Neck Goes VRrr: Reducing Rotation-Induced Virtual Reality Sickness through Neck Muscle Vibrations

Kun-Woo Song and Sang Ho Yoon, *Members, IEEE,*

***Abstract*—With the widespread use of virtual reality (VR), VR sickness is becoming a key barrier for users to have prolonged VR experience. To alleviate VR sickness, researchers focused on reducing sensory mismatch by aligning the visual information with other sensory cues during the VR experience. We present a wearable haptic interface enabling neck muscle vibration (NMV) with a multi-stimulus configuration. NMV's vibration on muscle spindles causes a haptic proprioceptive illusion of muscle stretch. Through NMV, we provide a simulated sensation of neck rotation to users without physically rotating the neck. For a left and right rotation on the yaw axis, we vibrated the sternocleidomastoid (SCM) muscles and splenius capitis (SC) muscles. Our lightweight interface vibrates different combinations of actuators on the left and right SCM and SC muscles to deliver multi-stimulus NMV in a desired illusory direction. We found that NMV sensation differs among individuals and is less effective during neck rotation. Based on these results, we developed a calibration and rendering process for NMV using real-time VR rotation information with varying viewpoint control. Our evaluation, which used a VR scene mimicking a common VR experience, showed that NMV effectively reduces rotation-induced VR sickness and improves the overall VR experience, such as presence.**

***Index Terms*—Haptics, Perception and psychophysics, Virtual reality, Human-computer interaction**

I. Introduction

As virtual reality (VR) technology becomes more widespread and advanced, the goal of a fully immersive experience is near fruition. However, the more a person is immersed in VR, the more likely that person may suffer from symptoms of VR sickness, including disorientation, drowsiness, eyestrain, and nausea [1]. These unpleasant sensations, in return, cause a decrease in user experience in VR [2], [3]. To tackle this problem, researchers have studied the causes and methods to reduce VR sickness.

Both hardware specifications and human factors induce VR sickness [4] but the neural mismatch model [5] is known as the main cause of VR sickness. This model shows how visual and vestibular conflict causes motion sickness. In particular, rotations in a VR environment elicit more severe VR sickness [6] due to back-and-forth and sawtooth-like eye reflex like optokinetic nystagmus (OKN) when focusing on moving objects [7], [8]. To this end, researchers have focused on developing methods to reduce the sensory mismatch. For example, previous works reduced the mismatch by adding sensory details [9], [10]. While some stimulated the vestibular system directly to cause illusory feelings of movement [11]–[13].

In this paper, we employ neck muscle vibration (NMV) to simulate the sensation of neck rotation and reduce rotation-induced VR sickness. The direct vibration on the muscle can simulate the sensation of the muscle lengthening without physically moving it [14]. A similar approach could be employed on the neck where a person could feel neck rotations with the vibration on the neck muscles [15], [16]. Although NMV has been used in medical applications, it has not been extensively exploited for VR applications. To this end, Kooijman et al. recently showed NMV's illusory effects on vection, presence, and, to an extent, VR sickness [17]. However, we further developed and proposed novel NMV control parameters, target muscle configuration, and delivery method with a more rigorous evaluation environment of VR sickness to expand NMV's application from a conventional proprioceptive illusion to a new interactive technology for VR.

It is also possible that the vibration from NMV distracts users and harms immersion to reduce VR sickness. To ensure that NMV reduces VR sickness by reducing sensory mismatch, we measured NMV's effect on presence. VR sickness and presence are inversely correlated with several factors such as sensory mismatch, vection, and navigation control affecting both [18]. Out of these factors, we note how a reduction of sensory mismatch and an increase in navigation control reduce VR sickness while increasing presence [18]. Following the recognized VR sickness-presence relationship, we evaluated NMV on 3 common VR rotation methods with varying levels of control: passive viewing, active viewing with a controller, and active viewing with head rotation.

In this paper, we develop a wearable haptic interface on the neck to deliver NMV with ease. Using real-time VR rotation information from the VR scene, our interface vibrates designated locations with selected durations on a 4-motor multi-stimulus configuration. This simulates rotation sensation on the yaw axis without physical neck rotations. With the proposed interface, we explored how the illusory rotation is affected by different neck muscle and vibration conditions. Through the results of the exploratory study, we construct a real-time NMV rendering approach for applying NMV to

Kun-Woo Song and Sang Ho Yoon are with the Human-Centered Interactive Technologies Lab, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea (email: kwsong0725@kaist.ac.kr, sangho@kaist.ac.kr).

Manuscript received April 19, 2021; revised August 16, 2021.

0000–0000/00$00.00 © 2021 IEEE

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3535942

the previously mentioned three rotation methods. We used the proposed rendering approach in our evaluation using three different VR rotation methods. To evaluate NMV, we measured VR sickness and presence through the sickness simulator questionnaire (SSQ) [19] and Slater-Usoh-Steed (SUS) questionnaire [20]. We found that NMV significantly reduces rotation-induced VR sickness while increasing presence. Our post-interview also indicated that most users preferred NMV in our evaluation VR scene, which featured several rotations.

Our contribution can be summarized as the following:

- A novel wearable haptic interface enabling proprioceptive illusion of rotation sensation using multi-stimulus NMV;
- An exploration to validate the perception change caused by multi-stimulus NMV with varying vibration duration and neck rotation-related conditions;
- A formulation of the calibration and haptic rendering process for multi-stimulus NMV using real-time VR rotation information;
- An evaluation of NMV's effect on rotation-induced VR sickness in a VR scene with varying viewpoint controls.

II. Related Works

A. Rotation-Induced VR Sickness

VR sickness, also known as cybersickness, is the unpleasant physical discomfort that arises from exposure to VR. Common symptoms include nausea, headache, fatigue, and eye strain [21]. Due to these symptoms, VR sickness deteriorates user experience [2], attention, and task performance [3]. These adverse effects prevent users from utilizing VR interface for medical rehabilitation [22] and entertainment [23]. Moreover, the occurrence conditions and effects of VR sickness differ among users and could cause disparity [24].

These consequences of VR sickness motivated researchers to search for causes of VR sickness, which include display field of view [25], latency [26], and immersion [1]. Researchers have also found human factors such as age [27], gender [28], and prior experience [29]. As evident from the wide variety of factors, there is no definite single cause of VR sickness. However, the neural mismatch model [5], which suggests the disagreement between visual information and other sensory cues to be the cause, is widely accepted as a comprehensive explanation for non-human factors. In particular, VR sickness is caused by a mismatch between the vision and the vestibular [30].

Out of the possible motions in VR, rotations induce more severe VR sickness [6] because of the high frequency of OKN [7], [8]. Kovalev et al. found that with greater rotation intensity, OKN's performance decreased and enhanced the illusion of self-motion (vection) [31].

Vection with sensory mismatch increases VR sickness [32]. However, when sensory mismatch is reduced, vection causes an opposite effect and reduces VR sickness [33]. This phenomenon is also characterized by an increase in presence [34]. Hence, if VR sickness is reduced and presence is increased, sensory mismatch must have been reduced. Presence is the sense of "being there" and has been used as a standard for high-quality VR experience [35]. More recent research on presence updates this definition to consist of two dimensions: "place illusion", which encompasses the traditional definition, and "plausibility", which is the sense of a virtual event happening [36]. In this paper, we refer to the place illusion dimension of presence when referring to presence.

Presence and VR sickness have a negative relationship with several factors affecting the relationship, such as sensory mismatch and level of user control [37], [38]. In our work, we propose a method of reducing sensory mismatch by applying proprioceptive haptic feedback to rotation-induced VR sickness. To this end, we focus on VR-specific rotation cases with distinctive viewpoint controls: passive viewing, active viewing with a controller, and active viewing with head rotation. We also measured presence to confirm the effectiveness of proprioceptive feedback in reducing sensory mismatch for rotation-induced VR sickness.

B. Reducing VR Sickness

Previous works reduced sensory mismatch by either diminishing visual cues to be less overwhelming or providing additional sensory information. Researchers reduced VR sickness through visual techniques such as cutout transitions [39], [40], field of view control [41], [42], and use of peripheral vision [43], [44]. While relatively simple to implement, in the end, visual approaches remove details from the VR scene, which is not favorable for a fully immersive experience [45]. Other approaches reduce VR sickness by providing additional sensory information across various modalities such as auditory [46], olfactory [9], and tactile senses.

Out of these, the tactile approaches through haptic feedback showed promising results through airflow [47]–[49], vibrotactile [10], [50]–[52], and electrical stimulation [11]–[13], [53]. However, many of these haptic feedbacks focus on specific VR scenarios such as biking [49] or walking [10].

To provide a sense of movement for broader VR scenarios, stimulating the vestibular system with haptic feedback is more effective. Here, the vestibular system in the inner ear provides a sense of balance and orientation. Galvanic vestibular stimulation (GVS) proved effective in reducing VR sickness for a cockpit simulator [13] and a VR roller coaster simulation [12]. However, GVS has unintended consequences such as discomfort and headaches for healthy individuals [54]. In light of this, others have proposed noisy bone-conductive vibration to stimulate the vestibular system [51]. However, this method lacks directional proprioceptive cues and achieves reduced VR sickness by "reducing vestibular reliability".

Like the vestibular system, the neck also plays an important role in human proprioception [55], [56]. Previous work applied transcutaneous electrical nerve stimulation behind the neck to reduce simulator sickness from a motion-based flight simulator [11]. On the other hand, Gálvez-García et al. employed galvanic cutaneous stimulation to decrease simulator sickness [53]. Still, potential safety risks exist when using the electrical stimulation approach. In this work, we employ real-time proprioceptive haptic feedback on the neck muscles with a targeted direction and relative magnitude. As far as we know, there has not been a real-time interface using haptic feedback on the neck muscles to reduce rotation-induced VR sickness.

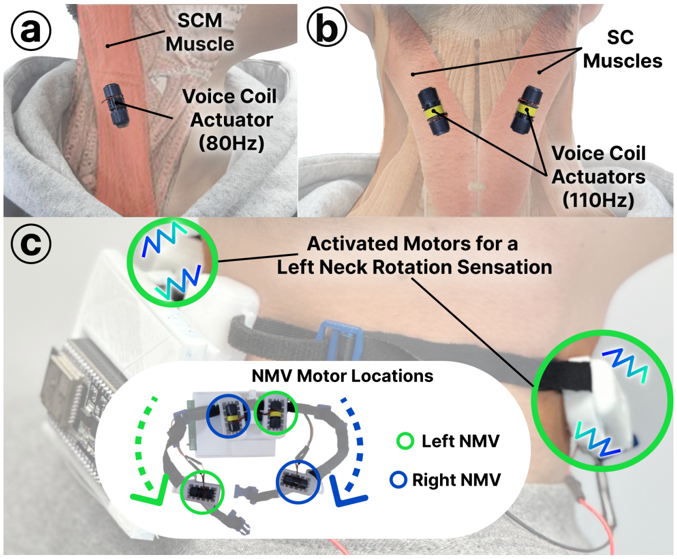

Fig. 1. (a) Location of the sternocleidomastoid (SCM) muscle on the neck and the placement of the motor. The SCM protrudes when the neck is rotated. (b) Location of splenius capitis (SC) and the placement of the motors. (c) NMV motor locations for left and right NMV. For instance, users would feel a leftward neck rotation sensation when the green-circled motors vibrate (left NMV).

