The Impact of Graviception on Human-Computer Interaction

Jean Vanderdonckt
jean.vanderdonckt@uclouvain.be
Université catholique de Louvain
Louvain Research Institute in Management and Organizations
Institute of Information and Communication Technologies, Electronics and Applied Mathematics
Louvain-la-Neuve, Belgium

Philippe Lefèvre
philippe.lefevre@uclouvain.be
Université catholique de Louvain
Institute of Information and Communication Technologies, Electronics and Applied Mathematics
Louvain-la-Neuve, Belgium

Radu-Daniel Vatavu
radu.vatavu@usm.ro
Ştefan cel Mare Univ. of Suceava
MintViz Lab, MANSiD Research Center
Suceava, Romania

Nuwan T. Attygalle
nuwan.attygalle@uclouvain.be
Université catholique de Louvain
Louvain Research Institute in Management and Organizations
Louvain-la-Neuve, Belgium

Laura-Bianca Bilius
laura.bilius@usm.ro
MintViz Lab, MANSiD Center, Ştefan cel Mare University of Suceava
Suceava, Romania

Gaëlle Calvary
gaelle.calvary@univ-grenoble-alpes.fr
Univ. Grenoble Alpes, CNRS, Grenoble INP, Laboratoire d'Informatique de Grenoble
Grenoble, France

Sophie Dupuy-Chessa
sophie.dupuy@niv-grenoble-alpes.fr
Univ. Grenoble Alpes, CNRS, Grenoble INP, Laboratoire d'Informatique de Grenoble
Grenoble, France

Merle T. Fairhurst
merle.fairhurst@tu-dresden.de
Chair of Acoustics and Haptics, Technische Universitat Dresden
Dresden, Germany

Tommy Nilsson
tommy.nilsson@esa.int
European Space Agency
Cologne, Germany
tommy.nilsson@fit.fraunhofer.de
Fraunhofer FIT
Sankt Augustin, Germany

Leif Oppermann
leif.oppermann@fit.fraunhofer.de
Mixed and Augmented Reality Systems, Fraunhofer FIT
Sankt Augustin, Germany

Paolo Roselli
roselli@mat.uniroma2.it
Università degli Studi di Roma "Tor Vergata"
Dept. of Mathematics
Roma, Italy

Giovanni Saggio
saggio@uniroma2.it
Università degli Studi di Roma "Tor Vergata"
Roma, Italy

Valérie Swaen
valerie.swaen@uclouvain.be
Université catholique de Louvain
Louvain Research Institute in Management and Organizations
Louvain-la-Neuve, Belgium

Figure 1: An example of graviception as an embodied mediator in human-computer interaction: end users perform wrist-based horizontal mid-air gestures in a centrifuge with normal gravity (a: 1 *g*), increased gravity (b: 1.5 *g*), and maximal gravity simulating a space shuttle at taking off (c: 2.7 *g*). In the last condition, the end user, almost pressed against the wall of the centrifuge due to the pressure, struggles to perform mid-air gestures.

Abstract

Graviception, the human sensory perception of gravity and body orientation, plays a fundamental, yet often overlooked, role in how individuals interact with interactive systems. Human–computer interaction has traditionally emphasized visual, auditory, and tactile modalities, while comparatively neglecting the influence of gravity perception on embodiment, attention, motor control, and user experience. This paper draws on the field of biomechanics to examine how graviception can impact interaction, such as the impact of vision and gravity on body movements, especially in immersive, hypogravity environments, mobile contexts of use, and accessibility. By positioning graviception as a first-class concern in embodied interaction, we suggest actionable implications for interaction design that consider graviceptive factors for designers and researchers developing future graviceptive-aware interactive systems. Each implication is described by a short statement, a detailed statement, a rationale, and a series of examples illustrating the impact of graviception on design decisions.

CCS Concepts

• **Human-centered computing** → **Human computer interaction (HCI)**; *Virtual reality*.

Keywords

Embodied interaction, Graviception, spatial cognition, Vestibular perception, Virtual Reality

ACM Reference Format:

Jean Vanderdonckt, Philippe Lefèvre, Radu-Daniel Vatavu, Nuwan T. Attygalle, Laura-Bianca Bilius, Gaëlle Calvary, Sophie Dupuy-Chessa, Merle T. Fairhurst, Tommy Nilsson, Leif Oppermann, Paolo Roselli, Giovanni Saggio, and Valérie Swaen. 2026. The Impact of Graviception on Human-Computer Interaction. In *Extended Abstracts of the 2026 CHI Conference on Human Factors in Computing Systems (CHI EA '26), April 13–17, 2026, Barcelona, Spain.* ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3772363.3799280

CHI EA '26, Barcelona, Spain

ACM ISBN 979-8-4007-2281-3/2026/04
https://doi.org/10.1145/3772363.3799280

1 Introduction

Human-Computer Interaction (HCI) with technology is inherently embodied [8]. Users perceive and act through bodies [44] that are continuously influenced by *graviception* (contraction of gravity and perception) [9], the sensory capacity to perceive gravity [21] and body orientation [15] that provides a persistent reference system for perception and action [43]. Although we are constantly exposed to the Earth's gravitational force field, our human body does not possess a sensory organ specifically dedicated to graviception. However, we receive a rich variety of cues from various sensory modalities [2], which, when combined, allow us to obtain a relatively accurate estimate of orientation [22] and value of gravitational acceleration [29].

The vestibular system [2], located in our inner ear and responsible for our ability to maintain balance, detects linear accelerations of the head due to the otoliths (Fig 2-a) [22,29]. However, they cannot distinguish between a translation and a change in the orientation of the head, as the physiological response is the same. This gives rise to an ambiguity that requires the inclusion of information from the semicircular canals, which detect head rotations. We can also "see" gravity, since it constrains the manipulation of objects (Fig 2-b) [18]: we deduce the orientation of gravity from their trajectory. Our visual environment is full of elements that indicate gravity [26]: the ground is horizontal to provide us with a stable base of support, while trees and buildings are vertical to resist the effects of gravity. When we hold an object in our hand, we activate our muscles so that they produce enough force to compensate for its weight via proprioception (Fig 2-c) [22]. Mechanoreceptors in our muscles and joints feel this sensation of effort and therefore play a role in the perception of gravity. Finally, our touch system (Fig 2-d) [39] allows us to feel the weight of an object through the deformation of our fingertips. These deformations are detected by mechanoreceptors in the skin and the information is transmitted to the brain for interpretation.

