficient and accurate real-time prediction of hand trajectories in virtual reality. This capability significantly enhances the proactive haptic concept by allowing for anticipatory tactile feedback. To the best of our knowledge, our work represents one of the first instances of utilizing a prediction model to apply the technology in a novel context, tapping into the temporal space just before touch.

The two exploratory user studies demonstrated the significant role of haptic experiences in the temporal space preceding visual interactions. The Preliminary Study confirmed that in advance haptic cues can be accurately delivered using our setup and the overall experience is not affected by the in advance delivery up to 100*ms*, aligned with [51], suggesting the sensations explored in the Perception Study are practical to use in existing applications.

Building on these findings, the Perception Study examined the relationship between the haptic profiles with users' perceived haptic experiences. We discovered notable correlations between sensation pairs such as *absorbing-radiating*, *soft-rigid*, *pushing-pulling*, and *static-elastic*. These relationships were further supported by participants' qualitative feedback from the post-study interviews.

The sensations participants reported align with their physical attributes; for example, *radiating* sensations can be generated using a 100*ms Constant* profile, while *absorbing* sensations are simulated more effectively with the *Pulse* profile at lower prediction times. We found that *soft* sensations are more pronounced with higher prediction times, such as the 100*ms decreasing* profile, reflecting how softer objects in real life tend to provide longer and gentler tactile feedback. Conversely, *rigid* sensations are reported more frequently in lower prediction time settings. Our results also support the property of *diffuse* sensations, which can be created using

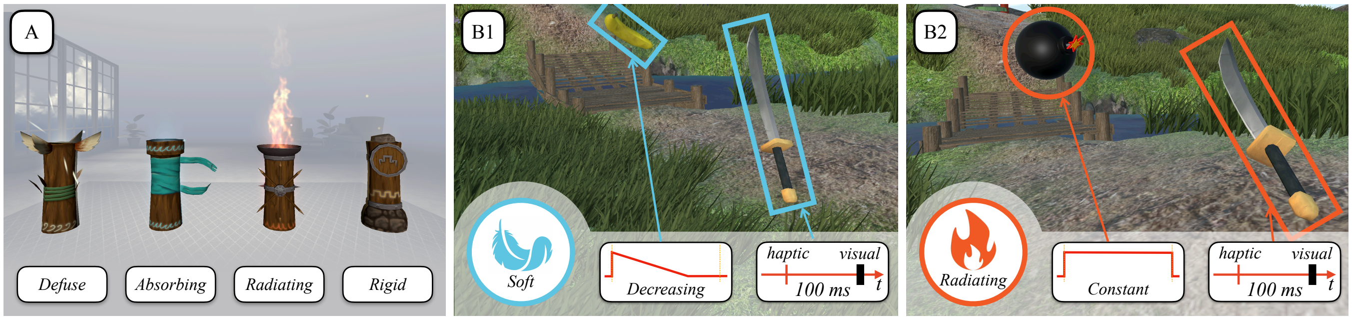

Figure 7: Two applications showcasing manipulated sensations using the proactive haptic system. (A) The *proactive haptics* sample room: Virtual objects on the table use specific prediction times with paired haptic profiles to demonstrate sensations in VR. Users can interact with objects and feel the sensations. (B) VR Fruit Ninja game: Modified to use the proactive haptic system to deliver soft sensations for fruits and radiating sensations for bombs. (B1) User about to cut a banana. (B2) User about to cut a bomb.

haptic cues delivered with 100*ms increasing* profile, perceiving the sensation before touching the object. Notably, *static* sensations were not reported in the 100*ms* setting, aligning with our hypotheses and the expected physical properties. These findings demonstrate the potential to create diverse pseudo-haptic experiences through in advance tactile cues, largely supporting our initial hypotheses and reflecting the physical properties of these sensations. When analyzing hand movement (position over time) against the terms, we found no specific movement patterns associated with any term.

6.2 Proactive Haptic Applications

The pseudo-sensations enabled by *proactive haptics* show that vibrotactile cues can simulate complex sensations traditionally associated with other haptic technologies, such as electroactuators, ultrasonics, and physical prompts. This is significant given the widespread accessibility of vibrotactile actuators. By manipulating haptic cues ahead of visual events, we can create richer and more nuanced haptic experiences in VR, expanding the potential applications of haptics in virtual environments.

We demonstrated the potential of *proactive haptics* in two VR applications. The first, a sample room app (Figure 7A), features various virtual objects, each producing a specific sensation using the prediction time and haptic profiles explored in this study. Users can experience a range of pseudo-haptic sensations, such as defuse, absorption, radiating, and rigidity, illustrating how *proactive haptics* can add depth to virtual environments.

We also integrated *proactive haptics* into an open-source VR game VR Fruit Ninja [3] (Figure 7B). This integration enables distinct sensations for different in-game elements—*soft* sensations for fruits like bananas, *rigid* sensations for watermelons, and *radiating* sensations for bombs. Combined with visual and auditory feedback, this approach could lead to more nuanced interactive VR experiences.

