# SwiVR-Car-Seat: Exploring Vehicle Motion Effects on Interaction Quality in Virtual Reality Automated Driving Using a Motorized Swivel Seat

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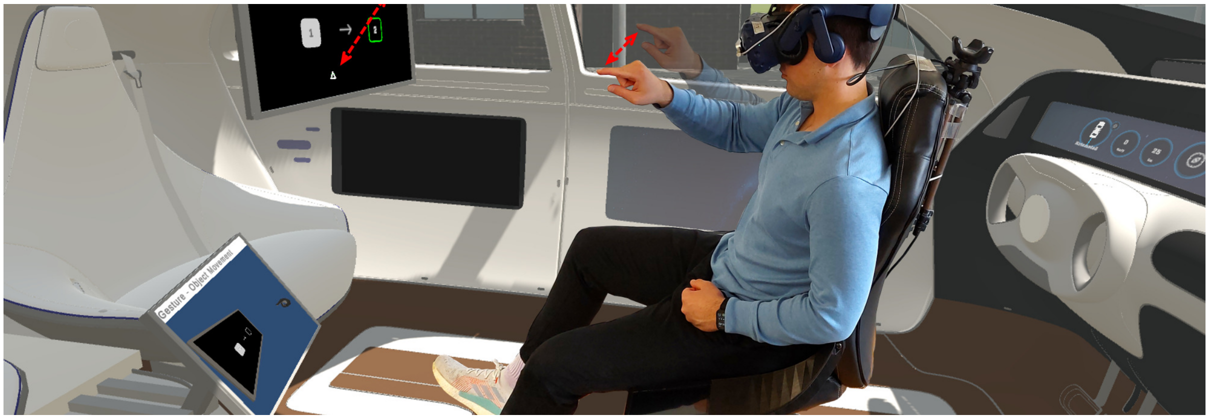

Fig. 1. *Gesture* controlled cursor while sitting on the *SwiVR-Car-Seat* and wearing a VR HMD in a virtual autonomous vehicle.



Autonomous vehicles provide new input modalities to improve interaction with in-vehicle information systems. However, due to the road and driving conditions, the user input can be perturbed, resulting in reduced interaction quality. One challenge is assessing the vehicle motion effects on the interaction without an expensive high-fidelity simulator or a real vehicle. This work presents *SwiVR-Car-Seat*, a low-cost swivel seat to simulate vehicle motion using rotation. In an exploratory user study ($N$=18), participants sat in a virtual autonomous vehicle and performed interaction tasks using the input modalities *touch*, *gesture*, *gaze*, or *speech*. Results show that the simulation increased the perceived realism of vehicle motion in virtual reality and the feeling of presence. Task performance was not influenced uniformly across modalities; *gesture* and *gaze* were negatively affected while there was little impact on *touch* and *speech*. The findings can advise automotive user interface design to mitigate the adverse effects of vehicle motion on the interaction.

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CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; User studies.

Additional Key Words and Phrases: Autonomous vehicles; interface design; vehicle motion simulation; interaction quality.

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## 1 INTRODUCTION

Autonomous vehicles (AVs) allow passengers to engage in non-driving related tasks (NDRTs) [61, 90] such as watching a movie, reading [28, 39] or work-related tasks like filling in documents. Currently, productive activities are done on mobile devices such as mobile phones and laptops. However, such devices might be inappropriate in AVs because vehicles do not necessarily provide an ergonomic and appropriate space for these [90] leading to tiredness during tasks and preventing engagement in NDRTs [39]. Recently, there has been a trend towards replacing traditional mechanical controls in vehicles, for example, buttons, knobs, and switches, with interactive displays, such as touchscreens [1]. Besides, many in-vehicle interaction concepts integrate multiple input modalities such as speech, gestures, or gaze to control the in-vehicle information system [4, 51, 64, 73, 76]. Such in-vehicle interaction concepts typically aim to enhance interaction regarding naturalness, efficiency, robustness, and flexibility [73]. Recent progress in head-mounted displays (HMDs) also enables passengers to leverage virtual reality (VR) and augmented reality (AR) for entertainment, leisure, and productivity in the vehicle environment [48]. Controlling a user interface (UI) with natural interaction such as gestures could make secondary input devices like mouse and keyboard redundant for specific tasks [90].