Therefore, graviception consists of multisensory integration [31] of these four systems (Fig. 2), each having its own response time (Fig. 3): 150 msec for the otoliths, 120 msec for the visual, 60 msec for proprioception, and 100 msec for touch. Unfortunately, this remains largely implicit or under-articulated in HCI research and

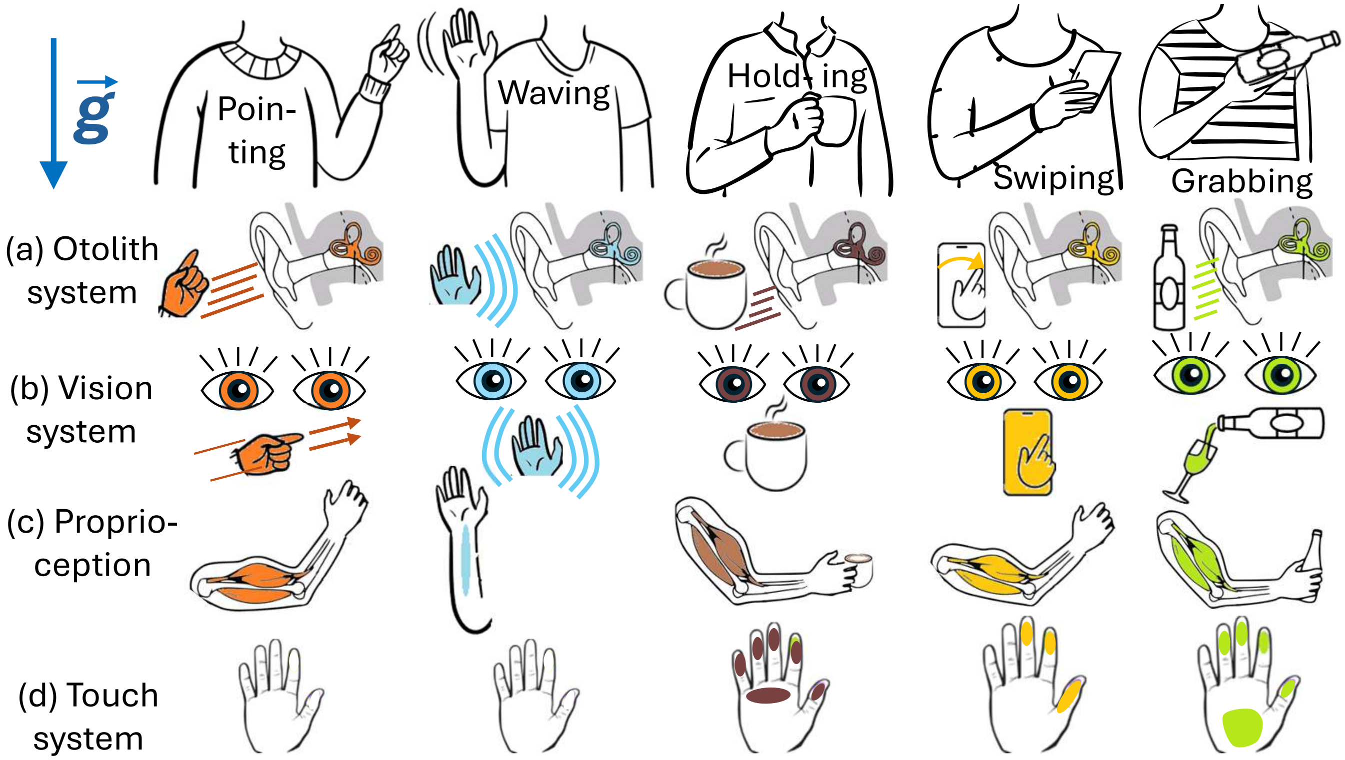

Figure 2: Human perception of gravity integrates cues from four systems: vestibular cues via the otolith system (a), visual (b), proprioceptive (c), and touch cues (d) to support spatial cognition and action. Interactive systems that ignore or conflict with these expectations can induce discomfort and performance breakdowns, motivating graviception-aware interaction design. For example, mid-air gestures, e.g., pointing, waving the hand, holding a cup of coffee, swiping on a smartphone, and grabbing and pouring a bottle induce different types of cues.

design. This omission was historically reasonable: interaction was predominantly planar, visually dominant, and used in stable postures. However, contemporary interaction increasingly involves spatial movement [4], bodily orientation [15], and immersion in isolated, confined, extreme environments [42], such as under water [30]. Virtual and augmented reality [9,19], mobile and wearable devices [4,19], mid-air gestures [17,38], and teleoperation systems [24] all require users to interpret spatial information while moving through gravity-bound environments [21]. Prior work in neuroscience demonstrates that gravity perception shapes spatial cognition, motor planning, and perceptual stability [2,22]. In HCI, sensory conflict has been linked to motion sickness [10,23,32,40], disorientation [6], and degraded task performance [19]. Yet, graviception itself is rarely treated as an explicit design dimension, despite that HCI is future-oriented by nature [36].

To address that gap, our research question is: How does graviception impact human–computer interaction? How should we account for it? To this end, we contribute (1) a synthesis of some graviception research findings relevant to HCI but found in other fields, mainly biomechanical engineering and an analysis of how graviceptive factors manifest in interactive systems (Section 2), and (2) some actionable implications for designing *graviception-aware* interaction to be further discussed (Section 3).

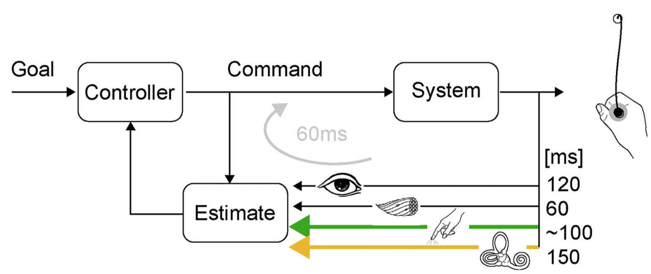

Figure 3: Model of the human graviception: response times from various systems [20].