6.3 Future Perspectives

The implications of *proactive haptics* go beyond this study. By introducing vibrotactile cues before visual interactions, this technology challenges traditional reactive haptics and opens new possibilities for user experience design. It allows for novel pseudo-haptic sensations, enhancing interaction realism and simulating a wider range of material properties and forces in virtual environments.

For designers, the temporal gap between visual and haptic cues offers an opportunity to refine user experiences by exploring visual-haptic asynchrony. This flexibility can augment the realism of visual cues or introduce intentional asynchrony to create unique perceptual effects. Beyond haptics, this concept can be applied to other multimodal systems, integrating anticipatory cues to enhance user experience.

Proactive haptics also lays the groundwork for further research into how manipulating feedback timing influences user perception, engagement, and interaction in both virtual and real-world contexts. By expanding the temporal domain of haptic feedback, we open new possibilities for dynamic interactions in VR, AR, and other digital interfaces, offering HCI researchers and developers fresh avenues for innovation in immersive experience design.

7 Future Work and Limitations

In our user study, we intentionally provided only critical visual feedback to minimize Colavita's visual dominance on tactile sensations [40]. This limited our evaluation of the interaction between haptic and visual cues. Future studies could explore how combining proactive haptic cues with more advanced visual feedback might enhance, modulate, or even override tactile sensations due to the visual dominance effect. While beyond the scope of this study, our findings suggest significant potential for further research.

Although the haptic profiles improved sensations, we only tested 6 simple profiles based on vibrotactile amplitude. More complex profiles and combinations could lead to more nuanced experiences. Additionally, the profiles were designed for short interactions, but longer or more complex profiles may be required for interactions like dwell and hover. We only studied the front selection scenario following [6], which provide fewer visual cues due to the depth effect. Future research should assess proactive haptics in side selection scenarios, where additional visual cues may shift visual-haptic asynchrony thresholds, realism, and perceived sensations.

[3] An open-source app on GitHub https://github.com/abmami/Fruit-Ninja-VR-Unity

The hand motion prediction model used in our study did not perform as well as the original model [8]. This discrepancy may stem from differences in device accuracy (Quest 3 vs. OptiTrack), data filtering, and the use of floating-point numbers for computational efficiency, which may have reduced precision. However, the current model is sufficient for evaluating the proactive haptic system, and its performance can improve as VR hardware advances. Additionally, synchronizing the prediction model with the headset's refresh rate (80 Hz) limited the study's scope, as this restricted the prediction interval to multiples of 12.5 ms. Future research with more advanced hardware supporting higher refresh rates could enable finer intervals and more accurate predictions. Finally, some participants reported varying perceptions of vibrotactile intensity, and some were confused about interaction directions (e.g., *pulling* vs. *pushing*), which may have affected response consistency. Future studies could address these issues by personalizing haptic feedback and clarifying terminology.

8 Conclusion

This study explores the potential of utilizing the proactive haptic space in enhancing mid-air haptic interactions. By investigating various haptic profiles, we have uncovered nuanced sensations that can be evoked through in advance tactile cues. Our findings reveal that proactive tactile cues can influence users' perceptions, creating sensations of stickiness, elasticity, and diffuseness depending on the timing and haptic profile. The study also highlights the complex interplay between different tactile sensations and their relationship to prediction times. While our research was conducted with limited visual feedback to isolate tactile effects, it opens up exciting avenues for future research in multimodal interactions.

Acknowledgments

This research was supported by various funding bodies and institutions. Dr. Anusha Withana is the recipient of a Discovery Early Career Researcher Award (DECRA) fellowship, funded by the Australian Government. Additionally, this work was supported by the Australian Government's National Health and Medical Research Council (NHMRC) under the 2022 Ideas Grant (Grant No. 2021183). We also acknowledge financial support from the University of Sydney's Digital Sciences Initiative through the DSI Research Pilot Project grant scheme. Furthermore, Dr. Andrea Bianchi received support from the Institute of Information & Communications Technology Planning & Evaluation (IITP)-ITRC grant, funded by the Korea government (MSIT) (IITP-2025-RS-2024-00436398). Dr. Juno Kim's work was supported by an Australian Research Council (ARC) Discovery Project (DP230100303).

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A Chi-squared and p-values for Sensation Terms Between Reactive and Proactive Haptic Conditions

Sensation	χ^2	p-value
weak	7.2781	0.00698
soft	4.6833	0.03046
localized	4.6686	0.03072
pulling	4.9858	0.02556
pulsing	4.2979	0.03816
elastic	5.964	0.01460
smooth	12.318	0.00044
slippery	6.1885	0.01286
sticky	4.8394	0.02782

B Stacked Normalized Frequency of Terms by Haptic Pattens and Prediction Time

Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009