Several studies investigated UI design in terms of usability of input modalities and displays in the vehicle environment (e.g., [32, 33, 37, 57, 63]). The majority of such studies do not take the effects of vehicle motion into account, as they are conducted on low-fidelity simulators [1]. However, the interaction quality is affected as body parts may involuntarily move in a different direction due to inertia, resulting in erroneous inputs and inaccuracies [1, 20]. Rectifying interaction errors or adapting to the noisy environment requires attention (cognitive, visual, and manual) [1, 20, 33]. Therefore, it is necessary to consider the potential effects of vehicle motion on new UI designs or novel interaction techniques. Some studies investigated such effects on touch-based interactions (e.g., [1, 20, 52, 77]). Still, there is a lack of work on how such forces affect the interaction with other input modalities (e.g., gesture, gaze, and speech). Besides, it is an open question which modalities are suitable for which interaction tasks during the influence of vehicle motion. A major challenge for assessing the effects of vehicle motion is to simulate the inertial forces and vehicle dynamics present in on-road driving. Driving simulators allow researchers to create safe and reproducible stimuli, enabling rapid and safe empirical exploration [18]. However, in-lab driving simulators are often static and cannot simulate motion, whereas high-fidelity simulators can replicate motion but are expensive and require high maintenance effort. Therefore, existing research has proposed on-road automated driving simulation methods, using a Wizard-of-Oz (WoZ) driver behind a partition to control the vehicle [5]. Still, such a simulation approach requires access to a real vehicle and suitable roads to drive on that are often limited to specific safe areas (e.g., designated test tracks). Besides, users may be distracted by other persons in the car (e.g., the WoZ driver or the study examiner).

We propose using a swivel seat motion simulator (e.g., [71]) that leverages rotation to create the illusion of self-motion in VR and simulate the desired forces to some degree [71, 93]. While this approach is not able to **perfectly** replicate these forces at all times, simulating some forces is preferable to not simulating these at all.

This work presents the *SwiVR-Car-Seat* motion platform, a motorized swivel seat based on work by Rietzler et al. [71] which we utilized to simulate vehicle motion using rotation in VR to explore the effects of vehicle motion on the interaction quality. A VR user study (*N*=18) was conducted in which participants sat in a simulated AV and

performed atomic interaction tasks (selection and movement) while using the input modalities touch, gesture, gaze, or speech with and without the simulated forces. The results show that the *SwiVR-Car-Seat* increased the feeling of vehicle motion to a moderately realistic degree and increased the feeling of presence in the simulation environment causing only minor simulator sickness symptoms. We found a non-uniform effect of vehicle motion simulation on task performance. Vehicle motion negatively impacted task performance when using gesture or gaze input, while there was little impact on touch and speech interaction. Besides, selection tasks were less affected by vehicle motion compared to movement tasks when using gesture or gaze. In contrast, there was nearly no difference in the performance of selection and movement tasks when using touch or speech.
*Contribution Statement:* (1) A concept for simulating vehicle motion using rotation in VR, including approaches for rotation duration, speed, sequence, and mapping of simulation areas to a virtual road using a motorized swivel seat supporting one-dimensional movement to simulate motion containing two touchscreens embedded into custom 3D printed seat armrests. (2) Findings of an exploratory VR user study ($N$=18) based on a simulation of a virtual ride in an AV, while objectively and subjectively assessing the effects of vehicle motion on the interaction quality with four input modalities (touch, gesture, gaze, or speech).

## 2 RELATED WORK

The proposed concept of vehicle motion simulation using rotation is based on (1) vection during sensory conflicts, (2) existing motion feedback systems in VR, and (3) vehicle simulation environments in academia and industry. Additionally, previous works regarding (4) input modalities in (autonomous) vehicles are presented that are considered in an evaluation of the (5) effects of vehicle motion on (6) atomic interaction tasks.