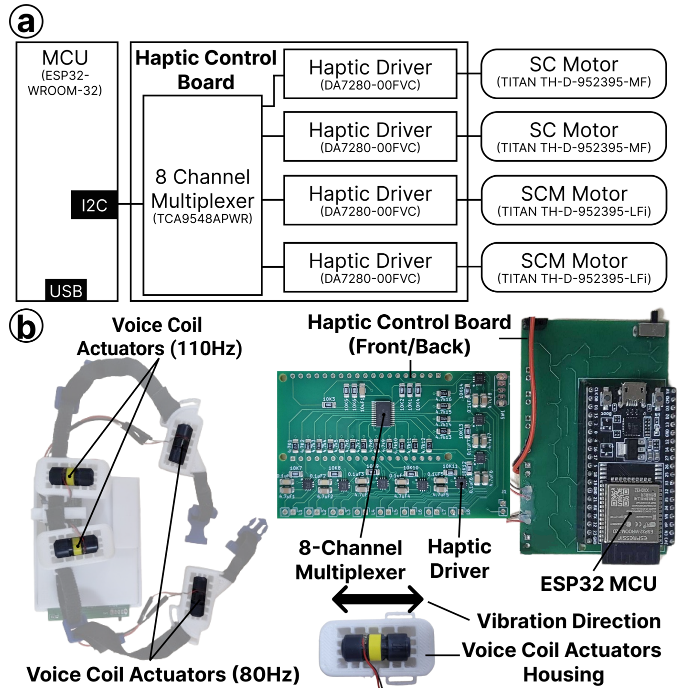

Fig. 2. (a) Haptic interface system diagram. (b) Components of our haptic interface. The 4 voice coil actuators vibrate in the longitudinal direction. We used TPU-based housing to dampen vibration while preventing skin irritation. The haptic control board consists of an ESP32 microcontroller, an 8-channel multiplexer, and 8 haptic drivers.

C. Neck Muscle Vibration

When the muscle is stimulated with vibration, primary endings in muscle spindles, which detect muscle stretch, are activated and individuals perceive the muscle lengthening [14]. This illusory effect has been applied to arms [57], [58] and legs [59], [60] to give sensations of movement or extensions. Unlike vibrations on the arm or leg, applying vibration to the neck influences the sense of orientation and visual motion [15], [16], [55]. By applying NMV to various neck muscles with different conditions, researchers have found how NMV provokes neck rotation sensations [55], [61]–[63], posture sway [64]–[66], and visual illusions [16], [67], [68].

Meanwhile, tendon vibration on the arm has been used by researchers for its illusory effects in VR. The illusion of arm movement matched with VR visual information helped employ more effective vision-induced kinesthetic illusions [69], pseudo-haptics [70], and rehabilitation [71]. Considering tendon vibration's wide variety of applications, it is worthwhile to explore the effect of NMV on users' vestibular proprioception.

Neck rotation sensations and posture sway induced by NMV effectively provide vestibular cues. By aligning vestibular cues with visual counterparts in VR, NMV provides a successful way to reduce sensory mismatch and VR sickness. Compared to other haptic methods that reduce VR sickness, NMV is more lightweight and less risky.

Kooijman et al. applied NMV by modulating vibration frequency for a VR plane simulator [17]. The paper explored how NMV strengthens illusory self-motion. However, they could not observe a clear relationship between NMV's illusion and VR sickness because of a "limited number of participants" who felt VR sickness due to less-intensive rotation inducement study conditions.

In this paper, we employ NMV through a wearable haptic interface with a multi-stimulus configuration that can be adapted to VR-specific rotations. We investigated NMV as a proprioceptive haptic feedback cue and its effectiveness in reducing sensory mismatch and, consequently, VR sickness. To examine the effects of NMV's proprioceptive illusion on VR sickness, we evaluated in a VR scene involving several rotations where users could rotate the camera, simulating typical VR usage scenarios.

III. NMV Haptic Interface

In this section, we describe the NMV haptic interface design and its components.

We apply NMV to reduce sensory mismatch for VR rotations on the yaw axis. To deliver this sensation, our system applies NMV to the sternocleidomastoid (SCM) muscle on the side of our neck (Figure 1a) and splenius capitis (SC) muscle behind our neck (Figure 1b). When physically rotating the neck, SCM and SC muscles are lengthened [72]. NMV on these muscles creates an illusory effect of rotation [61], [63], [66]. For a perceived left rotation, which we define as left NMV, the right SCM and left SC muscles are stimulated, and for a right rotation, defined as right NMV, the left SCM and right SC muscles are stimulated (Figure 1c).

Physical Interface Design Figure 2 illustrates the overall design of the proposed wearable NMV haptic interface. Our interface is an easy-to-equip, lightweight wearable worn around the neck (98 g). The haptic interface consists of 4 voice coil actuators (TH-D-952395-LFi, TH-D-952395-MF, TITAN Haptics) and a customized haptic control board, a microcontroller (ESP32-WROOM-32, Espressif), 3D printed housings (TPU 95A) for the motors and board, and straps (polyester, velcro) with 3D printed buckles (PLA) to hold the housings together.

The two motors (TITAN TH-D-952395-MF, TITAN Haptics) on the SC muscles are driven with 110 Hz [73]. The other two motors (TITAN TH-D-952395-LFi, TITAN Haptics) on the SCM are driven with 80 Hz [65], [66]. We chose these frequencies according to previous studies on NMV on these muscles to create a natural rotation sensation illusion [65], [66], [73]. Both motor models have a dimension of 9.5 x 9.5 x 23.06 mm. We used different motor models for the two muscle locations to deliver the strongest force for the given frequencies [74]. The motors vibrate in the longitudinal direction. To maximize motor contact area, we placed the motors so that the vibrations were parallel to the midpoint of the muscle for both muscles (Figure 1a,b). We measured the peak-to-peak amplitude of the two motors using an accelometer (ADXL335, Analog Devices), resulting in 1.2 G for the SCM motor and 0.8 G for the SC motor.

The haptic control board consists of a multiplexer (TCA9548APWR, Texas Instrument) and 8 haptic drivers (DA7280-00FVC, Dialogue) (Figure 2). It connects to the MCU (LOLIN D32 V1.0.0 ESP-32 WiFi-Bluetooth Combo) and can receive power from an external source. When activated for NMV, motors on the SCM consume 22∼24 mA and those on SC consume 25∼27 mA. We connected the MCU with our Unity 3D code through a USB cable, which had an end-to-end latency less than 4 ms.

The 3D printed housings for the motor were printed with a flexible material. By using TPU, the housing dampens vibrations from the motors so that it does not affect other muscles and provides less irritation on the user's neck. We also added slits inside the motor housing to dampen vibration and rounded edges for less irritation (Figure 2). To measure how much the housing dampens the vibration, we measured the peak-to-peak amplitude after attaching an accelerometer outside the motor housing for TPU and PLA. The motor housing printed with TPU resulted in an amplitude of 0.4 G (SCM) and 0.3 G (SC), while the PLA version resulted in an amplitude of 0.7 G (SCM) and 0.4 G (SC). The board housing also was printed with a flexible material as it is in direct contact with SC motor housings.

These housings are connected with thin, sturdy straps (polyester, velcro). The straps are adjustable using velcro and a 3D printed tri-glide buckle. A 3D printed side release buckle connects the SCM motor housings to equip the interface easily.

However, to further implement a real-time system, we lack information on how long NMV should be applied and when it should be applied. We shed light on this detail in our exploratory study.

Equipping the Interface To equip the interface, we first identified the location of the SCM and SC muscles. To find the SCM muscle, we instructed participants to rotate their necks to the side to find the SCM muscle tightening. For most participants, the SCM muscle was visible after rotation, but for those whose SCM muscle did not show visibly, we found the muscle by touch. The SC motors were placed on the tensed SC muscle when participants were asked to look down. After placing the motor housings in their respective locations, we tightened the straps of the interface until the participants reported discomfort. We then loosened the strap a bit to relieve the discomfort.

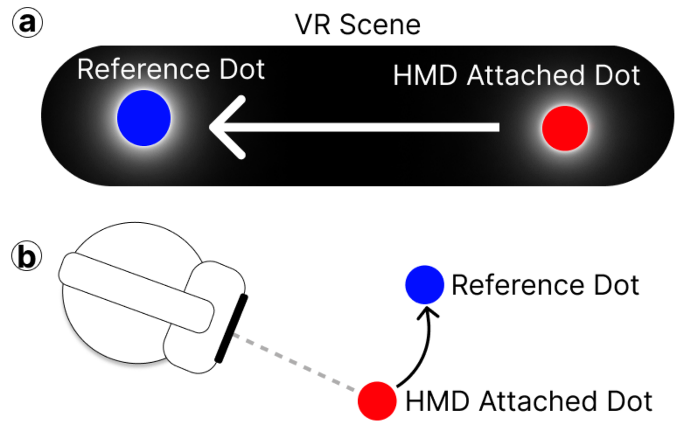

Fig. 3. The overall exploratory study setup. (a) User view of the VR scene simulating a dark room, and (b) top-down view of the exploratory study. Participant rotates the neck to align the HMD attached dot with the reference dot.

We measured the preload force of the motors on the neck for 10 people when equipping the interface using a pressure sensor (S15-4.5N, SingleTact). The SCM motors pressed on the neck with a pressure range of 1.0∼1.6 N and the SC motors pressed on the neck with a pressure range of 1.0∼1.2 N.

IV. Exploratory Study

We carried out an exploratory study to find the proper parameters and settings to employ real-time NMV in VR. NMV has been used in the medical field for rehabilitation and to observe proprioceptive differences between asymptomatic individuals and those with injuries [75]. In these works, researchers applied NMV for longer periods and with fixed neck postures. As such, we lack information on how much vibration should be applied on dynamic neck postures for shorter and sporadic instances, which is common in VR environments.

Our two-part exploratory study sheds light on formulating our algorithm to fit NMV for reducing rotation-induced VR sickness. First, we examined how short-duration NMV changes perceived neck rotation. In the second part, we investigated the effects of applied NMV during neck rotation. In this study, we set the participant's neutral neck position as 0° and considered right rotation as the positive direction. We recruited 9 participants (mean age: 25.1, SD: 1.69, 5 male, 4 female). No participants had any history of neck injury.

To study the effects of NMV, previous literature used a dark room environment to eliminate unnecessary visual information [16]. In this study, we used a VR headset (Meta Quest 3) to place the users in a dark room to simulate a study environment similar to that of previous work.