2 Related Work and Background

Background. Graviception refers to the perception of gravity's direction and magnitude [5], distinct from proprioception [22] (limb position sense) and interoception [12] (internal bodily states) by connecting four systems:

(1) *The vestibular system*: this organ, which is located in the bony labyrinth of the inner ear, comprises two components [2], i.e., the *otoliths*, which perceive linear acceleration and head tilt relative to gravity [31], and the *semicircular canals*, which

perceive angular acceleration by responding to rotational acceleration [29].

(2) *The visual system*: verticality and horizon lines contribute to perceiving up/down orientation [26].
(3) *The proprioceptive system*: our innate sense of position, movement, and effort in space, allow us to move, balance, and coordinate our movements.
(4) *The somatosensory input*: pressure on the feet, body support surfaces, and muscle tensions inform orientation.

Graviception influences spatial judgments, motor control, and perceptual stability: spatial orientation is influenced by body posture and gravitational cues [18], motor planning depends on predictive internal models of gravity [14]. When signals coming from these four systems conflict, performance and comfort degrade. As long as the signals from the four systems of graviception converge [33], motor and cognitive controls function normally [24]. However, as soon as signals from one of these systems are no longer consistent with those received by the other systems, these controls can be significantly disrupted. The most telling example is that of a virtual reality user moving in a mobile context: if physical movement in the mobile context goes in one direction while movement in virtual reality goes in another direction, the visual system produces signals that are inconsistent with those produced by proprioception. This causes a disruption that degrades user performance [33], reduces spatial accuracy [5], increases error rates [3], and induces cybersickness [23]. These negative effects suggest that graviception acts as an impactful constraint on interaction.

Graviception offers an emerging approach to HCI by leveraging the four subsystems for novel interface design, which we refer to as ***graviception-aware HCI design*** or ***graviceptive HCI design***. Some studies already explored how graviception can be integrated into HCI, but very anecdotically or partially. Mittelstaedt[28] demonstrated that human trunk graviceptors impact body posture perception. Hemmert et al.[16] developed weight-shifting mobile phones that dynamically alter gravitational properties, suggesting three potential application domains: augmenting digital content, creating ambient displays, and enhancing wayfinding. Fallman[11] exaggerated tilt interaction beyond metaphorical representations, instead grounding interface design in physical world interactions. Lefebvre et al.[24] show that vestibular and somatosensory signals impact the spatial perception and motor planning/control: the tilts of an observer's body and those of an object perceived in virtual reality, and the directions of body rotation and manual movements, on visual perception and object orientation control are impacted.

While the research is still nascent, these studies indicate graviception's potential to create more embodied, intuitive HCI by directly incorporating gravitational sensing and movement. Graviception-aware HCI is particularly appropriate in emerging interfaces such as Virtual Reality (VR), Augmented Reality (AR), haptic interaction [27], mobile computing, accessibility [35] and teleoperation [9, 34], which all place end users in dynamic spatial contexts of use. These systems frequently decouple signals from various systems, such as visual cues from vestibular signals [1], thereby amplifying graviceptive conflict. Graviception can impact several interaction modalities, such as:

- *Interaction in Extended Reality*: Users in virtual environments (e.g., VR and AR) often report disorientation when virtual gravity does not align with vestibular cues, leading to motion sickness [40] and reduced immersion. Tasks requiring precise vertical judgments (e.g., stacking objects) suffer when visual gravity cues conflict with body orientation.
- *Mobile interaction*: Tilting a smartphone alters the relationship between gravity and UI elements. Users sometimes misinterpret tilt-based actions when gravitational feedback contradicts visual feedback.
- *Haptic interaction*: Devices mounted on the body influence perceived force feedback depending on body orientation, which impacts movement control. The lack of graviceptive cues may reduce haptic realism. Similarly, haptic devices manipulated in extreme conditions can be impact by distorted movement control [27].
- *Gestural interaction*: Mid-air gestures are particularly exposed to gravity. Figure 1 shows an experimental setup where horizontal wrist-based mid-air gestures are particularly impacted by the rotational speed of a centrifuge. In the last condition simulating a spatial vehicle at taking off, the vision and the gravity induced by the rotational speed significantly impact the arm capability to produce gestures.

In sum, while there are some preliminary investigations, the intersection considered between graviception and HCI in under-articulated. On the one hand, there are some references about how graviception in humans is influenced by organs in the trunk, not by mechanoreceptors in legs or skin, but without any direct relation to HCI discussed. On the other hand, there are some references exploring HCI using human body movements as input, finding more flexible and naturalistic interfaces, but do not specifically address graviception. There are indeed studies on interaction that consider factors specific to graviception, even if they do not use this terminology.

3 Implications for Graviception-Aware HCI

We propose actionable implications to integrate graviceptive considerations into design, prototyping, and evaluation of interaction, whether for a system, a study, or a design method. To derive these implications, graviception, as considered in biomechanical engineering and neuroscience, is conceptually extrapolated into HCI design decisions. Before that, we acknowledge that graviception impacts several HCI aspects:

- *Spatial cognition*: estimates of distance, orientation, and object placement change with body posture and gravity [18].
- *Motor control*: reaching, pointing, and locomotion depend on predicting how gravity will affect movement [14].
- *Attention and perception*: visual processing prioritizes stable environmental frames; gravity congruence aids interpretation of motion and object behaviour [31].
- *Cognitive load*: in environments where sensory cues conflict (e.g., in microgravity [7], VR [40]), users experience cognitive load, motion sickness, or degraded performance due to mismatched graviceptive expectations.