### 2.1 Vection during Sensory Conflicts and Motion Feedback Systems

Vection is the subjective experience of self-motion [3, 54]. The vestibular system only detects acceleration, thus, by applying a rotational acceleration to simulate accelerating/braking vehicle motion in VR (similar to [71, 93]), the illusion of self-motion (vection) can be created. To provide visual and vestibular stimuli, Rietzler et al. [71] gave a non-conformant vestibular stimulus (rotational acceleration) synchronously with a visual stimulus. They found that a rotational impulse combined with visual motion was found to increase vection [71, 93]. However, vection could cause simulator sickness [24] as it is often attributed to sensory conflict [41, 66].

One other way to resolve sensory conflicts is to use motion feedback [10, 21, 46, 65, 71]. Therefore, motion platforms create related motions to match virtual ones and can be categorized according to their supported degrees of freedom (DoF). Supporting high DoF is costly (the NADS-1 [53] costs $80 million); therefore, it was investigated whether lower DoF suffice to create a sense of realistic motion, which was the case [10, 21, 71]. There are also commercial products such as the HapSeat [10], rotoVR [75] (1 DoF swivel chair), or yawVR [94] (3 DoF chair). In contrast to rotoVR and in line with the implementation of SwiVRChair [21, 71], the motion platform is not controlled by the user. Instead, it focuses on the user being controlled by the virtual environment.

### 2.2 Input Modalities

Previous AV studies investigated the use of touch panels for drivers to appropriate maneuvers when reaching an automation limit [88, 89] or to select AV maneuvers (e.g., change lanes) [29]. These were positioned on the steering wheel [14, 36, 60] or in the center/middle console [1, 52, 76]. Hand gesture was also used for maneuver-based intervention [11] and to control in-car lateral and longitudinal AV motions [47]. Similarly, Rümelin et al. [76] used free-hand pointing gestures, and Fujimura et al. [17] used hand-constrained pointing gestures for input. Eye gaze as a standalone input was used, e.g., by Poitschke et al. [64] for referencing or selecting objects [51, 73]. Besides, multimodal input was used to ease challenges with unimodal interaction. For example, gaze was used to localize the target and hand gestures to coordinate pointing [34, 72]. Speech input was implemented to support driver-vehicle cooperation and select vehicle maneuvers [4]. For example, Roider et al. [73], Nesselrath et al. [51], and Sezgin et al. [78] studied the selection of objects inside the vehicle using speech commands. However, voice input may not work well in a noisy environment (e.g., group conversations), and drivers may not completely trust speech recognition or may become confused about the appropriate command to initiate desired actions [7, 11].

Most studies were conducted in low-fidelity driving simulators without motion feedback (e.g., [19, 69, 72, 73, 76]). However, vehicle motions induced by road and driving conditions probably have a strong impact on results. This is especially relevant for studies measuring interaction precision [19] or completion time [52].

### 2.3 Effects of Vehicle Motion on Interaction

Ng and Brewster [52] compared pressure input and haptic feedback for in-car touchscreens between a low-fidelity driving simulator and a real vehicle. Accuracy was similar while selection time was worse in the real vehicle. Similarly, Ahmad et al. [1] demonstrated that vehicle motion affects the effort for selection. While important in the context of conventional driving, the effect of vehicle motion on interaction quality is critical in the military context [20, 33, 77] given the tasks being undertaken (e.g., critical mission planning and battle management tasks) and the environments in which modern-day land warfare operations typically occur (e.g., variable and unpredictable terrain). Goode et al. [20] found that the study participants rated the workload as higher and the system as less usable on the unsealed road. Salmon et al. [77] also showed that lower accuracy and longer task completion times occurred in a motion condition (inside a real vehicle) besides greater subjective and physiological workload and lower perceived usability.