To provide participants with information on their orientation, we placed two dots in the VR scene (Figure 3a). We attached a 5 cm diameter red dot in front of the participant's

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3535942

view to follow the participant's head orientation. We placed a single 6 cm diameter blue dot as reference markers to denote different neck angles. Both dots were placed 1.5 m away from the participant in the virtual environment. By instructing participants to align the red dot with the blue dot, participants rotated their necks to target angles (Figure 3b). When we applied NMV, these two dots were disabled to remove all visual cues. Before beginning each part, we calibrated the 0° blue dot with the participant's subjective forward direction.

To minimize rotation of body parts other than the neck, participants sat in a static chair and were instructed to rotate only their necks while keeping their torsos still.

A. Part 1: Stationary NMV

First, we explored the effects of NMV with short durations. Although long-duration NMV showed noticeable deviation in human proprioception [63], the vibration duration typically lasts minutes. However, the long-duration requirement is not suitable for VR where primary means of interactions only span for 1∼2 s. Thus, we investigated short durations from 0.5 s to 2.0 s, varying the durations by 0.5 s. We expected the sensation of rotation to increase as duration increases. We applied NMV with participants fixing their necks to 0°. We always guided users to start at 0° because applying NMV to contracted muscles for short durations does not yield significant differences for deviation in rotation sensation [63].

Procedure Before starting the experiment, participants received instructions and answered a pre-study questionnaire, including the history of previous neck-related injuries. After the instructions, we equipped participants with the haptic interface and the VR HMD.

Participants were given one of 8 random combinations from 2 NMV directions (left and right) and 4 vibration durations (0.5 s, 1.0 s, 1.5 s, 2.0 s). After the vibration ended, we instructed participants to rotate their necks to the position induced by the given vibration. If the participants felt nothing, they were instructed to stay still. Then, we recorded the resulting neck rotation angle. To accurately measure the rotations perceived by participants, we calibrated the HMD so that the participant's subjective forward matches our system's 0° (blue reference dot). We used this calibrated 0° to measure the perceived difference after participants were induced with NMV. We conducted 4 blocks for each participant with a 1-minute break in between and removed the first block as a practice. This part of the study took approximately 20 minutes. For the combination order for each participant, refer to Appendix A.

Results Through the vibration of the right SCM and left SC, we intended a left rotation sensation and vice versa. However, few participants felt the opposite sensation from our intended rotation. After counting the recorded angles, if more than 80% of the responses were the opposite of our intended direction, we determined their responses reversed. Out of the remaining 9 participants, 5 felt the neck moving in the opposite direction (P1, P2, P3, P4, P7). Albeit with a smaller proportion, a similar result has happened with Taylor et al.'s work where 3 out of 9 participants reported an opposite direction [62]. While the reasoning behind the intended NMV direction is sound, the individual differences and complexity of neck muscle anatomy make determining which muscles were activated by NMV difficult [62]. In our evaluation, we took extra care of vibrator placement and equipped the interface to ensure it didn't move too much. For the participants who felt the opposite direction, we multiplied their results by -1. By doing so, we compared the absolute magnitude of NMV perception, for a more accurate statistical analysis.

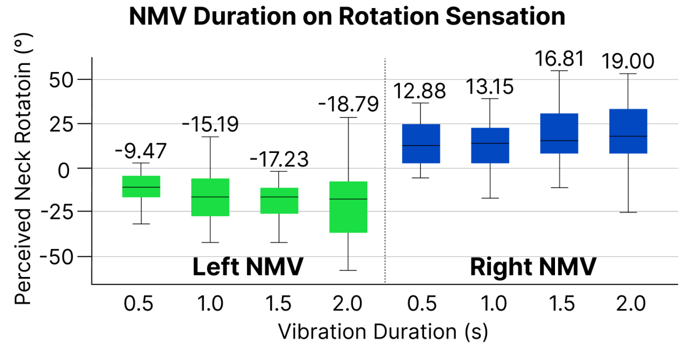

Fig. 4. Boxplots of average perceived illusory neck rotation. The numbers above each boxplot show the median. Outliers were removed to show only the relevant data. Positive values indicate right rotation and negative indicate left.

TABLE I
AVERAGE PERCEIVED ILLUSORY NECK ROTATION FOR EACH PARTICIPANT. PARTICIPANTS WHO FELT THE OPPOSITE ROTATION ARE DENOTED WITH A ∗. BOLDED NUMBERS INDICATE RESULTS SHOWING A STEADY INCREASE IN PERCEIVED ROTATION AS DURATION INCREASES.

	Perceived Neck Rotation (°)							
Direction	Left NMV				Right NMV			
Duration	0.5s	1.0s	1.5s	2.0s	0.5s	1.0s	1.5s	2.0s
P1*	**-9.1**	**-13.8**	**-15.5**	**-14.8**	14.3	13.3	12.9	18.9
P2*	-4.2	-2.8	-6.1	-7.4	**4.1**	**2.2**	**9.0**	**11.6**
P3*	3.2	-22.4	-13.8	-20.8	30.9	-5.3	10.8	14.8
P4*	-12.5	-20.9	-24.1	-34.6	20.5	20.1	31.5	44.0
P5	-11.4	-4.7	-3.8	-5.4	16.0	16.2	22.5	19.0
P6	-12.2	-20.8	-12.0	-18.6	-0.1	10.6	0.2	-0.9
P7*	-22.8	-30.7	-42.3	-47.0	25.4	36.2	41.1	48.0
P8	**-4.3**	**-9.7**	**-14.5**	**-15.1**	4.8	9.1	11.1	8.1
P9	-5.6	-10.9	-22.9	-5.4	-0.1	16.0	10.3	7.5

The perceived illusory neck rotation demonstrates the effect of NMV direction (Figure 4). To understand the effects of durations and individual differences, we analyzed the data for left NMV and right NMV separately. A Kruskal-Wallis test on participants for left and right NMV showed that participants had a significant difference (left NMV: $p < 0.001$, right NMV: $p < 0.001$). However, for the duration, there was no significant difference, which was unexpected considering how the illusory rotation magnitude progressively increased as duration increased (Figure 4). The full statistics can be found in Appendix A.

Hence, we examined the average perceived illusory neck rotation for each duration for each participant (Table I). Duration's effect differed per participant. Some participants had a steady increase in magnitude as duration increased (P1, P2, P8). However, some participants felt similar or even less illusory neck rotations for greater durations (P4, P5). The absolute magnitude also showed large individual bias. For example, P4 and P7 showed high sensitivity to NMV for illusory neck rotations as large as 40°, whereas P2 and P8 reported neck rotation of barely over 10°.

Using the Kruskal-Wallis test result and the average values, we conclude individual differences in NMV sensitivity exist. We reflected these results in our real-time NMV rendering by adding a calibration stage to formulate an NMV profile for each user, which includes NMV direction and sensitivity.

B. Part 2: NMV during Neck Rotation

Next, we observed the effects of NMV while the neck muscle strain changes continuously. For various VR interaction purposes, users frequently look around in VR scenes by rotating their necks. This tells us that we need to confirm the effect of NMV when the neck is in rotation motion. As far as we know, NMV during neck rotation has not been studied.

In this part of the study, we observed NMV applied during left and right rotations. When the neck was halfway through the rotation, we either applied 1.0 s of left NMV, 1.0 s of right NMV, or no vibration and recorded the angle after the participant felt like they arrived at the target angle. We expected the different NMVs to alter participants' sense of proprioception and cause significant differences between the recorded angles.

Procedure After a 5-minute break from the previous part, participants were given a short explanation of the experiment. Then, we equipped participants with the NMV interface and the VR HMD.

We used the same dots to turn the participant's neck to the starting angle after modifying the reference dots' location. We animated the blue dot to rotate around the participant 60° to the left and right with a speed of $30°/s$. We chose $30°/s$ so that NMV will end before participants finish rotating their necks. With the HMD attached dot enabled, participants followed the reference animation to practice the speed and destination of the neck rotation by aligning the dots together. We provided 6 attempts for the training.

After training, we instructed the participants to return to 0° using the reference dots and disabled both the reference and head-attached dots. When the participants started rotation, we applied NMV for 1.0 s when the participant passed the 30° point. We then recorded the resulting angle.

With either left or right rotation and 3 possible NMV directions (none, left, right), participants carried out 6 possible combinations in random order. We conducted 4 blocks for each participant with a 1-minute break in between and removed the first block as a practice. This part of the study took approximately 30 minutes. For the combination order for each participant, refer to Appendix B.

Results Like the first part, we reversed the NMV direction tag in the data for participants who felt an opposite rotation (P1, P2, P3, P4, P7). Figure 5 shows boxplots for deviation from the target angle (60°). We assumed that the extra rotation perception would alter participants' senses of the trained 60°. For instance, in the case of left rotation, left NMV would have yielded less rotation, while right NMV would have made participants rotate their necks more.

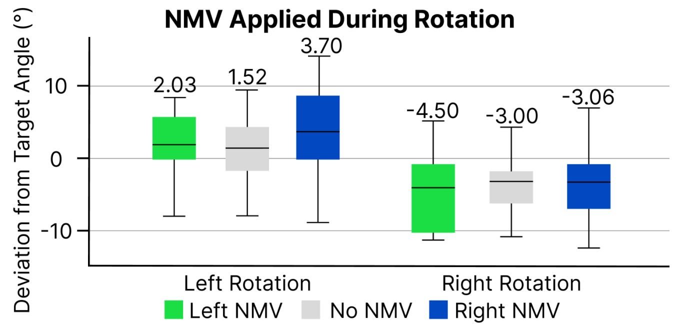

Fig. 5. Boxplots of deviation from target angle of 60°. The number above each boxplot shows the median. Outliers were removed to show only the relevant data.

For no vibration, participants showed a median difference of 1.52° for left rotation and -3.00° for right rotation for no vibration. However, for left rotation, participants moved a median of 2.03° and 3.70° less than the targeted 60° for left and right NMV. Likewise, for right rotation participants moved less with a median of 4.50° for left NMV and 3.06° for right NMV. A Kruskal-Wallis test showed that applying left or right NMV for corresponding rotation directions had no significant difference from the case without NMV. The full statistics can be found in Appendix B. From the results, we conclude that NMV is not effective if applied during neck rotation. We reflect the result in our real-time NMV rendering by initiating NMV as soon as neck rotation begins to minimize the time NMV becomes ineffective.

V. Real-Time NMV for VR Rotations

From the exploratory study, we have found that participants: 1) may feel the opposite illusory rotation from the intended NMV, 2) exhibit distinctive sensitivities to NMV, and 3) show no effect of NMV when the neck is physically rotating. Based on these findings, we devised a calibration process and NMV rendering approach. First, we obtain the user's direction and sensitivity for NMV to compensate for individual differences. Second, to avoid cases of NMV during rotation, we apply NMV as soon as the camera rotation begins in VR.

A. Calibration for NMV

Through calibration, we formulate each user's NMV profile, which contains the user's sensation direction and sensitivity level for NMV. Based on the exploratory study results and typical human neck rotation range and duration [76], [77], we created two levels of sensitivity where *Low* sensitivity contains two NMV durations (0.5 s and 1.5 s), and *High* sensitivity contains three NMV durations (0.5 s, 1.0 s, and 1.5 s).