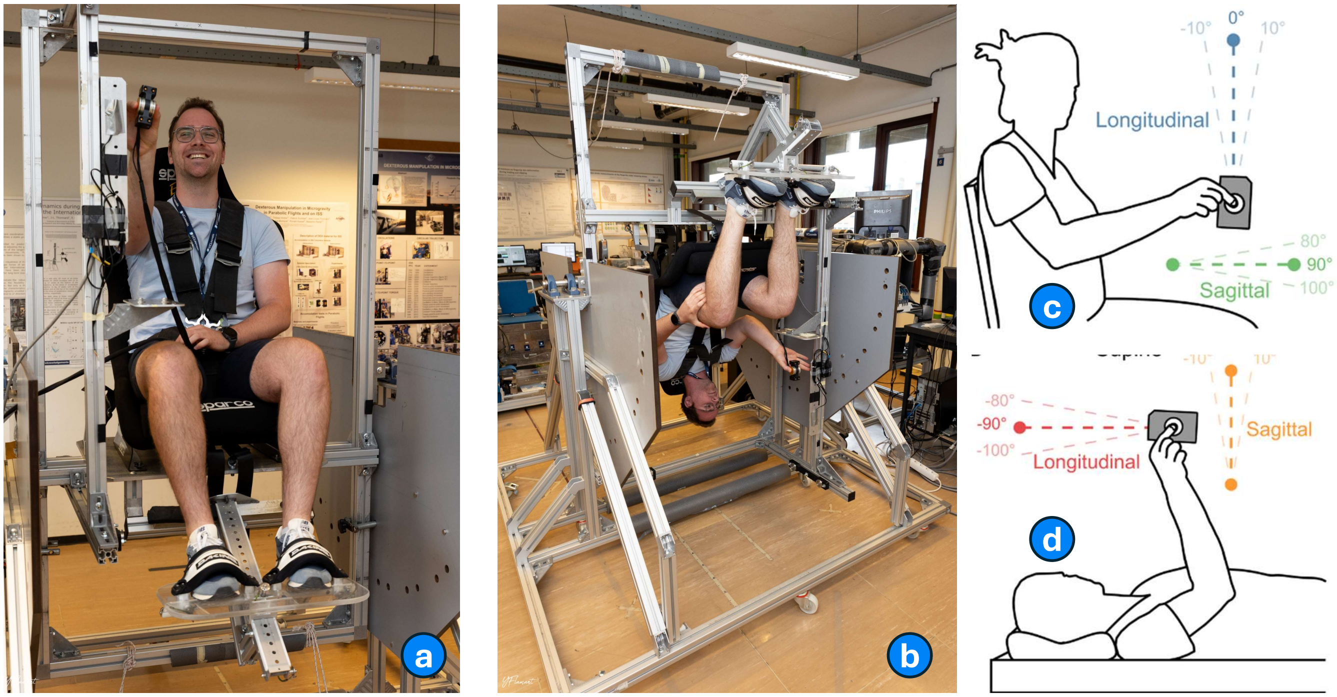

Figure 4: An example of a graviceptive-aware setup: a user manipulating an object in a swivel chair in normal position (a), upside-down position (b). A reference system perpendicular to gravity (d) is used instead of a parallel one (c).

> ✍ **Invent and use graviceptive-aware experimental setups.** To explicitly take into account factors related to graviception, the experimental setup must be specifically tailored for this purpose by capturing metrics impacted by graviception. **Rationale**: a graviceptive-aware setup should be able to detect and interpret metrics such as orientation and gravitational cues, acceleration vectors, tilt angles, and orientation changes relative to the gravity field. Recording these metrics allows to distinguish gravity-induced signals from other forces or movements, ensuring that observed interaction can be accurately attributed to gravitational perception rather than external factors.

Examples. A user sitting in a chair attached to the ceiling with a flexible and controllable spring that modulates the effect of gravity by simulating Earth acceleration ($g \approx 9.81 m/s^2$), Moon acceleration ($g \approx 1.62 m/s^2$), and Mars acceleration ($g \approx 3.71 m/s^2$), captures vertical jumps through inertial sensors such as accelerometers and gyroscopes (Fig. 4). Mid-air gestures of users are captured by a Kinemic wrist-based sensor depending on the circular acceleration of a centrifuge (i.e., $1g$ for normal gravity, $1.5g$ for increased gravity, and $2.7g$ to simulate gravity at taking off of a rocket - Fig. 1). Orientation-aware displays are adapted depending on the angle of a swivel chair (Fig. 4). **Impact on HCI**. Using graviceptive-aware experimental setups impact HCI design decisions by revealing how gravity and body orientation influence perception, movement, and interaction. When designers understand how users respond differently while standing, sitting, tilting, or moving, they can create interfaces that adapt to these conditions, such as how vision and gravity influence body movements and how body orientation impacts movement control. This leads to interaction techniques that feel more natural, reduce physical and cognitive strain, and remain robust across various contexts of use. Overall, graviceptive awareness encourages designs that align more closely with embodied human experience rather than assuming a fixed, gravity-neutral user posture, which is further addressed in the next implication.

> ✍ **Align virtual gravity with contextual requirements.** To ensure gravity congruence, especially in immersive environments, the virtual gravity should be aligned with real gravity unless purposefully altered for effect. **Rationale**: visual cues, such as consistent lighting and horizon lines, strengthen graviception for dynamic feedback; when objects move in a VR scene, that is itself moving, a realistic acceleration/deceleration should be simulated to support intuitive interaction and to avoid visual inconsistency.

Examples. In VR object manipulation [14] or target selection [45], physics engines should simulate weight and inertia faithfully to avoid floating objects without explanation. Fig. 5 illustrates a spring chair attached to the ceiling that accommodates high jumps by simulating inertia to identify new locomotion patterns, while navigating in a VR scene representing a Mars walk [41]. **Impact on HCI.** By ensuring this alignment, designers can better grasp how end users interpret space, motion, and causality within a UI. When virtual gravity matches the context of use, such as mimicking real-world gravity for training (Fig. 1-a) or deliberately altering it for exploration (Fig. 5), interactions are expected to become more learnable and meaningful. Designers must therefore decide whether to reinforce users' real-world expectations (e.g., by supporting realism and concordance with real-world) or to intentionally diverge from them (e.g., to explore novel interaction techniques or to better shape existing ones). This alignment affects choices around object behaviour, navigation methods, feedback timing, and user orientation.

> ✍ **Use graviceptive cues to preserve spatial orientation.** Visual vertical cues, such as horizons, vertical axes, and landmarks should be provided to reinforce gravitational direction. **Rationale**: the posture awareness should be preserved by detecting the current user's posture (e.g., standing, sitting, tilted) and by adjusting interface feedback accordingly (e.g., reorient HUD elements when walking on the Moon [4]).

