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Modulating Perceived Properties of Beverages Through Visuomotor Distortion in Virtual Reality

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概要: This study explores how pseudo-haptic feedback based on visuomotor distortion can alter the perception of weight, viscosity, and sweetness when drinking milk tea in virtual reality (VR). Using a time-warp method that visually slows down hand movements, we manipulated the perceived heaviness of a virtual cup while keeping its physical properties constant. Participants compared the properties of the beverages (weight, viscosity, and sweetness) with and without visuomotor distortion of the drinking motion. Results suggest that this visuomotor distortion significantly increases perceived weight and viscosity, but no apparent perceived sweetness change. These findings highlight the potential of visual-motor manipulation as a low-cost method for enhancing experiences of drinking beverages in VR.

キーワード： Virtual Reality, Pseudo-Haptics, Drinking Perception

1. Introduction

Overconsumption of sugar-sweetened beverages has been associated with obesity, diabetes, and other health complications [10]. Reducing excessive intake of sweet drinks is therefore an important public health goal.

Virtual Reality (VR) has been increasingly used in healthcare to support behavior change, pain management, and rehabilitation [11]. Immersive environments can modulate users' attention, perception, and motivation, making VR a promising platform for health-related interventions.

Among VR-based techniques, pseudo-haptics stands out as a low-cost and hardware-free method for creating force illusions by visually manipulating hand or object motion [12]. It can induce sensations such as heaviness, stiffness, and resistance, and has been widely studied in object manipulation tasks.

However, conventional pseudo-haptic research has primarily focused on mechanical properties, such as virtual object weight or friction, rather than exploring its effects on perception during actual consumption. In particular, its potential to influence multi-sensory food or beverage experience—such as perceived viscosity or sweetness—remains largely unexplored.

In this study, we investigate whether pseudo-haptic visual feedback can modulate how a drink is perceived during consumption in VR. By introducing a visual delay in hand motion (a time-warp effect), we examine how this manipulation affects the perceived physical and gustatory properties of the beverage.

2. Related Work

2.1 Pseudo-Haptic Weight Illusions via Tracking Delay

Pseudo-haptics is a software-based technique that creates the illusion of force or resistance by manipulating visual or motor cues. One common method is hand tracking delay, where the virtual hand lags behind the real hand, leading to a perceived increase in object weight. Taima et al. [1] were among the first to introduce a pseudo-haptic method that amplifies or reduces the visual displacement during lifting to influence perceived weight; they found that increasing visual movement (amplification factor $>$ 1) made the object feel lighter and reduced fatigue in repetitive lifting tasks. Hwang et al. [2] demonstrated that delaying the visual hand significantly enhanced perceived heaviness in a controller-free VR task. Kim et al. [3] and Hirao et al. [4] confirmed this effect in both hand tracking and controller-based conditions, showing that motion-based mismatches are effective in altering weight perception. Rietzler et al. [5] used subtle tracking offsets to simulate weight and resistance, while Moosavi et al. [6] compared various pseudo-haptic strategies and found that direct control–display (C/D) scaling most reliably simulated physical effort. These studies support the feasibility of inducing weight perception using visuomotor manipulation.

2.2 Effects of Physical Weight on Food and Taste Perception

Beyond virtual manipulation, physical studies have shown that the weight of real-world containers can alter how food and drink are perceived. Piqueras-Fiszman and Spence [7] found that heavier cups made beverages feel more filling, denser, and satiating, even when the drink remained the same. Michel et al. [8] showed that heavier cutlery improved taste evaluations, making food seem more favorable and enjoyable. Similarly, Tal et al. [9] reported that heavy serving dishes led participants to consume larger portions compared to lighter dishes. These findings suggest that physical weight can act as a cue for richness, fullness, and value. This study draws on this literature by applying a visual simulation of heaviness — via pseudo-haptic delay (i.e., visuomotor distortion) — to examine whether similar perceptual changes emerge when drinking from a virtually "heavier" cup.

3. Method

3.1 Overview

This study adopts a similar visual manipulation strategy to Taima et al. [1]. For clarity in this paper it is referred as *time-warp* and this study also investigates whether such technique can influence users' perception of a beverage's weight, viscosity, and sweetness during a drinking task in virtual reality (VR). These metrics selected because they represent distinct but interrelated aspects of the drinking experience. Weight was included to verify a well-established pseudo-haptic effect: that visual manipulation such as time-warp can increase the perceived weight of a virtual object.Viscosity and sweetness, in contrast, were selected to explore whether pseudo-haptic manipulations affect not only motor-related sensations but also subjective taste perceptions.