To formulate the NMV profile, we shortened and modified the first part of the exploratory study. Since we only use 3 possible durations for 2 directions, we apply 3 sets of 6 NMV configurations (2 directions $\times$ 3 NMV durations) to users in a random order. We then record the angle of the illusory neck rotation users felt. Like our results analysis in the previous section, we count the number of reversed illusory neck rotations to determine if the user feels NMV in the

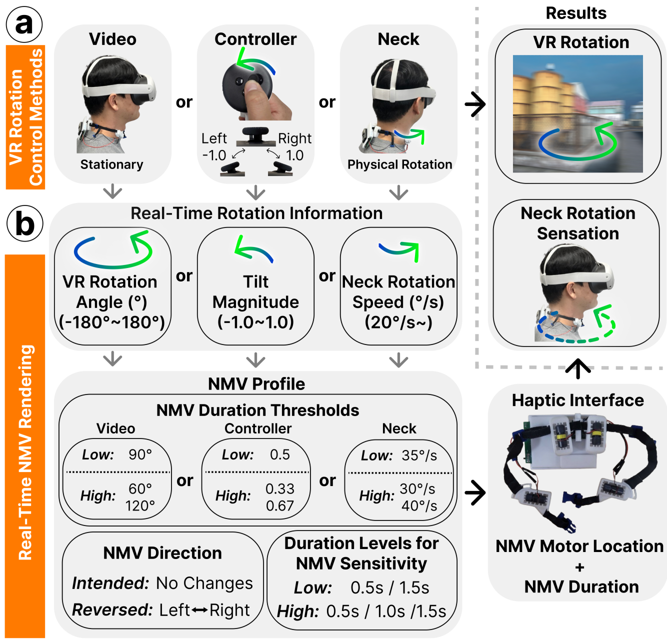

Fig. 6. (a) Users experience VR rotations through passive viewing in *Video*, direct control with a joystick in *Controller*, or physically rotating their heads in *Neck*. (b) To render real-time NMV, *Video* uses camera rotation angles from the VR scene, *Controller* uses tilt angles from the joystick, and *Neck* uses neck rotation speed. Using the calibrated NMV profile, we render NMV at the designated motor location and duration.

opposite direction. We also compare the average perceived angles of each 6 configurations to determine whether the user does feel a difference between the 3 NMV durations with a 0.5 s difference.

After we obtain the user's NMV profile, we send the NMV motor location and duration that fits the profile. If the user's NMV direction is opposite, we vibrate the opposite SCM and SC motors instead of the intended motors.

B. NMV Rendering Approach

We applied NMV to three camera rotation methods (Figure 6a) where we varied how users controlled rotation in VR: *Video*, *Controller*, and *Neck*. When rotation in the VR scene occurs, we obtain real-time rotation information and parse that information according to the user's NMV profile. Here, we vibrate different sets of motors with designated duration according to the NMV profile (Figure 6b). We use thresholds as a boundary condition to determine which NMV duration is rendered. For *Low* sensitivity, one threshold value determines either 0.5 s or 1.5 s NMV is rendered. For *High* sensitivity, the two threshold values determine whether 0.5 s, 1.0 s, or 1.5 s NMV is rendered.

Video The *Video* method refers to the passive viewing approach, where the user has no control over camera rotations. To prevent other biases from the user, we constrained users to look forward without physical neck rotations.

Since we know how much the camera will rotate beforehand, applying NMV for video is straightforward. Depending on the VR rotation angle, we applied different NMV durations. For *low sensitivity* profile, we used 90° as a threshold value to trigger 0.5 s or 1.5 s vibrations. For *high sensitivity*, we used 60° and 120° as threshold values to trigger 0.5 s, 1.0 s, or 1.5 s accordingly.

Controller The *Controller* method is an active viewing approach where users control the rotation with the joystick on the controllers. We only considered cases where users' necks stay stationary. Unlike *Video*, which already has predetermined rotations, the active viewing cannot have predetermined information about when users will rotate in the VR scene. Therefore, we employed the real-time information available at the very beginning of a rotation with an initial buffer of 200 ms to predict the user's intended rotation amount.

Meta Quest 3's controller API provides a float value between -1.0 and 1.0 for the joystick input with a 50 Hz frame rate. The input sign determines the direction (negative for left and positive for right), while the absolute value refers to the joystick's tilt magnitude used for VR rotations.

We assumed that the greater the tilt magnitude, the greater the user's intended rotation. We categorized tilt magnitude according to threshold values, which are 0.5 for *Low* sensitivity and 0.33 and 0.67 for *High* sensitivity. We saved these categorized values in a sliding window (10 frames, 200 ms) and found the most occurring category. If it occurred for more than 30% of the window, we converted the category to the adequate NMV duration, which was 0.5 s / 1.5 s or 0.5 s / 1.0 s / 1.5 s, depending on the sensitivity level.

Neck The *Neck* method is an active viewing approach with the greatest control freedom. The user controls the camera by rotating their neck. In most VR applications, the neck rotation matches the camera rotation with no rotation amplification. However, users can achieve a larger rotation without minimal physical movement with rotation amplification [78]. We considered VR experiences with rotation amplification for the *Neck* method as it causes sensory mismatch.

From our exploratory study, we found that there was no significant effect of NMV during neck rotation. Hence, NMV must be applied before or after the neck rotation motion is completed to be effective. However, applying NMV after would cause the vibration to continue even when there is no camera rotation. Since this would increase sensory mismatch, we initiate the vibration as soon as the neck rotation starts.

We predicted the user's intended rotation amount using the initial angular speed of head rotation. We assumed that the faster the speed, the bigger the resulting head rotation. We obtained angle values on the yaw axis from the HMD at 50 Hz. We used the average speed of a 10-frame sliding window to minimize hardware noise. However, users tended to make small movements and generated noise because of the HMD weight. To compensate for this, we considered only rotations with angular speed greater than $20°/s$. The thresholds for *Neck* are 35° for *Low* sensitivity and $30°/s$ and $40°/s$ for *High* sensitivity. We applied NMV for 0.5 s/1.5 s or 0.5 s/1.0 s/1.5 s, depending on the sensitivity level.

VI. VR Sickness & Presence Evaluation

In this section, we evaluated the performance of the proposed real-time NMV system on rotation-induced VR sickness

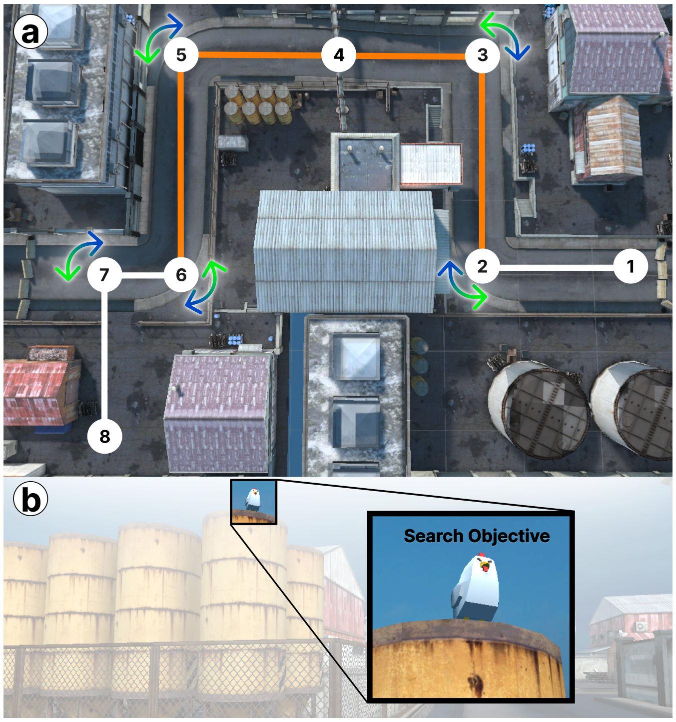

Fig. 7. (a) The path participants went through. Participants could only control rotation. Forward and backward movement was controlled automatically by the system. Arrows indicate corners where the camera view rotated for *Video* and *Neck*. Paths highlighted in orange are path segments with rotations for the *Video* method. (b) Participants had to find a chicken figure using different control methods.

and presence. Through the exploratory study, we confirmed that NMV evokes proprioceptive illusions of rotation sensations on the neck without physically rotating the neck. To examine the effect of NMV on VR sickness, we referred to previous studies exploring VR sickness reduction through lowering sensory mismatch [10], [12]. Using our real-time NMV system, we expected to lower sensory mismatch, which in turn reduces VR sickness. To confirm decreased VR sickness through lowered sensory mismatch, we also measured presence, which we expected to increase according to the negative relationship between VR sickness and presence [18].

A. Evaluation Design

Participants We recruited 20 new participants (mean age: 26.1, SD: 3.48; 11 male, 9 female). None of them had any history of vestibular or neck injury or diseases. Of the participants, 2 had no VR experience with 5 having frequent use at least once a month. After calibration, we found that 6 participants felt the opposite direction, and 10 participants had *Low* sensitivity.

VR Scene The scene consisted of a long winding road (Figure 7a). To keep the effect of linear vection constant, participants only had control over camera rotation, and the camera moved along the road automatically. The participants started at point 1 (Figure 7a) and moved along the path until point 8. After reaching point 8, participants moved back along the same path back to point 1. At point 4, participants stopped for 3 seconds both on the way forward and back and 5 seconds on point 8.

Participants used one of three camera control methods: *Video*, *Controller*, and *Neck*. For *Video*, users looked forward and could not control the camera rotation at all. For each corner, the camera automatically rotated to the path direction, and longer paths (Figure 7a) contained random rotations ($70°, 80°, 130°$, or $140°$). The camera rotated at a rate of $100°/s$. For *Controllers*, users could control the camera rotation through a controller, but like *Video*, they kept their heads forward. The camera rotated at a rate of 120°/s per tilt amount, which ranged between -1.0~1.0. Lastly, for *Neck*, users could control the camera by turning their necks. However, to ensure that users could explore the whole scene without moving their torso, the angle was linearly amplified by a factor of 3. For *Neck*, we instructed users to only rotate their necks on the yaw axis while keeping their torso still.

Each control method had 3 possible NMV settings: *Baseline*, *Fixed*, and *Adaptive*. For *Baseline*, we did not apply any vibrations while we applied vibrations with the calibrated direction of camera rotation for *Fixed* and *Adaptive* settings. For *Fixed* condition, we applied an NMV duration of 1.0 s. For *Adaptive* condition, we rendered the amount of rotation according to the user's NMV profile (*Low*: 0.5 s / 1.5 s; *High*: 0.5 s / 1.0 s / 1.5 s). This resulted in a total of 9 combinations (3 control methods $\times$ 3 NMV settings). Each participant experienced all combinations in a random order.