Therefore, on-road driving simulation [18] and employing a WoZ driver to control the vehicle [5, 12] was proposed. However, such on-road simulators require access to a (real) vehicle besides a suitable road to drive on and potentially time-consuming work to adjust these (WoZ), making them more expensive than low-fidelity driving simulators.

### 2.4 Atomic Interaction Tasks

There are various domain- or application-specific tasks (desired user actions) in an in-vehicle information system. To reduce the necessity to implement numerous interaction applications, a few basic interaction 'building blocks', which most complex system interactions are composed of, can be used [8], called *atomic interaction tasks*.

Such tasks are independent of the application context or hardware technologies that enable unique interactions (e.g., pressing the hand palm on a touchscreen [42], or using artificial skin interfaces [82]) and cannot be divided further into subtasks. Based on previous work on universal 3D interaction tasks [8, 23], this work focuses on two *atomic interaction tasks*: (1) selection and (2) manipulation.

## 3 CONCEPT OF VEHICLE MOTION SIMULATION USING ROTATION

Vehicle motion refers to the vehicle's translation along and rotation about all three axes (i.e., longitudinal, lateral, and vertical). Rotations of a vehicle around these three axes correspond to the vehicle body's angular momentum in roll, yaw, and pitch [68]. In the autonomous driving context, these movements are controlled by the vehicle. However, this work focuses only on the longitudinal and lateral vehicle motions. Only these can be represented using a one-dimensional swivel seat either as a one-to-one match (rotation) or by utilizing the vection principle (acceleration/braking).

A road consists of the fundamental zones *straights* and *curves*. Vehicle motion is defined by *acceleration* and *braking*. According to Rietzler et al., it is already sufficient to use short rotation pulses to generate the feeling of forwarding motion or acceleration [71]. Based on their findings, acceleration/braking zones are simulated by a short angular impulse (rotation) to the right/left (see Figure 2 a and b). This alteration in direction should ensure that users (if they can perceive the direction) perceive a variation between acceleration and braking. The rotation

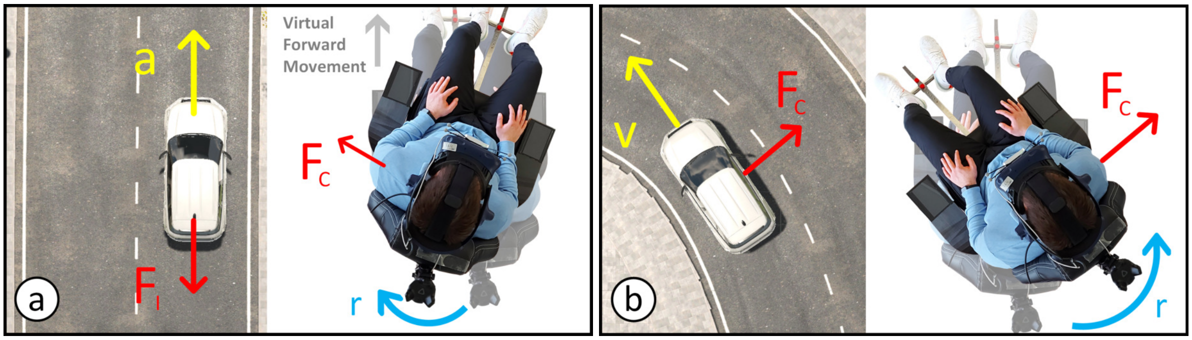


Fig. 2. (a) Inertial force $\vec{F_I}$ acts on passengers while a vehicle is accelerating with $\vec{a}$. Centrifugal force $\vec{F_C}$ acts on the user while the *SwiVR-Car-Seat* is rotating with a distance of $r$, meanwhile, forward movement is presented in VR. (b) Centrifugal force $\vec{F_C}$ acts on passengers in a vehicle with velocity $\vec{v}$ and while on the *SwiVR-Car-Seat* displayed for left curve. Arrow magnitudes/directions are only included for clarification and do not exactly match real forces.

speed depends on how strong the vehicle accelerates/brakes. In contrast, the rotation duration corresponds to the acceleration/braking duration of the vehicle, which the user also perceives in VR. As the visual perception is stronger than the perception of the vestibular system, this approach creates an illusion of self-motion (see Section 2.1).