図 1: Manipulating taste perception through pseudo-haptics.

A within-subjects design was used with two conditions: Baseline (no pseudo-haptic effect) and Pseudo-Haptics (time-warp applied). In each condition, participants compared a standard reference cup to a visually identical comparison cup and evaluated perceptual differences after drinking.

3.2 System and Implementation

The experiment was developed in Unity and executed on a Meta Quest 3 using a built-in hand tracking system. To achieve pseudo-haptic feedback, we implemented a time-warp method, which introduces a visual delay between the user's real hand and its virtual representation. As shown in Fig. 2

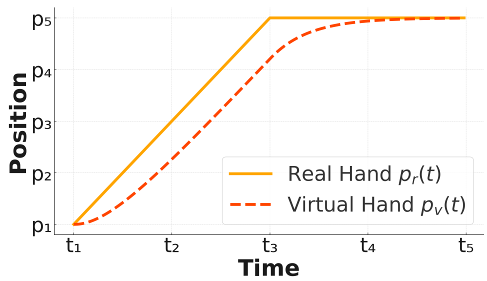

図 2: Time and position comparison between real and virtual hand during time-warp.

This manipulation was applied only in the Pseudo-Haptics condition. The time-warp technique is achieved through the following formula:

$$\mathbf{P}_v(t+\Delta t) = \mathbf{P}_v(t) + h \cdot \Delta t \cdot (\mathbf{P}_r(t) - \mathbf{P}_v(t)) \qquad (1)$$

where:

- $\mathbf{P}_v(t)$: the virtual hand position at time t
- $\mathbf{P}_r(t)$: the real hand position at time t
- Δt: the time step (frame duration)
- $h \in (0,1]$: the time-warp coefficient that controls the speed of interpolation

This formula has also been adopted in prior pseudo-haptics research [2][4][3], who demonstrated that such visually delayed feedback effectively alters users' perception of weight in VR environments.In addition to hand tracking, the cup used in the drinking task was physically tracked using a Meta Quest controller, which was rigidly attached to the outside of the cup. The cup weighed approximately 250 grams, while the controller added an additional 124 grams. This setup allowed accurate real-time tracking of the cup's movement in 3D space throughout the task. as shown in Figure. 3

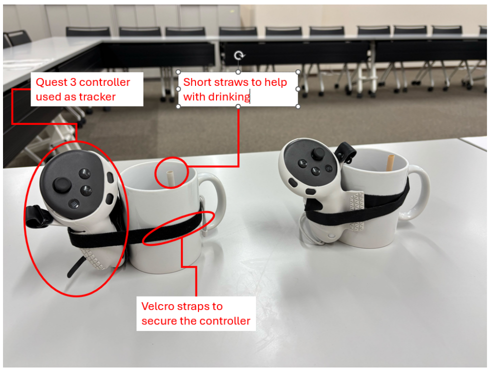

図 3: Cup tracking setup.

3.3 Procedure

participants wore the HMD and were shown a guided animation on the drinking motion first.Then the headset shows both the standard cup (reference, always without pseudo-haptics) and the comparison cup (either with or without pseudo-haptics, depending on the condition). They were instructed to take a sip from each, shown in Fig. 4.

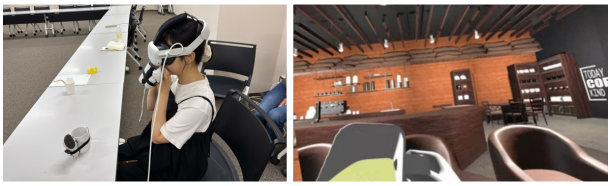

図 4: Observer's view and the participant's view.

After each trial, which includes a standard cup sip and a comparison cup sip, participants verbally reported their impressions of the comparison cup relative to the standard. Each participant completed six trials total (three under each condition), with the order of conditions randomized. Between trials, cups were refilled with 20ml of milk tea. At the start of each sip, participants were given water to rinse their mouths to prevent flavor carryover.