To remove the placebo effect of vibration, we did not notify the participants about the objective of the evaluation. Instead, we told users that the evaluation aimed to find the best mode of VR navigation. As shown in Figure 7b, random chicken figures were placed along the path of the VR scene, which participants were instructed to find. By providing objectives that could only be found by rotating the camera, we ensured participants would rotate the camera when they had control.

Questionnaires To measure VR sickness, we asked participants to fill out the simulator sickness questionnaire (SSQ) [19]. SSQ asks participants to rate 16 symptoms with a score of 0 to 3, with 0 being no symptoms and 3 being severe. The 16 symptoms are categorized into three aspects of VR sickness: nausea, oculomotor, and disorientation. The scores for each aspect and the total score were calculated using the formulas given in the original paper.

To measure the presence, we asked participants to answer the Slater-Usoh-Steed (SUS) presence questionnaire [20]. The questionnaire consists of six 7-point Likert scale questions asking variations of sense of being, sense of realness, and extent of the virtual environment remembered as a "place". We chose the SUS questionnaire over other presence questionnaires because of its small number of questions as participants had to repeat the questionnaire for each 9 combinations. The questionnaires were all answered outside of the virtual environment to minimize VR continuously affecting the participants even after the experience.

Procedure For this evaluation, we employed a within-subject design. For the combination order for each participant, refer to Appendix C. Participants sat on a non-swivel chair that stayed in a fixed location to prevent their bodies from turning.

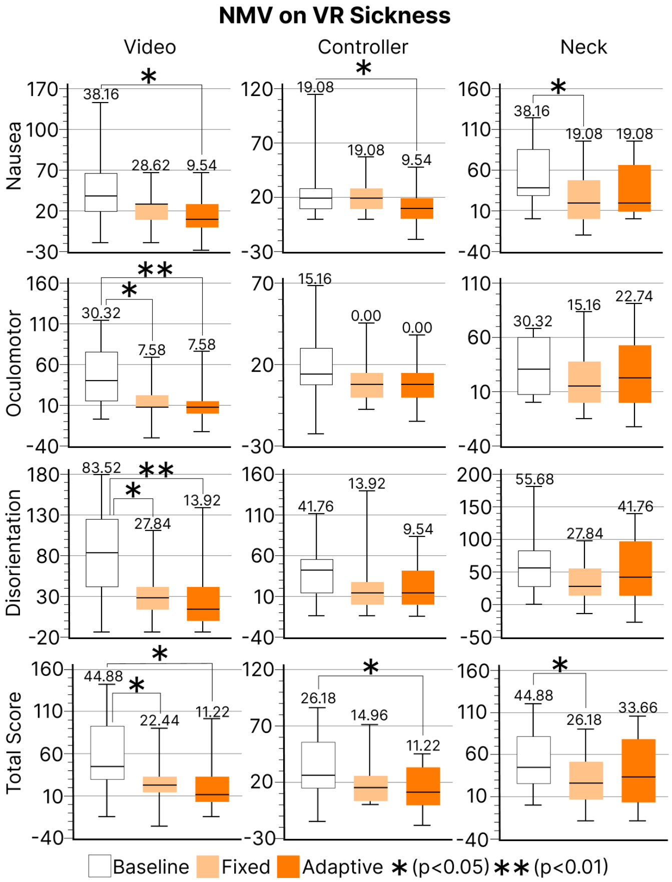

Fig. 8. Boxplots for relative nausea, oculomotor, disorientation, and total score from the SSQ questionnaire for each rotation method and NMV setting combination. The number on the bar shows the median.

Before starting the evaluation, participants were notified about possible VR sickness and that the evaluation could stop if the participants showed severe symptoms of VR sickness or if they wanted to. Then, we equipped participants with our haptic interface and carried out the calibration process. The equipment and calibration took no more than 15 minutes.

After calibration, participants filled out the pre-experience SSQ questionnaire to record their baseline symptoms. Then, they wore the HMD device (Meta Quest 3) and Bluetooth headphones playing white noise. In the VR scene, participants were told which rotation method they would use and were instructed to find as many chickens in the VR scene as possible. After completing the path, participants removed the HMD device and filled out the post-experience SSQ questionnaire and the SUS presence questionnaire.

The participants were given a minimum of 3 minutes of rest [79]. If the total score of the post-experience SSQ questionnaire was greater than 25, participants rested for a minimum of 5 minutes [80], [81]. We asked participants whether they wanted more rest after the minimum break time. If they wanted more rest, they rested for 2 additional minutes and were asked the same question. We repeated this process until the participant felt their VR sickness symptoms subsided. After the rest, participants proceeded to the next combination after filling out the pre-experience SSQ questionnaire again.

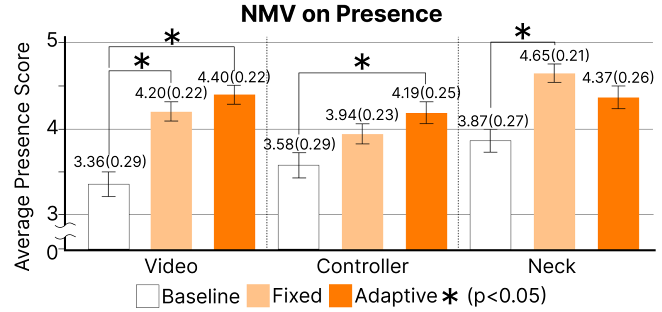

Fig. 9. Average responses from SUS presence questionnaire. The numbers above the bar show average and standard error, which is also shown by the error bars.

The whole experiment lasted for an average of 1.5 hours. After completing all combinations, participants answered which combination they preferred the most, and we conducted a short interview about their VR experience.

B. Results

During the evaluation, two participants (P6, P16) dropped out because they felt severe VR sickness. One participant (P7) felt little to no VR sickness symptoms throughout the whole evaluation. P7's maximum post-experience SSQ total score was 3.74, with 8 of them being 0. Because of this, we removed the SSQ scores of these three participants. We then obtained the relative SSQ scores by subtracting the pre-experience SSQ results from the post-experience SSQ results. For presence, we removed P6 and P16's SUS presence questionnaire results as they could not finish all 9 combinations but included P7's results. We used the average score of 6 questions for analysis. Both data for VR sickness and presence were not normally distributed. Thus, we employed a two-tailed Wilcoxon signed-rank test with a significance value of 0.05. The full statistics can be found in Appendix C.

Significant Results for VR Sickness The boxplots of the relative SSQ total score with pairs with significant differences are shown in Figure 8. For the *Video* method, there was a significant difference between *Baseline* and *Fixed* setting for oculomotor ($p = 0.024 < 0.05$), disorientation ($p = 0.0119 < 0.05$), and total score ($p = 0.0394 < 0.05$). For *Baseline* and *Adaptive* setting, all aspects of VR sickness showed significant differences, including nausea ($p = 0.0157 < 0.05$), oculomotor ($p = 0.0068 < 0.01$), disorientation ($p = 0.0063 < 0.01$), and total score ($p = 0.0111 < 0.05$). There was no significant difference between the *Fixed* and *Adaptive* setting. For the *Controller* method, there was only a significant difference between *Baseline* and *Adaptive* setting for nausea ($p = 0.0347 < 0.05$) and total score ($p = 0.0465 < 0.05$). For the *Neck* method, there was only a significant difference between *Baseline* and *Fixed* setting for nausea ($p = 0.0162 < 0.05$) and total score ($p = 0.0255 < 0.05$).

Despite of decreasing trend for relative oculomotor and relative disorientation, there was no significant difference between NMV settings except for the *Video* method. Only relative nausea and relative SSQ total score were significantly reduced for settings with NMV for all methods.

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3535942

Significant Results for Presence The average responses of the SUS presence questionnaire and pairs with significant differences are shown in Figure 9. There was a significant increase of presence for both *Fixed* ($p = 0.0370 < 0.05$) and *Adaptive* ($p = 0.0105 < 0.05$) settings compared to *Baseline* for the *Video* method. However, for *Controller*, only *Adaptive* had a significant increase ($p = 0.0416 < 0.05$). For *Neck*, only *Fixed* setting had a significant increase ($p = 0.0436 < 0.05$).

VR Sickness and Presence The NMV settings that had a significant reduction in VR sickness had a significant increase in presence. Presence also showed an increasing trend as more control freedom was given. This agrees with previous studies that showed an inverse relationship between VR sickness and presence [18]. For all methods, we observed a reduction in VR sickness and increased presence for any NMV settings. Therefore, we conclude that NMV effectively reduces VR sickness by reducing the sensory mismatch.

Difference between Methods With NMV's effectiveness for all methods confirmed, we now look into each method and analyze their differences. While other methods showed significant differences in only nausea and total score, *Video* showed a significant score decrease for all areas. With control, participants could anticipate rotations and their direction. However, in *Video*, users had no control over the camera rotations. The *Baseline* scores for *Video* in Figure 8 demonstrate the negative effect lack of control had. Only after applying NMV, did the scores decrease to similar levels as other methods. NMV's proprioceptive feedback compensated *Video*'s lack of control and reduced SSQ scores far more than other rotation methods.

For the *Neck* method, unlike other methods, the *Fixed* setting had a significant score decrease compared to *Baseline*, while *Adaptive* did not have a significant effect. The only difference between *Fixed* and *Adaptive* were the durations of NMV. While *Fixed* only runs 1.0 s vibrations, *Adaptive* administers 0.5 s, 1.0 s, and 1.5 s vibrations. Considering the ineffectiveness of NMV during rotation, as we observed in the second part of the exploratory study, we hypothesize that 1.5 s had a different effect during rotation that caused NMV to be less effective than 1.0 s. We further explore this difference in the following section.

User Preference Users showed varied preferences for rotation methods, but they preferred methods with NMV. When we counted preference for NMV, we aggregated the counts for the *Fixed* and *Adaptive* rendering approaches, as participants were unable to differentiate between the two.

Out of the 18 participants who completed the experiment, 14 preferred NMV, 2 had no preference, and 2 preferred no NMV. The participants who preferred vibration mostly did so because they felt less nauseous from VR sickness with NMV. *"The camera rotation with the vibration made it realistic and less dizzy"* (P9). Some participants also preferred NMV because of the natural feel it provided. *"The vibration felt as though it aligned with the intention of the camera rotation"* (P10).

Device Comfort Many participants were interested in the form factor with some even taking selfies after equipping the haptic interface. In the interview, they mainly commented on the weight compared to the HMD (P15) and the comfort. *"I liked the device. It was comfortable"* (P11).