Regarding curve zones, the rotation is differentiated by direction, duration, and speed. It corresponds to the curve's length, similar to the acceleration/braking zone as passengers perceive forces during the entire curve. In sharp curves, stronger forces act on the vehicle's passengers, which is why a relatively fast rotation speed was used in such cases. The rotation direction corresponds to the type of curve in this concept. Therefore, the seat rotates to the left in a left curve and vice versa in a right curve (see Figure 18). As shown in Figure 18, the respective forces are not identical (slightly different magnitudes and directions), which is why this force simulation of driving in a curve does not exactly match an actual curve. One exemplary calculation of the forces for the real vehicle and the *SwiVR-Car-Seat* is given in Appendix A. Straight road parts do not have to be simulated because the vestibular system only perceives accelerations.

While acceleration/braking and driving in a curve can interfere, our simulator can only simulate one type of motion feedback. We argue that AVs will smoothly execute the curve without needing to decelerate. While the preferred driving style of automated vehicles is still under research (e.g., [13, 43, 95]), Yusof et al. [95] showed that more defensive or even light rail traffic (see [43]) which uses reduced speed and acceleration/deceleration profiles, is preferred. Based on this rationale, our simulation did not have deceleration in curves and, therefore, acceleration/braking could not interfere with the simulation of a curve.

## 4 IMPLEMENTATION

We present the main parts of our implementation: The *SwiVR-Car-Seat* hardware, a motorized swivel chair to enable accurate rotational movements and the implementation of the input modalities touch, gesture, gaze, and speech. A Vive Pro Eye was used.

### 4.1 SwiVR-Car-Seat

The hardware setup of the current *SwiVR-Car-Seat* prototype (see Figure 3) is based on the *SwiVRChair* by Gugenheimer et al. [21] and on the further revised version used in the *VRSpinning* concept by Rietzler et al. [71].

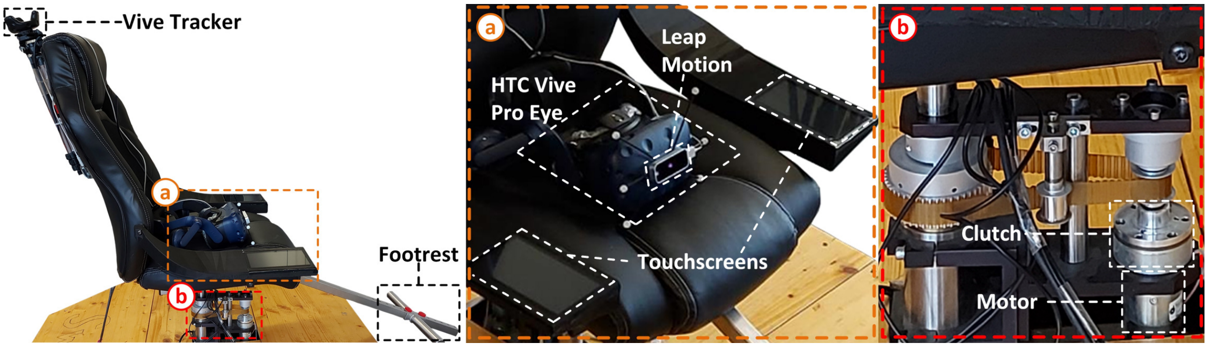


Fig. 3. Hardware setup of *SwiVR-Car-Seat*. A footrest is attached to the seat to not perceive the rotational direction. The rotation values of the Vive tracker were used to remove the seat's physical rotation from the virtual view.

Motor speeds between 5°/*s* and 25°/*s* were tested successively to determine the appropriate speed for the force simulation (based on [71]). For fast-driven curve types, such as *sharp curves*, the curve sequence of a *roundabout* (sharp right, sharp left, sharp right), and the *chicanes*, the motor speed was set to 18°/*s*. For *long curves*, the speed was set to 8°/*s*. The speed for acceleration/deceleration was bound between 10°/*s* and 20°/*s* and depended on the movement of the simulated AV.