Examples. Spatial orientation for users in a centrifuge (Fig. 1) can be preserved by providing consistent sensory cues that help the brain interpret motion and direction correctly: a visible floor, a constant ceiling, and fixed horizon lines aligned with the direction of artificial gravity (Fig. 1-b), allow the visual system to anchor the body's orientation. Gradual spin-up and spin-down rates reduce conflicting signals between the inner ear and visual input. Together, synchronized visual, vestibular, and physical cues help the brain adapt and maintain a coherent spatial frame of reference while inside the rotating environment. *Orientation-responsive displays* [13], which are user interfaces and display systems that dynamically adjust their content or functionality based on their physical orientation and spatial relationship to the user and environment, such as based on head orientation [15].

Impact on HCI. Using graviceptive cues has a strong impact on UI design, particularly during prototyping and evaluation. Incorporating gravity-aligned cues helps users maintain a stable sense of "up," "down," and spatial continuity. During prototyping, this encourages designers to test interactions across different body postures and device orientations, revealing breakdowns in orientation that might otherwise go unnoticed. In evaluation, graviceptive cues become measurable factors affecting usability, error rates, and user comfort, that would be otherwise left unconsidered. Designing with graviceptive cues leads to UIs that reduce disorientation, lower cognitive load, and better support users' embodied [8] understanding of space.

> ✍ **Minimize graviceptive conflict.** To ensure sensory consistency, situations where visual, inertial, and vestibular cues about movement and orientation conflict should be avoided. **Rationale**: smooth transitions should be always established: when changing environments (e.g., switching scenes in VR), fade or guide transitions to allow users' gravity expectations to update.

Examples. In VR locomotion, physical treadmills or subtle physical motion cues could be combined with visual movement to reduce sensory mismatch and ensure sensorimotor coherence [1,21]. User interface elements, such as those of a head-up display [4], should be oriented so that "down" on the display always aligns with the artificial gravity direction felt by the user's body, toward their feet, not the real gravity. The horizon line, progress bars, and directional arrows remain fixed relative to this perceived down direction. Animated transitions could ensure a transition between the real gravity and the artificial one, provided that they are kept smooth and slow, avoiding sudden rotations or flips that would perturb vestibular and proprioceptive cues. **Impact on HCI.** Minimizing graviceptive conflict guides designers to align visual, motion, and interaction cues with users' gravitational expectations to prevent disorientation and discomfort. This results in UIs that are more comfortable, interpretable, and reliable, particularly in immersive or motion-intensive contexts.

> ✍ **Explicitly include graviceptive factors during evaluation.** Incorporate tasks that assess orientation perception and motor control under different gravity-related conditions. **Rationale**: such factors could include physiological measures, questionnaires, motion sickness scales, and postural sway analysis to identify issues related to graviceptive conflict.

Examples. During usability evaluation of immersive systems, explicitly ask participants about perceived realism of weight and spatial orientation. While no widely accepted stand-alone questionnaire exists to evaluate graviceptive-aware factors, several questionnaires assess related aspects, such as gravitational imprint [43], cybersickness [6]. Graviception measures could include the *Subjective Visual Vertical* (where participants align a line to what they perceive as vertical) and the *Subjective Postural Vertical* (where participants judge body orientation relative to gravity). Fig. 4-a shows that a participant manipulating an object while lying down (Fig. 4-b) can be analyzed with a reference system whose sagittal and longitudinal axes are reoriented according to their position rather than according to actual gravity (Fig. 4-c,d). This reference system could enrich user studies (e.g., [4,14,15,26]) as well as their design methods (e.g., [21,22]).

Impact on HCI. Traditional evaluation metrics, such as task completion time, error rate, and subjective satisfaction, may look acceptable under stable conditions but degrade significantly when users are tilted, moving, or immersed in 3D environments. Including graviceptive-sensitive factors should identify unexpected usability errors, reasons for increased cognitive load, and early signs of discomfort or motion conflict. Quantitative factors could estimate spatial orientation stability through deviation from intended movement paths, frequency of unintended rotations or drift, and reorientation time after tilt or motion. Qualitative factors could incorporate new items in user experience questionnaires related to perceived stability and groundedness, feeling of instability, and sense of embodiment.

> ✍ **Support accessibility and variability in graviception.** Sensitivity to graviceptive conflict varies widely across users and should be explicitly addressed. **Rationale**: the individual differences of users in vestibular sensitivity should be considered to preserve accessibility [45], e.g., by providing options to adjust motion intensity, gravity simulation, and visual motion cues. For users with vestibular disorders, alternative feedback channels (e.g., enhanced visual cues or haptic feedback) should be considered to support spatial tasks.

Examples. Include settings to reduce motion animations and tilt-based interactions for users prone to discomfort. Consider a balance between internal validity and ecological validity by introducing three levels of fidelity to perceiving graviception: *low* fidelity (e.g.,

Figure 5: An example of a graviceptive-aware design: a user sitting in a spring chair attached to the ceiling navigating in virtual reality under normal conditions (a), with low-gravity simulation (b), and walking back (c).

by operating in a swimming pool), *medium* fidelity (e.g., by operating during a parabolic flight), and *high* fidelity (e.g., by operating in a spatial station). WalkingVibe [32] minimizes cybersickness while optimizing realism in VR walking. **Systems** could also be enriched by considering these aspects. Gunslinger [25] enables users to control large displays with hand gestures in an arms-down, vertical posture, which could be impacted by graviception depending on the user and the context of use. Gesture recognizers [38] should become also graviception-aware: users interacting with horizontal gestures in the centrifuge (Fig. 1-b and Fig. 1-c) can be significantly impacted by the circular acceleration on their arm and the corresponding gesture recognizer (e.g., [7]) should be adapted accordingly. **Impact on HCI.** Graviceptive-aware user interface design improves accessibility by accommodating users with impaired balance, proprioception, or mobility, ensuring interactions remain stable and interpretable across different postures and orientations. Regarding rehabilitation, it supports safer, more effective therapy by aligning UI feedback with patients' perception, enabling gradual retraining of balance, spatial awareness, and motor control. Understanding the impact of graviception on accessibility should make it possible to improve these UIs not only for people with disabilities, but also to mitigate potential problems for able-bodied people.