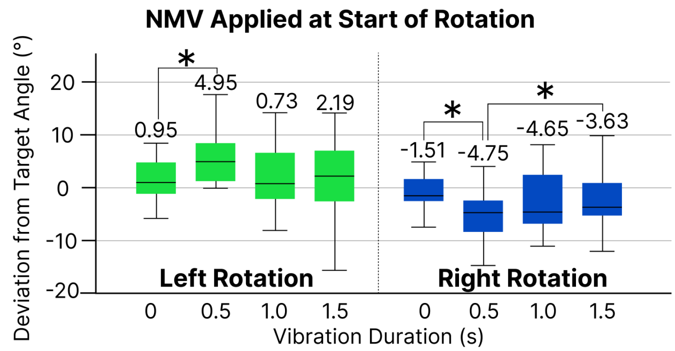

Fig. 10. Boxplots of deviation from the target angle of 60° for (a) left rotation and (b) right rotation. Positive values show deviation towards the right and negative values show deviations towards the left. Asterisks show pairs with significant differences with $p < 0.05$.

VII. NMV during Neck Rotation Revisited

In our VR sickness and presence evaluation, we found that for *Neck* method, *Fixed* setting, which activated the wearable for a fixed duration of 1.0 s, performed better than our *Adaptive* setting, which had durations between 0.5 s, 1.0 s, and 1.5 s. To further explain this result and confirm our hypothesis discussed with our results, we modified the second part of our exploratory study to analyze *Fixed* and *Adaptive* settings for the *Neck* method.

A. Procedure

For this study, we recruited 5 participants (mean age: 25.2, SD: 2.28; 3 male, 2 female). The procedure for the study was identical to the second part of the exploratory study. However, we modified the variables. Participants either rotated their necks 60° to the left or right at the speed of $60°/s$. We added a faster speed than the original $30°/s$ to observe the effects of the NMV continuing after the user finishes moving their neck. To recreate the same conditions as the evaluation, after calibration for each participant, we only applied NMV in the same direction with durations of 0 s, 0.5 s, 1.0 s, and 1.5 s. Most importantly, we started the vibration as soon as the participant rotated their neck instead of starting it in the middle of the rotation. With 2 possible directions and 4 durations, participants tried 8 combinations for 5 blocks with a 1-minute break in between. The study took no longer than an hour. For the combination order for each participant, refer to Appendix D.

B. Results

The boxplots of the results are shown in Figure 10. An Anderson-Darling test showed that the data for turning left and right had a normal distribution. As such, we conduct a one-way ANOVA on both directions to examine the effect of NMV duration.

For left rotation (figure 10a), the 4 durations showed significant change ($F(3, 96) = 3.16, p = 0.028 < 0.05$). A Tukey's test showed that 0.5 s had a significant difference from 0 s ($p = 0.044 < 0.05$). For right rotation (figure 10b), the 4 durations showed significant change ($F(3, 96) = 4.56, p = 0.005 <$

0.05). A Tukey's test showed 0.5 s had a significant difference from 0 s ($p = 0.004 < 0.05$) and 1.5 s ($p = 0.032 < 0.05$). The full statistics can be found in Appendix D.

Each rotation required participants to try to start at $0°$ and end $60°$ left or right while rotating their neck at $60°/s$. The significant results show that for 0.5 s vibration duration for each left and right rotation was effective. Participants perceived a full $60°$ neck rotation even though they actually rotated their necks less. Unlike the results of the exploratory study, this study reveals that NMV affects the perception of neck rotation if applied at the beginning of the rotation.

Based on this study and the exploratory study's results, we conclude that in cases of fast and short physical rotations, NMV should be applied for a short duration immediately after the neck rotation starts. Otherwise, NMV would continue even though the physical rotation has long finished, resulting in little to no effect on proprioceptive perception. This also sheds light on why *Fixed* performed better than *Adaptive* for *Neck*. For *Video* and *Controller*, where the neck is stationary, longer NMV duration directly translates to a larger perceived rotation. However, for fast rotations in *Neck*, *Adaptive*'s 1.5 s NMV was not as effective at providing a perceived rotation of greater magnitude.

VIII. Discussion

Real-Time NMV Using a Multi-Stimulus Haptic Interface Our results showed that NMV causes a significant reduction in rotation-induced VR sickness and a significant increase in presence. Both *Fixed* and *Adaptive* conditions that used NMV showed an improvement over *Baseline*, which is a result no other work has observed. Our motivation is to explore NMV's effect on VR sickness, so we have not compared this with other haptic methods that reduce VR sickness. A comparison between NMV and such methods is a worthy research to pursue in the future.

The increased presence aligns with Kooijman et al.'s work examining NMV's effect on VR sickness, presence, and vection. Their results showed a positive effect on presence and vection, but could not confirm the effect on VR sickness [17]. Although we did not measure vection, our results confirmed the increase in presence.

However, Kooijman et al. could not ensure whether the effects of NMV in VR were “attributed to proprioceptive or tactile stimulation” [17]. In this work, through the exploratory study, we confirmed our delivery method of NMV induce proprioceptive illusion. Furthermore, we observed the feasibility of using short-duration NMV to induce proprioceptive feedback and designed calibration methods to employ NMV for practical VR interactions.

Based on previous works on the relationship between VR sickness and presence and the results of our exploratory study, we conclude that our NMV rendering with a real-time haptic interface successfully reduced VR sickness by reducing sensory mismatch [18].

NMV Considerations In our exploratory study, we observed that 5 out of 9 participants felt the opposite perception of the intended NMV [62]. Even after careful motor placement and fit, we saw 6 out of 20 participants who felt the opposite perception. However, by calibrating the direction, we still observed reduced VR sickness and increased presence. Considering the complexity and individual differences in neck muscle anatomy [62], we recommend the use of calibration for NMV to minimize these differences.

Next, due to *Fixed* setting's better performance for *Neck* in the evaluation, we conducted an additional study on NMV applied at the start of neck rotation. We found that how 0.5 s at the beginning of rotation yielded a significant difference in perceived rotation, but longer durations did not have any effects or even worse effects for fast and short neck rotations. To this end, future implementations of real-time NMV for fast physical neck rotations should consider using NMV with short vibration duration (e.g., 0.5 s).

NMV During Neck Rotations While short vibration duration is effective for fast, short neck rotations, this may not be the case for slower, longer neck rotations. A study on arm tendon vibration during movement showed how arm position perception differed depending on vibration timing and arm velocity [82]. While there are differences between arm and neck muscles, we can infer that the same holds for the neck considering the results of our studies. Our paper observed no effect of short-duration NMV applied during a 30°/s rotation and a significant perception difference for short-duration NMV at the start of a 60°/s rotation. However, future researchers applying NMV with neck rotations should be wary of potentially differing results in different conditions.

Potential Applications for NMV Although we only used *Video*, *Controller*, and *Neck* in our evaluation, other VR navigation methods are available where NMV can be applied as well. Researchers propose novel VR navigation techniques to overcome physical constraints such as occupied hands [83] or neck rotation limitations [84]. However, these methods tend to suffer from discomfort due to VR sickness. By using NMV with these techniques, users can bypass physical constraints without discomfort.

NMV also can be applied to various VR interactions. GVS has proven effective in reducing VR sickness and providing a more immersive 360° video experience [85]. Using the same principles reducing sensory mismatch with a targeted direction, applying NMV for immersive 360° videos can provide a more enjoyable experience. Similar to using electrical muscle stimulation to guide the user's point of view [86], NMV can be used for effective guidance in VR by rotating the user's view without VR sickness.

NMV also has potential VR applications aside from VR sickness. Out of the 20 participants, P7 had no symptoms of VR sickness due to previous VR experience. P7 experienced *Neck* method, which had an amplified rotation with a factor of 3, with NMV before trying *Neck* without vibration. P7 did not have any comments the first time, but the second time P7 tried *Neck*, P7 was surprised to realize now how the rotations have been amplified. Even if P7 did not feel VR sickness symptoms, NMV's proprioceptive feedback helped the *Neck* method feel more natural despite the sensory mismatch. P7's comment suggests future applications of NMV beyond VR sickness. NMV's proprioceptive illusion can create motion guidance or augmented rotation to enable natural and immersive VR

This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2025.3535942

experiences.

Limitations and Future Works The methods used for the first part of the exploratory study heavily relied on how accurately the participants could recreate the illusory neck rotation. Previous studies on NMV used random and sinusoidal rotations on a rotating platform or chair to observe the effects of NMV [61], [63], which removes self-report bias.

In the VR sickness evaluation, while participants were provided with sufficient breaks and asked whether they were fine to continue, the subjective nature of SSQ is susceptible to carry-over effects from VR sickness. Recording SSQ with objective measures such as postural sway or psychophysical indicators [87] or comparing with other baseline VR sickness reduction methods would yield a more accurate reflection of the impact of NMV on VR sickness reduction.

Furthermore, to observe the effects of user control, we strictly separated the rotation methods in our evaluation. However, in a typical VR experience, users are more likely to use more than one of the methods together. To render real-time NMV for several simultaneous rotation inputs, we will need to explore the effect of NMV in those situations.

In this work, we only explored yaw-axis neck rotation. However, our interface can simulate pitch-axis neck rotation with different SCM and SC muscle combinations. For future work, we would like to explore the possibility of applying multi-axes neck rotation sensation using different combinations of NMV. While we adopted a duration-based NMV rendering with discrete fixed durations based on our exploratory studies, a continuous rendering approach would be ideal for a better generalized NMV application. To achieve continuous multi-axes NMV rendering, we will need to conduct in-depth perception studies, such as comparing the effect of visual illusion and NMV, calculating individual NMV impact for different muscle locations, or measuring just noticeable differences for NMV durations. With these future works, we expect NMV to be more applicable to a broader scope of VR scenarios and cover a wider range of VR camera rotations to reduce rotation-induced VR sickness.

IX. Conclusion

In our work, we demonstrate that NMV, an illusory sensation of neck rotation caused by proprioceptive stimulation, reduces rotation-induced VR sickness effectively through reduced sensory mismatch. We devised a multi-stimulus configuration haptic interface capable of providing neck rotation sensation on the yaw axis without physical rotation. We found NMV's large individual differences and ineffectiveness during physical neck rotation. Keeping these results in mind, we implemented a real-time NMV for VR rotations using *Video*, *Controller*, and *Neck* control methods. Our evaluation results showed a significant reduction in rotation-induced VR sickness and a significant increase in presence. Our additional study also showed that only a short duration of NMV is effective for neck rotation. In conclusion, we encourage and look forward to more NMV applications in the VR community that will enable a more enjoyable and immersive VR experience for everyone.

References

[1] S. Martirosov, M. Bureš, and T. Zítka, "Cyber sickness in low-immersive, semi-immersive, and fully immersive virtual reality," *Virtual Reality*, vol. 26, no. 1, pp. 15–32, 2022.

[2] A. Somrak, I. Humar, M. S. Hossain, M. F. Alhamid, M. A. Hossain, and J. Guna, "Estimating vr sickness and user experience using different hmd technologies: An evaluation study," *Future Generation Computer Systems*, vol. 94, pp. 302–316, 2019.

[3] K. J. Mimnaugh, E. G. Center, M. Suomalainen, I. Becerra, E. Lozano, R. Murrieta-Cid, T. Ojala, S. M. LaValle, and K. D. Federmeier, "Virtual reality sickness reduces attention during immersive experiences," *IEEE Transactions on Visualization and Computer Graphics*, 2023.