3.4 Evaluation Metrics

Participants reported three perceptual values after each trial: the aforementioned weight, viscosity and sweetness.A magnitude estimation method was used: the standard cup was defined as 100 for all metrics, and participants reported values for the comparison cup based on perceived difference (e.g., 120 = 20% heavier).

3.5 Participants

Total of 12 participants were recruited in this study. 7 are females and 5 are males. Participants' age ranges from 21 to 37 years, with the average age being 28.

4. Results

For each participant, the average rating across trials was computed separately for the Off and On conditions for all three perceptual metrics. A paired-samples t-test was then performed on these means.

Participants reported significantly higher perceived weight in the pseudo-haptic condition ($M = 112.36$, $SD = 11.64$) compared to the baseline ($M = 96.81$, SD $= 4.05$), $t(11) = -4.45$, $p = .001$ and $d = 1.24$. Similarly, viscosity ratings were significantly greater under the pseudo-haptic condition ($M = 108.19$, $SD = 6.29$) than under the baseline condition ($M = 99.03$, $SD = 4.58$), $t(11) = -3.87$, $p = .003$ and $d = 0.81$. In contrast, sweetness ratings showed no significant difference between the two conditions ($M = 102.64$ vs. 103.89), $t(11) = 0.59$, $p = .57$ and $d = -0.08$.

As shown in Figure 5, participants generally perceived the cup as heavier in the pseudo-haptic condition. This trend aligns with prior findings that delayed visual hand motion can increase perceived effort or resistance during lifting tasks.

A similar pattern was observed for viscosity: participants rated the drink as significantly thicker when time-warp was present. This suggests that pseudo-haptic feedback may induce a cross-modal illusion, where increased effort or motion lag is interpreted as greater fluid resistance. The magnitude and consistency of this effect across participants support the idea that pseudo-haptic delay not only influences object weight, but may also extend to the perception of liquid texture such as viscosity during consumption.

In contrast, sweetness ratings did not show a significant difference between conditions. This indicates that pseudo-haptic manipulation alone may not directly alter subjective taste perception, at least in the absence of corresponding changes in flavor or other multi-sensory cues.

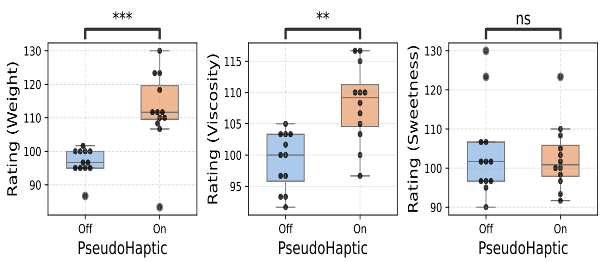

図 5: Swarm plots showing participant ratings for Weight, Viscosity, and Sweetness under two conditions: time-warp Off and On.

5. Discussion

These results demonstrate that visuomotor distortion, implemented as a time-warp, significantly influences participants' perceptual judgments during a VR drinking task. Specifically, participants rated the comparison cup as heavier and more viscous when pseudo-haptic feedback was applied, confirming the hypothesized effects on perceived weight and viscosity. Although sweetness ratings did not differ significantly between conditions, the overall pattern supports the idea that visual manipulations of hand motion can modulate the perception of physical properties during consumption.

The increase in perceived weight aligns with prior research showing that delaying visual hand tracking increases the subjective effort of lifting virtual objects [1, 2, 3, 4]. Our findings extend this effect from discrete lifting tasks to a continuous drinking motion, reinforcing the robustness of pseudo-haptic weight illusions. The observed effect on viscosity suggests a cross-modal transfer, in which slowed hand motion may be interpreted as increased liquid resistance — a novel finding that builds on existing work in object manipulation by extending it to consumable fluids in VR.

In contrast, the lack of a significant change in sweetness ratings suggests that pseudo-haptic manipulation alone may be insufficient to alter subjective taste perception, at least under the present conditions, indicating that pseudo-haptic cues may primarily influence motor and tactile properties rather than flavor attributes.

Several limitations must be acknowledged. While the current study includes data from 12 participants, larger samples are needed to assess the generalizability and robustness of these effects. Additionally, participants only consumed a single type of milk tea, and other beverage types (e.g., juice, water, thick shakes) may interact differently with visual delay cues.

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