> ✍ **Incorporate wearable haptics for graviceptive navigation.** Directional haptic feedback should be calibrated relative to the user's upright orientation, not merely device coordinates. **Rationale**: Wearables providing directional haptic cues should align vibration patterns with gravitational reference frames.

Examples. Tactile belts that guide users relative to true north should calibrate considering the user's upright posture. ExoSkin [37] is a morphing haptic feedback that augments spacesuit gloves by controlling the transfer of haptic information from external touch to internal touch. **Impact on HCI.** This UI design should convey gravity-aligned cues, such as directional vibration or pressure gradients, to support navigation without relying solely on visual information. These haptic signals should be consistent, low-latency, and adaptable to user posture and movement so that graviceptive guidance remains consistent across changing contexts of use [38].

4 Conclusion

Graviception shapes how users perceive and work with interactive systems. Recognizing graviception as a relevant modality, integrating four systems, in HCI bridges a gap between embodied human capabilities and interaction design. As interfaces become more spatial and immersive, ignoring gravity's influence can inadvertently increase cognitive load, frustration, and exclusion. Conversely, intentionally leveraging graviceptive cues can enhance intuitiveness, presence, and performance. We coined and defined the term "graviception-aware HCI design" to reflect this consideration. To substantiate its application, we suggest some implications, each being expressed with a short sentence, a long statement, a rationale behind it, and some examples. We also discussed how graviception-aware HCI can be incorporated into studies, design methods, and systems. While this work is primarily conceptual and in its infancy, it establishes a foundation for future empirical validation of graviception-aware HCI. Challenges remain: accurately measuring graviceptive integration in real time, individual differences complicate accessibility design. However, incorporating graviceptive considerations need not be technically prohibitive.

Acknowledgments

Radu-Daniel Vatavu and Jean Vanderdonckt acknowledge support from a grant of the Romanian Ministry of Research, Innovation and Digitization, CCCDI-UEFISCDI, PN-IV-P8-8.3-PM-RO-BE-2024-0003, within PNCDI IV and Wallonnie-Bruxelles International (WBI) Grant no. 650763 (WBI ref. PAD/CC/VP/TM - Roumanie - SUB/2024/650763)—project XXR (Novel Extended Reality Models and Software Framework for Interactive Environments with Extreme Conditions). Nuwan Attygalle and Jean Vanderdonckt are supported by the EU EIC Pathfinder-Awareness Inside challenge "Symbiotik" project (1 October 2022-30 September 2026) under Grant no. 101071147. Jean Vanderdonckt acknowledges the support of the Louvain4Space technological platform. Merle Fairhurst acknowledges funding by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany's Excellence Strategy – EXC 2050/2 – Project ID 390696704 – Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop" (CeTI) of TUD Dresden University of Technology.

References

[1] Marco Alessandrini, Alessandro Micarelli, Andrea Viziano, I. Pavone, Giovanni Costantini, Daniele Casali, Fabio Paolizzo, and Giovanni Saggio. June 2017. Body-worn triaxial accelerometer coherence and reliability related to static posturography in unilateral vestibular failure. *Acta Otorhinolaryngol Ital.* 37, 3 (June 2017), 231–236. doi:10.14639/0392-100X-1334

[2] Dora E. Angelaki and Kathleen E. Cullen. 2008. Vestibular System: The Many Facets of a Multimodal Sense. *Annual Review of Neuroscience* 31 (2008), 125–150. doi:10.1146/annurev.neuro.31.060407.125555

[3] Daniel Bachmann, Frank Weichert, and Gerhard Rinkenauer. 2018. Review of Three-Dimensional Human-Computer Interaction with Focus on the Leap Motion Controller. *Sensors* 18, 7 (2018). doi:10.3390/s18072194

[4] Leonie Bensch, Tommy Nilsson, Jan Wulkop, Paul Demedeiros, Nicolas Daniel Herzberger, Michael Preutenborbeck, Andreas Gerndt, Frank Flemisch, Florian Dufresne, Georgia Albuquerque, and Aidan Cowley. 2024. Designing for Human Operations on the Moon: Challenges and Opportunities of Navigational HUD Interfaces. In *Proceedings of the ACM International Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 718, 21 pages. doi:10.1145/3613904.3642859

[5] Marc D. Binder. 2009. *Graviception*. Springer Berlin Heidelberg, Berlin, Heidelberg, 1766–1767. doi:10.1007/978-3-540-29678-2_2082

[6] Nilotpal Biswas, Anamitra Mukherjee, and Samit Bhattacharya. 2024. "Are you feeling sick?" – A systematic literature review of cybersickness in virtual reality. *Comput. Surveys* 56, 11, Article 284 (June 2024), 38 pages. doi:10.1145/3670008

[7] Loïc Chomienne, Patrick Sainton, Fabrice R. Sarlegna, and Lionel Bringoux. 2025. Hypergravity is more challenging than microgravity for the human sensorimotor system. *npj Microgravity* 11, 2 (2025). doi:10.1038/s41526-024-00452-x

[8] Paul Dourish. 2004. *Where the Action Is - The Foundations of Embodied Interaction*. MIT Press. http://mitpress.mit.edu/books/where-action

[9] Florian Dufresne, Tommy Nilsson, Geoffrey Gorisse, Enrico Guerra, André Zenner, Olivier Christmann, Leonie Bensch, Nikolai Anton Callus, and Aidan Cowley. 2024. Touching the Moon: Leveraging Passive Haptics, Embodiment and Presence for Operational Assessments in Virtual Reality. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 413, 18 pages. doi:10.1145/3613904.3642292

[10] Ahmed Ibrahim Ahmed Mohamed Elsharkawy, Aya Abdulnasser Saed Ataya, Dohyeon Yeo, Eunsol An, Seokhyun Hwang, and SeungJun Kim. 2024. SYNC-VR: Synchronizing Your Senses to Conquer Motion Sickness for Enriching In-Vehicle Virtual Reality. In *Proceedings of the ACM International Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 257, 17 pages. doi:10.1145/3613904.3642941

[11] Daniel Fallman. 2002. An Interface with Weight: Taking Interaction by Tilt beyond Disembodied Metaphors. In *Human Computer Interaction with Mobile Devices*, Fabio Paternò (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 291–295.