[4] E. Chang, H. T. Kim, and B. Yoo, "Virtual reality sickness: A review of causes and measurements," *International Journal of Human–Computer Interaction*, vol. 36, pp. 1658–1682, 10 2020. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/10447318.2020.1778351

[5] J. T. Reason, "Motion sickness adaptation: a neural mismatch model," *Journal of the royal society of medicine*, vol. 71, no. 11, pp. 819–829, 1978.

[6] W. Lo and R. H. So, "Cybersickness in the presence of scene rotational movements along different axes," *Applied ergonomics*, vol. 32, no. 1, pp. 1–14, 2001.

[7] S. Hu and R. M. Stern, "Optokinetic nystagmus correlates with severity of vection-induced motion sickness and gastric tachyarrhythmia." *Aviation, space, and environmental medicine*, vol. 69, no. 12, pp. 1162–1165, 1998.

[8] J. T. Ji, R. H. So, and R. T. Cheung, "Isolating the effects of vection and optokinetic nystagmus on optokinetic rotation-induced motion sickness," *Human factors*, vol. 51, no. 5, pp. 739–751, 2009.

[9] N. Ranasinghe, P. Jain, D. Tolley, S. Karwita Tailan, C. C. Yen, and E. Y.-L. Do, "Exploring the use of olfactory stimuli towards reducing visually induced motion sickness in virtual reality," in *Proceedings of the 2020 ACM Symposium on Spatial User Interaction*, 2020, pp. 1–9.

[10] Y.-H. Peng, C. Yu, S.-H. Liu, C.-W. Wang, P. Taele, N.-H. Yu, and M. Y. Chen, "Walkingvibe: Reducing virtual reality sickness and improving realism while walking in vr using unobtrusive head-mounted vibrotactile feedback," in *Proceedings of the 2020 CHI conference on human factors in computing systems*, 2020, pp. 1–12.

[11] H. Chu, M.-H. Li, Y.-C. Huang, and S.-Y. Lee, "Simultaneous transcutaneous electrical nerve stimulation mitigates simulator sickness symptoms in healthy adults: a crossover study," *BMC complementary and alternative medicine*, vol. 13, pp. 1–10, 2013.

[12] M. Sra, A. Jain, and P. Maes, "Adding proprioceptive feedback to virtual reality experiences using galvanic vestibular stimulation," in *Proceedings of the 2019 CHI conference on human factors in computing systems*, 2019, pp. 1–14.

[13] M. J. Cevette, J. Stepanek, D. Cocco, A. M. Galea, G. N. Pradhan, L. S. Wagner, S. R. Oakley, B. E. Smith, D. A. Zapala, and K. H. Brookler, "Oculo-vestibular recoupling using galvanic vestibular stimulation to mitigate simulator sickness," *Aviation, space, and environmental medicine*, vol. 83, no. 6, pp. 549–555, 2012.

[14] G. M. Goodwin, D. I. McCloskey, and P. B. C. Matthews, "Proprioceptive illusions induced by muscle vibration: Contribution by muscle spindles to perception?" *Science*, vol. 175, pp. 1382–1384, 3 1972. [Online]. Available: https://www.science.org/doi/10.1126/science.175.4028.1382

[15] J. Kasper, R. H. Schor, and V. J. Wilson, "Response of vestibular neurons to head rotations in vertical planes. ii. response to neck stimulation and vestibular-neck interaction," *Journal of Neurophysiology*, vol. 60, pp. 1765–1778, 11 1988.

[16] B. Biguer, I. M. L. Donaldson, A. Hein, and M. Jeannerod, "Neck muscle vibration modifies the representation of visual motion and direction in man," *Brain*, vol. 111, pp. 1405–1424, 1988. [Online]. Available: https://academic.oup.com/brain/article-lookup/doi/10.1093/brain/111.6.1405

[17] L. Kooijman, H. Asadi, C. Gonzalez Arango, S. Mohamed, and S. Nahavandi, "Investigating the influence of neck muscle vibration on illusory self-motion in virtual reality," *Virtual Reality*, vol. 28, no. 2, pp. 1–21, 2024.

[18] S. Weech, S. Kenny, and M. Barnett-Cowan, "Presence and cybersickness in virtual reality are negatively related: a review," *Frontiers in psychology*, vol. 10, p. 415654, 2019.

[19] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *The international journal of aviation psychology*, vol. 3, no. 3, pp. 203–220, 1993.

[20] M. Usoh, E. Catena, S. Arman, and M. Slater, "Using presence questionnaires in reality," *Presence*, vol. 9, no. 5, pp. 497–503, 2000.

[21] E. M. Kolasinski, "Simulator sickness in virtual environments," 1995.

[22] X. Li, D.-B. Luh, R.-H. Xu, and Y. An, "Considering the consequences of cybersickness in immersive virtual reality rehabilitation: A systematic review and meta-analysis," *Applied Sciences*, vol. 13, no. 8, p. 5159, 2023.

[23] C. Yildirim, "Cybersickness during vr gaming undermines game enjoyment: A mediation model," *Displays*, vol. 59, pp. 35–43, 2019.

[24] M. C. Howard and E. C. Van Zandt, "A meta-analysis of the virtual reality problem: Unequal effects of virtual reality sickness across individual differences," *Virtual Reality*, vol. 25, no. 4, pp. 1221–1246, 2021.

[25] Y. Y. Kim, E. N. Kim, M. J. Park, K. S. Park, H. D. Ko, and H. T. Kim, "The application of biosignal feedback for reducing cybersickness from exposure to a virtual environment," *Presence: Teleoperators and Virtual Environments*, vol. 17, no. 1, pp. 1–16, 2008.

[26] P. DiZio and J. R. Lackner, "Circumventing side effects of immersive virtual environments," *Advances in human factors/ergonomics*, vol. 21, pp. 893–896, 1997.

[27] G. D. Park, R. W. Allen, D. Fiorentino, T. J. Rosenthal, and M. L. Cook, "Simulator sickness scores according to symptom susceptibility, age, and gender for an older driver assessment study," in *Proceedings of the human factors and ergonomics society annual meeting*, vol. 50, no. 26. SAGE Publications Sage CA: Los Angeles, CA, 2006, pp. 2702–2706.

[28] J. Hakkinen, T. Vuori, and M. Paakka, "Postural stability and sickness symptoms after hmd use," in *IEEE international conference on systems, man and cybernetics*, vol. 1. IEEE Yasmine Hammamet, 2002, pp. 147–152.

[29] S. Freitag, B. Weyers, and T. W. Kuhlen, "Examining rotation gain in cave-like virtual environments," *IEEE transactions on visualization and computer graphics*, vol. 22, no. 4, pp. 1462–1471, 2016.

[30] L. J. Hettinger and G. E. Riccio, "Visually induced motion sickness in virtual environments," *Presence: Teleoperators & Virtual Environments*, vol. 1, no. 3, pp. 306–310, 1992.

[31] A. Kovalev, O. Klimova, M. Klimova, and A. Drozhdev, "The effects of optokinetic nystagmus on vection and simulator sickness," *Procedia computer science*, vol. 176, pp. 2832–2839, 2020.

[32] B. Keshavarz, B. E. Riecke, L. J. Hettinger, and J. L. Campos, "Vection and visually induced motion sickness: how are they related?" *Frontiers in psychology*, vol. 6, p. 129781, 2015.

[33] S. Palmisano, R. Mursic, and J. Kim, "Vection and cybersickness generated by head-and-display motion in the oculus rift," *Displays*, vol. 46, pp. 1–8, 2017.

[34] B. E. Riecke, J. Schulte-Pelkum, M. N. Avraamides, M. V. D. Heyde, and H. H. Bülthoff, "Cognitive factors can influence self-motion perception (vection) in virtual reality," *ACM Transactions on Applied Perception (TAP)*, vol. 3, no. 3, pp. 194–216, 2006.

[35] M. Minsky, "Telepresence," 1980.

[36] M. Slater, D. Banakou, A. Beacco, J. Gallego, F. Macia-Varela, and R. Oliva, "A separate reality: An update on place illusion and plausibility in virtual reality," *Frontiers in virtual reality*, vol. 3, p. 914392, 2022.

[37] K. M. Stanney and P. Hash, "Locus of user-initiated control in virtual environments: Influences on cybersickness," *Presence*, vol. 7, no. 5, pp. 447–459, 1998.

[38] B. G. Witmer and M. J. Singer, *Measuring presence in virtual environments*. US Army Research Institute for the Behavioral and Social Sciences Alexandria, VA, 1994.

[39] M. J. Habgood, D. Moore, D. Wilson, and S. Alapont, "Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique," in *2018 IEEE conference on virtual reality and 3D user interfaces (VR)*. IEEE, 2018, pp. 371–378.

[40] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey, "Point & teleport locomotion technique for virtual reality," in *Proceedings of the 2016 annual symposium on computer-human interaction in play*, 2016, pp. 205–216.

[41] J. E. Bos, S. C. de Vries, M. L. van Emmerik, and E. L. Groen, "The effect of internal and external fields of view on visually induced motion sickness," *Applied ergonomics*, vol. 41, no. 4, pp. 516–521, 2010.

[42] A. S. Fernandes and S. K. Feiner, "Combating vr sickness through subtle dynamic field-of-view modification," in *2016 IEEE symposium on 3D user interfaces (3DUI)*. IEEE, 2016, pp. 201–210.

[43] H. Buhler, S. Misztal, and J. Schild, "Reducing vr sickness through peripheral visual effects," in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2018, pp. 517–9.

[44] Y. Wei, J. Zheng, and R. H. So, "Allocating less attention to central vision during vection is correlated with less motion sickness," *Ergonomics*, vol. 61, no. 7, pp. 933–946, 2018.

[45] M. Slater, V. Linakis, M. Usoh, and R. Kooper, "Immersion, presence and performance in virtual environments: An experiment with tri-dimensional chess," in *Proceedings of the ACM symposium on virtual reality software and technology*, 1996, pp. 163–172.

[46] B. Keshavarz and H. Hecht, "Pleasant music as a countermeasure against visually induced motion sickness," *Applied ergonomics*, vol. 45, no. 3, pp. 521–527, 2014.

[47] S. D'Amour, J. E. Bos, and B. Keshavarz, "The efficacy of airflow and seat vibration on reducing visually induced motion sickness," *Experimental brain research*, vol. 235, pp. 2811–2820, 2017.

[48] J. Harrington, C. Headleand *et al.*, "A somatic approach to combating cybersickness utilising airflow feedback," 2019.

[49] A. Matviienko, F. Müller, M. Zickler, L. A. Gasche, J. Abels, T. Steinert, and M. Mühlhäuser, "Reducing virtual reality sickness for cyclists in vr bicycle simulators," in *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 2022, pp. 1–14.

[50] S.-H. Liu, N.-H. Yu, L. Chan, Y.-H. Peng, W.-Z. Sun, and M. Y. Chen, "Phantomlegs: Reducing virtual reality sickness using head-worn haptic devices," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2019, pp. 817–826.