The Vive tracking system interprets the seat rotation as regular head movements, therefore, we counterbalanced the physical rotation of the seat in VR using the Vive tracker. Because the VR camera cannot be manipulated directly in Unity, its parent GameObject is instead rotated by this delta angle in the opposite direction.

## 4.2 Input Modalities

Common input modalities used were touch [47], speech [78], gesture [17], and eye-based input [64]. The implementation is exemplary to enable comparability. The interaction concept is based on interactions via an on-screen cursor controlled by touch, gesture, or gaze to enable targeted interactions. For an improved visual differentiation of input modalities, the respective modalities were assigned their own basic geometric cursor shapes (rectangle for touch, see Figure 4 b; triangle for gesture, see Figure 5 b; and circle for gaze, see Figure 6 b). We avoided a mouse and a keypad in the study as our focus was on intuitive interaction modalities that do not require additional hardware for the user. For a mouse, for example, dedicated space for a mounted board is necessary. Also, future interaction concepts for AVs do not, to the best of our knowledge, include mouse or keyboards. Additionally, we hypothesize that it will be superior to the proposed modalities as it is currently used excessively.

*4.2.1 Touch-based Interaction.* We used two 7 inch capacitive touchscreens to recognize touch input (see Figure 4 a) to support the preferred hand [44]. These were attached to the seat to enable accessibility regardless of rotation. We employed LeanTouch [92] and Fingers [27] to recognize touch input. To select an object on the virtual screen, the user moves the cursor to the target area using simple finger movements so that the cursor intersects the object. As soon as the user taps the touchscreen with any finger, the object is selected, and a cursor animation is played, indicating a successful tap interaction (see Figure 4 b). To move an object, the user has to select the object first, the object then follows its movements (see Figure 4 c). After another tap, the object is detached from the cursor.

*4.2.2 Gesture-based Interaction.* For gesture interaction, a Leap Motion Controller (Leap Motion Unity SDK version 4.7.1) with the *Essential Leap-Motion Gesture Detection* Unity asset [2] was used.


Fig. 4. (a) User tapping on a touchscreen embedded into the seat armrest. (b) Touch-based selection of an element: (1) moving the cursor over the element, and (2) tapping one time to select. (c) Touch-based movement of an element: (1) tapping the element to attach it to the cursor, (2) moving the cursor/element to the target location, and (3) single tap to release it.

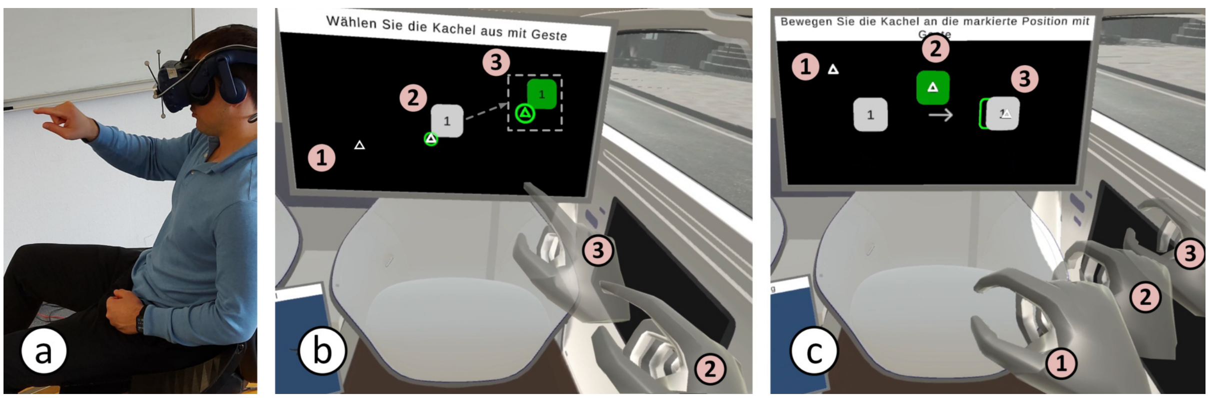


Fig. 5. (a) A user interacting with gesture. (b) Gesture-based selection of an element: (1) moving the cursor over the element, (2) start of air push gesture, and (3) end of air push that selects the element. (c) Gesture-based movement of an element: (1) moving the cursor over the element, (2) pressing thumb and index finger together and "dragging" the element to the target, and (3) disrupting the gesture releases the element.