[12] Norman Farb, Jennifer Daubenmier, Cynthia J. Price, Tim Gard, Catherine Kerr, Barnaby D. Dunn, Anne Carolyn Klein, Martin P. Paulus, and Wolf E. Mehling. 2015. Interoception, contemplative practice, and health. *Frontiers in Psychology* Volume 6 - 2015 (2015). doi:10.3389/fpsyg.2015.00763

[13] Sands Fish. 2022. Orientation-Responsive Displays for Microgravity. In *Proceedings of the SpaceCHI 2.0 Workshop, Advancing Human-Computer Interaction for Space Exploration at CHI 2022 (SpaceCHI 2.0)*. MIT Media Lab, MA, USA, 5 pages. https://drive.google.com/open?id=1BUQDkbt6tSCJ759Z00FuaEmm6Af5h2z9

[14] J Randall Flanagan, Miles C Bowman, and Roland S Johansson. 2006. Control strategies in object manipulation tasks. *Current Opinion in Neurobiology* 16, 6 (2006), 650–659. doi:10.1016/j.conb.2006.10.005 Motor systems / Neurobiology of behaviour.

[15] Michel Guerraz, Jean Blouin, and Jean-Louis Vercher. 2003. From head orientation to hand control: evidence of both neck and vestibular involvement in hand drawing. *Experimental Brain Research* 150, 3 (2003), 40–49. doi:10.1007/s00221-003-1411-y

[16] Fabian Hemmert, Susann Hamann, Matthias Löwe, Josefine Zeipelt, and Gesche Joost. 2010. Weight-shifting mobiles: two-dimensional gravitational displays in mobile phones. In *Extended Abstracts of Proceedings of ACM International Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI EA '10)*. Association for Computing Machinery, New York, NY, USA, 3087–3092. doi:10.1145/1753846.1753922

[17] Masoumehsadat Hosseini, Tjado Ihmels, Ziqian Chen, Marion Koelle, Heiko Müller, and Susanne Boll. 2023. Towards a Consensus Gesture Set: A Survey of Mid-Air Gestures in HCI for Maximized Agreement Across Domains. In *Proceedings of the ACM International Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 311, 24 pages. doi:10.1145/3544548.3581420

[18] Ian P. Howard. 1982. *Human Visual Orientation*. Wiley, Chichester, UK.

[19] Jason Jerald. 2015. *The VR Book: Human-Centered Design for Virtual Reality*. ACM Books, New York, NY, USA. doi:10.1145/2792790

[20] Hari T. Kalidindi and Frédéric Crevecoeur. 2023. Human reaching control in dynamic environments. *Current Opinion in Neurobiology* 83 (2023), 102810. doi:10.1016/j.conb.2023.102810

[21] Marie Keime, Loïc Chomienne, Cédric Goulon, Patrick Sainton, Thomas Lapole, Rémy Casanova, Martin Bossard, Caroline Nicol, Cécile Martha, Benoit Bolmont, Arnaud Hays, Fabrice Vercruyssen, Pascale Chavet, and Lionel Bringoux. 2023. How about running on Mars? Influence of sensorimotor coherence on running and spatial perception in simulated reduced gravity. *Frontiers in Physiology* 14 (2023). doi:10.3389/fphys.2023.1201253

[22] James R. Lackner and Paul DiZio. 2005. Vestibular, Proprioceptive, and Haptic Contributions to Spatial Orientation. *Annual Review of Psychology* 56 (2005), 115–147. doi:10.1146/annurev.psych.55.090902.142023

[23] Joseph J. LaViola. 2000. A discussion of cybersickness in virtual environments. *SIGCHI Bull.* 32, 1 (Jan. 2000), 47–56. doi:10.1145/333329.333344

[24] Maëlis Lefebvre, João Bolina Rei, Elena López-Contreras González, Raphaëlle N. Roy, and Vsevolod Peysakhovich. 2025. Spatial Compatibility and Intersensory Conflicts in Teleoperation: Impact on Object Orientation Control in Virtual Reality. *J. Hum.-Robot Interact.* 14, 4, Article 62 (July 2025), 16 pages. doi:10.1145/3724132

[25] Mingyu Liu, Mathieu Nancel, and Daniel Vogel. 2015. Gunslinger: Subtle Arms-down Mid-air Interaction. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 63–71. doi:10.1145/2807442.2807489

[26] Paul R. MacNeilage, Martin S. Banks, Daniel R. Berger, and Heinrich H. Bülthoff. 2007. A Bayesian Model of the Disambiguation of Gravitoinertial Force by Visual Cues. *Experimental Brain Research* 179, 2 (2007), 263–290. doi:10.1007/s00221-006-0792-0

[27] Julie Manon, Jean Vanderdonckt, Michael Saint-Guillain, Vladimir Pletser, Cyril Wain, Jean Jacobs, Audrey Comein, Sirga Drouet, Julien Meert, Ignacio S. Casla, Olivier Cartiaux, and Olivier Cornu. 2025. A Multi-Session Evaluation of a Haptic Device in Normal and Critical Conditions: a Mars Analog Mission. *Int. J. Interact. Multim. Artif. Intell.* 9, 3 (2025), 164. doi:10.9781/IJIMAI.2025.04.001

[28] Horst Mittelstaedt. 1997. Interaction of Eye-, Head-, and Trunk-Bound Information in Spatial Perception and Control1. *Journal of Vestibular Research* 7, 4 (1997), 283–302. arXiv:https://journals.sagepub.com/doi/pdf/10.3233/VES-1997-7402 doi:10.3233/VES-1997-7402

[29] Hironobu Morita, Hiroshi Kaji, Yoichi Ueta, and Chikara Abe. 2020. Understanding vestibular-related physiological functions could provide clues on adapting to a new gravitational environment. *The Journal of Physiological Sciences* 70, 1 (2020), 17. doi:10.1186/s12576-020-00744-3

[30] Florian 'Floyd' Mueller, Maria F. Montoya, Sarah Jane Pell, Leif Oppermann, Mark Blythe, Paul H Dietz, Joe Marshall, Scott Bateman, Ian Smith, Swamy Ananthanarayan, Ali Mazalek, Alexander Verni, Alexander Bakogeorge, Mathieu Simonnet, Kirsten Ellis, Nathan Arthur Semertzidis, Winslow Burleson, John Quarles, Steve Mann, Chris Hill, Christal Clashing, and Don Samitha Elvitigala. 2024. Grand challenges in WaterHCI. In *Proceedings of the ACM International Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 225, 18 pages. doi:10.1145/3613904.3642052