[51] S. Weech, J. Moon, and N. F. Troje, "Influence of bone-conducted vibration on simulator sickness in virtual reality," *PloS one*, vol. 13, no. 3, p. e0194137, 2018.

[52] G. Lucas, A. Kemeny, D. Paillot, and F. Colombet, "A simulation sickness study on a driving simulator equipped with a vibration platform," *Transportation research part F: traffic psychology and behaviour*, vol. 68, pp. 15–22, 2020.

[53] G. Gálvez-García, M. Hay, and C. Gabaude, "Alleviating simulator sickness with galvanic cutaneous stimulation," *Human factors*, vol. 57, no. 4, pp. 649–657, 2015.

[54] K. S. Utz, K. Korluss, L. Schmidt, A. Rosenthal, K. Oppenländer, I. Keller, and G. Kerkhoff, "Minor adverse effects of galvanic vestibular stimulation in persons with stroke and healthy individuals," *Brain Injury*, vol. 25, no. 11, pp. 1058–1069, 2011.

[55] T. Mergner, C. Siebold, G. Schweigart, and W. Becker, "Human perception of horizontal trunk and head rotation in space during vestibular and neck stimulation," *Experimental Brain Research*, vol. 85, pp. 389–404, 6 1991. [Online]. Available: http://link.springer.com/10.1007/BF00229416

[56] B. Armstrong, P. McNair, and D. Taylor, "Head and neck position sense," *Sports Medicine*, vol. 38, pp. 101–117, 2008.

[57] C. Capaday and J. Cooke, "The effects of muscle vibration on the attainment of intended final position during voluntary human arm movements," *Experimental Brain Research*, vol. 42, no. 2, pp. 228–230, 1981.

[58] W. Rohmert, H. Wos, S. Norlander, and R. Helbig, "Effects of vibration on arm and shoulder muscles in three body postures," *European journal of applied physiology and occupational physiology*, vol. 59, pp. 243–248, 1989.

[59] Y. Ivanenko, R. Grasso, and F. Lacquaniti, "Influence of leg muscle vibration on human walking," *Journal of neurophysiology*, vol. 84, no. 4, pp. 1737–1747, 2000.

[60] V. Gurfinkel, Y. S. Levik, O. Kazennikov, and V. Selionov, "Locomotor-like movements evoked by leg muscle vibration in humans," *European Journal of Neuroscience*, vol. 10, no. 5, pp. 1608–1612, 1998.

[61] R. Panichi, F. M. Botti, A. Ferraresi, M. Faralli, A. Kyriakareli, M. Schieppati, and V. E. Pettorossi, "Self-motion perception and vestibulo-ocular reflex during whole body yaw rotation in standing subjects: The role of head position and neck proprioception," *Human Movement Science*, vol. 30, pp. 314–332, 4 2011. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0167945710001739

[62] J. L. Taylor and D. I. McCloskey, "Illusions of head and visual target displacement induced by vibration of neck muscles," *Brain*, vol. 114, pp. 755–759, 1991. [Online]. Available: https://academic.oup.com/brain/article-lookup/doi/10.1093/brain/114.2.755

[63] V. E. Pettorossi, R. Panichi, F. M. Botti, A. Biscarini, G. M. Filippi, and M. Schieppati, "Long-lasting effects of neck muscle vibration and contraction on self-motion perception of vestibular origin," *Clinical Neurophysiology*, vol. 126, pp. 1886–1900, 10 2015.

[64] Y. P. Ivanenko, R. Grasso, and F. Lacquaniti, "Neck muscle vibration makes walking humans accelerate in the direction of gaze," *The Journal of physiology*, vol. 525, no. 3, pp. 803–814, 2000.

[65] M. Bove, G. Courtine, and M. Schieppati, “Neck muscle vibration and spatial orientation during stepping in place in humans,” *Journal of Neurophysiology*, vol. 88, pp. 2232–2241, 11 2002.

[66] G. Courtine, A. M. De Nunzio, M. Schmid, M. V. Beretta, and M. Schieppati, “Stance-and locomotion-dependent processing of vibration-induced proprioceptive inflow from multiple muscles in humans,” *Journal of neurophysiology*, vol. 97, no. 1, pp. 772–779, 2007.

[67] H.-O. Karnath, D. Sievering, and M. Fetter, “The interactive contribution of neck muscle proprioception and vestibular stimulation to subjective ?straight ahead? orientation in man,” *Experimental Brain Research*, vol. 101, pp. 140–146, 1994. [Online]. Available: http://link.springer.com/10.1007/BF00243223

[68] H.-O. Karnath, “Transcutaneous electrical stimulation and vibration of neck muscles in neglect,” *Experimental Brain Research*, vol. 105, pp. 321–324, 8 1995. [Online]. Available: http://link.springer.com/10.1007/BF00240969

[69] D. Hagimori, S. Yoshimoto, N. Sakata, and K. Kiyokawa, “Tendon vibration increases vision-induced kinesthetic illusions in a virtual environment,” in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2019, pp. 952–953.

[70] Y. Hirao, T. Amemiya, T. Narumi, F. Argelaguet, and A. Lécuyer, “Leveraging tendon vibration to enhance pseudo-haptic perceptions in vr,” *IEEE Transactions on Visualization and Computer Graphics*, pp. 1–15, 2023. [Online]. Available: https://ieeexplore.ieee.org/document/10234714/

[71] S. Le Franc, M. Fleury, M. Cogne, S. Butet, C. Barillot, A. Lecuyer, and I. Bonan, “Influence of virtual reality visual feedback on the illusion of movement induced by tendon vibration of wrist in healthy participants,” *Plos one*, vol. 15, no. 11, p. e0242416, 2020.

[72] L. Mazzini and M. Schieppati, “Activation of the neck muscles from the ipsi- or contralateral hemisphere during voluntary head movements in humans. a reaction-time study,” *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, vol. 85, pp. 183–189, 6 1992.

[73] T. Yagi, G. Hatano, and T. Morizono, “Role of dorsal neck proprioceptive inputs to vestibular compensation in humans,” *Journal of Nippon Medical School*, vol. 65, no. 4, pp. 291–297, 1998.

[74] *TacHammer Drake Datasheet*, TITANHaptics, 2023. [Online]. Available: https://titanhaptics.com/wp-content/uploads/2023/05/TacHammer-Drake-Datasheet-1.pdf

[75] K. Jamal, S. Leplaideur, F. Leblanche, A. M. Raillon, T. Honoré, and I. Bonan, “The effects of neck muscle vibration on postural orientation and spatial perception: A systematic review,” *Neurophysiologie Clinique*, vol. 50, pp. 227–267, 9 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0987705319302242

[76] V. F. Ferrario, C. Sforza, G. Serrao, G. Grassi, and E. Mossi, “Active range of motion of the head and cervical spine: a three-dimensional investigation in healthy young adults,” *Journal of orthopaedic research*, vol. 20, no. 1, pp. 122–129, 2002.

[77] H. S. Bahat, E. Sprecher, I. Sela, and J. Treleaven, “Neck motion kinematics: an inter-tester reliability study using an interactive neck vr assessment in asymptomatic individuals,” *European Spine Journal*, vol. 25, pp. 2139–2148, 2016.

[78] E. D. Ragan, S. Scerbo, F. Bacim, and D. A. Bowman, “Amplified head rotation in virtual reality and the effects on 3d search, training transfer, and spatial orientation,” *IEEE transactions on visualization and computer graphics*, vol. 23, no. 8, pp. 1880–1895, 2016.

[79] B. Keshavarz, R. Ramkhalawansingh, B. Haycock, S. Shahab, and J. Campos, “Comparing simulator sickness in younger and older adults during simulated driving under different multisensory conditions,” *Transportation research part F: traffic psychology and behaviour*, vol. 54, pp. 47–62, 2018.

[80] N. Tanaka and H. Takagi, “Virtual reality environment design of managing both presence and virtual reality sickness,” *Journal of physiological anthropology and applied human science*, vol. 23, no. 6, pp. 313–317, 2004.

[81] J. D. Moss, J. Austin, J. Salley, J. Coats, K. Williams, and E. R. Muth, “The effects of display delay on simulator sickness,” *Displays*, vol. 32, no. 4, pp. 159–168, 2011.

[82] P. Cordo, V. S. Gurfinkel, L. Bevan, and G. K. Kerr, “Proprioceptive consequences of tendon vibration during movement,” *Journal of neurophysiology*, vol. 74, no. 4, pp. 1675–1688, 1995.

[83] D. Zielasko, S. Horn, S. Freitag, B. Weyers, and T. W. Kuhlen, “Evaluation of hands-free hmd-based navigation techniques for immersive data analysis,” in *2016 IEEE symposium on 3D user interfaces (3DUI)*. IEEE, 2016, pp. 113–119.

[84] E. Langbehn, J. Wittig, N. Katzakis, and F. Steinicke, “Turn your head half round: Vr rotation techniques for situations with physically limited turning angle,” in *Proceedings of Mensch und Computer 2019*, 2019, pp. 235–243.

[85] C. Groth, J.-P. Tauscher, N. Heesen, M. Hattenbach, S. Castillo, and M. Magnor, “Omnidirectional galvanic vestibular stimulation in virtual reality,” *IEEE transactions on Visualization and Computer Graphics*, vol. 28, no. 5, pp. 2234–2244, 2022.

[86] Y. Tanaka, J. Nishida, and P. Lopes, “Demonstrating electrical head actuation: Enabling interactive systems to directly manipulate head orientation,” in *CHI Conference on Human Factors in Computing Systems Extended Abstracts*, 2022, pp. 1–5.

[87] E. Chang, H. T. Kim, and B. Yoo, “Virtual reality sickness: a review of causes and measurements,” *International Journal of Human–Computer Interaction*, vol. 36, no. 17, pp. 1658–1682, 2020.

Kun-Woo Song Kun-Woo is a second-year masters student at Korea Advanced Institute of Science and Technology (KAIST). He received a bachelor's degree in mathematical sciences and the school of computing from KAIST. He currently is a member of the Human-Centered Interactive Technologies Lab in the Graduate School of Culture Technology at KAIST. He is interested in different haptic illusions to create a more immersive and entertaining VR experience.

Sang Ho Yoon Sang Ho Yoon is an assistant professor in the Graduate School of Culture Technology at the Korea Advanced Institute of Science and Technology (KAIST), with a joint appointment in the School of Computing and Graduate School of Metaverse. He leads the Human-centered Interactive Technologies Lab (HCI Tech Lab). His research focuses on developing natural user interactions that address physical, mental, and social barriers with novel haptic interface and sensing techniques. Before his academic career, Dr. Yoon gained industry experience as a Principal Engineer at Samsung Research, a Research Engineer at Microsoft Applied Sciences Lab, and held research positions at Apple, LG Electronics, and LG Display. He received his Ph.D. in Mechanical Engineering from Purdue University and B.S. and M.S. degrees in Mechanical Engineering from Carnegie Mellon University.