[31] Laurent Opsomer, Simon Vandergooten, Michele Tagliabue, Jean-Louis Thonnard, Philippe Lefèvre, and Joseph McIntyre. 2025. A Singular Theory of Sensorimotor Coordination: On Targeted Motions in Space. *Journal of Neuroscience* 45, 8 (2025). arXiv:https://www.jneurosci.org/content/45/8/e1384242024.full.pdf doi:10.1523/JNEUROSCI.1384-24.2024

[32] Yi-Hao Peng, Carolyn Yu, Shi-Hong Liu, Chung-Wei Wang, Paul Taele, Neng-Hao Yu, and Mike Y. Chen. 2020. WalkingVibe: Reducing Virtual Reality Sickness and Improving Realism while Walking in VR using Unobtrusive Head-mounted Vibrotactile Feedback. In *Proceedings of the ACM International Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3313831.3376847

[33] Bernhard E. Riecke, Jörg Schulte-Pelkum, Marios N. Avraamides, Markus Von Der Heyde, and Heinrich H. Bülthoff. 2006. Cognitive factors can influence self-motion perception (vection) in virtual reality. *ACM Trans. Appl. Percept.* 3, 3 (July 2006), 194–216. doi:10.1145/1166087.1166091

[34] Giovanni Saggio and Mariano Bizzarri. 2014. Feasibility of teleoperations with multi-fingered robotic hand for safe extravehicular manipulations. *Aerospace Science and Technology* 39 (2014), 666–674. doi:10.1016/j.ast.2014.05.018

[35] Giovanni Saggio, Stefano Bocchetti, Carlo Alberto Pinto, and Giancarlo Orengo. 2011. Electronic Interface and Signal Conditioning Circuitry for Data Glove Systems Useful as 3D HMI Tools for Disabled Persons. In *Proceedings of the International Conference on Health Informatics* (Rome, Italy) *(HEALTHINF 2011)*, Vicente Traver, Ana L. N. Fred, Joaquim Filipe, and Hugo Gamboa (Eds.). SciTePress, 248–253.

[36] Camilo Sanchez, Sui Wang, Kaisa Savolainen, Felix Anand Epp, and Antti Salovaara. 2025. Let's Talk Futures: A Literature Review of HCI's Future Orientation.

In *Proceedings of the ACM International Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, Article 487, 36 pages. doi:10.1145/3706598.3713759

[37] Sue Ann Seah, Marianna Obrist, Anne Roudaut, and Sriram Subramanian. 2015. Need for Touch in Human Space Exploration: Towards the Design of a Morphing Haptic Glove – ExoSkin. In *Human-Computer Interaction – INTERACT 2015*, Julio Abascal, Simone Barbosa, Mirko Fetter, Tom Gross, Philippe Palanque, and Marco Winckler (Eds.). Springer International Publishing, Cham, 18–36.

[38] Arthur Sluÿters, Quentin Sellier, Jean Vanderdonckt, Vik Parthiban, and Pattie Maes. 2023. Consistent, Continuous, and Customizable Mid-Air Gesture Interaction for Browsing Multimedia Objects on Large Displays. *International Journal of Human–Computer Interaction* 39, 12 (2023), 2492–2523. arXiv:https://doi.org/10.1080/10447318.2022.2078464 doi:10.1080/10447318.2022.2078464

[39] Irene Valori, Jasmin L. Merkel, Giovanna Furlan, Tobias Grossmann, and Merle T. Fairhurst. 2025. Touch facilitates newborns' self-regulation: Systematic review of multidimensional arousal outcomes. *Neuroscience & Biobehavioral Reviews* 178 (2025), 106353. doi:10.1016/j.neubiorev.2025.106353

[40] Thomas van Gemert, Niels Christian Nilsson, Teresa Hirzle, and Joanna Bergström. 2024. Sicknificant Steps: A Systematic Review and Meta-analysis of VR Sickness in Walking-based Locomotion for Virtual Reality. In *Proceedings of the ACM International Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 632, 36 pages. doi:10.1145/3613904.3641974

[41] Jean Vanderdonckt, Radu-Daniel Vatavu, Julie Manon, Michael Saint-Guillain, Philippe Lefevre, and Jessica J. Marquez. 2024. Might as Well Be on Mars: Insights on the Extraterrestrial Applicability of Interaction Design Frameworks from Earth. In *Extended Abstracts of the ACM International Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, Article 239, 8 pages. doi:10.1145/3613905.3650807

[42] Radu-Daniel Vatavu and Jean Vanderdonckt. 2025. What is Extreme in Human-Computer Interaction Research?. In *Adjunct Proceedings of the 27th International Conference on Mobile Human-Computer Interaction (MobileHCI '25 Adjunct)*. Association for Computing Machinery, New York, NY, USA, Article 17, 7 pages. doi:10.1145/3737821.3749561

[43] O. White, J. Gaveau, L. Bringoux, and F. Crevecoeur. 2020. The gravitational imprint on sensorimotor planning and control. *Journal of Neurophysiology* 124, 1 (2020), 4–19. arXiv:https://doi.org/10.1152/jn.00381.2019 doi:10.1152/jn.00381.2019 PMID: 32348686.

[44] Amanda Williams, Eric Kabisch, and Paul Dourish. 2005. From Interaction to Participation: Configuring Space Through Embodied Interaction. In *UbiComp 2005: Ubiquitous Computing, 7th International Conference, UbiComp 2005, Tokyo, Japan, September 11-14, 2005, Proceedings (Lecture Notes in Computer Science, Vol. 3660)*, Michael Beigl, Stephen S. Intille, Jun Rekimoto, and Hideyuki Tokuda (Eds.). Springer, 287–304. doi:10.1007/11551201_17

[45] Zhiqing Wu, Duotun Wang, Shumeng Zhang, Yuru Huang, Zeyu Wang, and Mingming Fan. 2024. Toward Making Virtual Reality (VR) More Inclusive for Older Adults: Investigating Aging Effect on Target Selection and Manipulation Tasks in VR. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 24, 17 pages. doi:10.1145/3613904.3642558