The user can select with an *Air Push* gesture based on a touchless interaction concept from Ultraleap [85]. Once their hand starts moving forwards, users need to cover a distance of approximately 10cm to execute a “tap” and select an object (see Figure 5 b).

The user can perform a movement by a remote *Pinch* gesture. The *Pinch* works similar to a direct pinch gesture on, e.g., touchscreens, but requires the cursor to intersect/select the on-screen target. When the user presses the thumb and index finger of any hand together, the object is attached to the cursor (see Figure 5 c). The object is dropped when the user stops the gesture. The *Pinch* gesture was chosen instead of a combination of *Air Push* gestures to take advantage of the specific strengths of gesture-based interaction.

*4.2.3 Gaze-based Interaction.* For eye-tracking, we used the built-in Tobii eye tracker of the HTC Vive Pro Eye (using Tobii Eye Tracking SDK version 1.3.3.0 and the Tobii Gaze-2-Object-Mapping [83]). Due to cursor jittering, the 1€-Filter [9] was used to smooth cursor movements with a frequency of 120 ms. The selection was implemented using dwell time, which was set to 0.5 seconds [58]. The circle around the cursor visualizes the dwell time (see Figure 6 b). The object movement via gaze follows a three-step process analogous to touch and gesture: select via dwell time, move, and de-select via refocusing.

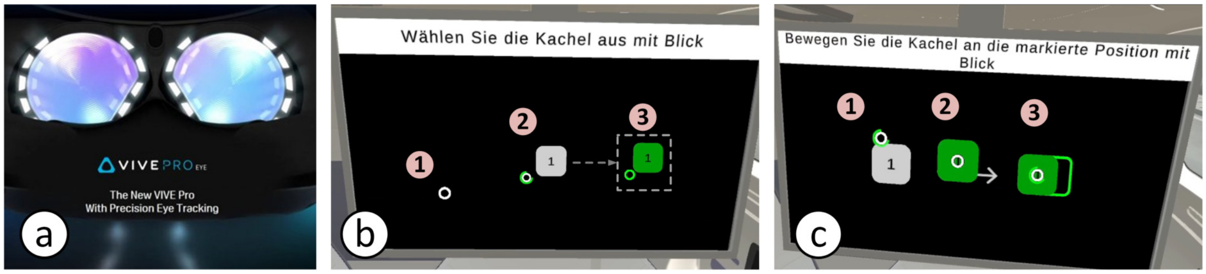


Fig. 6. (a) Integrated Tobii eye-tracking in the HTC Vive Pro Eye, taken from [84]. (b) Gaze-based selection of an element: (1) moving the cursor over the element, (2) focusing the element triggers the dwell timer to run, and (3) when the dwell time is over the focused element is selected. (c) Gaze-based movement of an element: (1) selecting the element to attach it to the cursor, (2) moving the element along the gaze, and (3) selecting the element again to release it.

*4.2.4 Speech-based Interaction.* For speech recognition, we used Unity's built-in phrase recognition [86]. No cursor is necessary, however, the numbers on the tiles are used for the movement task (e.g., see Figure 7 b and c). These are also displayed when using the other three input modalities (touch, gesture, and gaze) for internal validity. As our study was conducted in Germany, we report the German commands and their translations. To select an object, the user says the template speech command *"Wähle Objekt x aus"* ("Select object x"). To move an object, the user says, *Bewege x nach y* ("Move x to y").

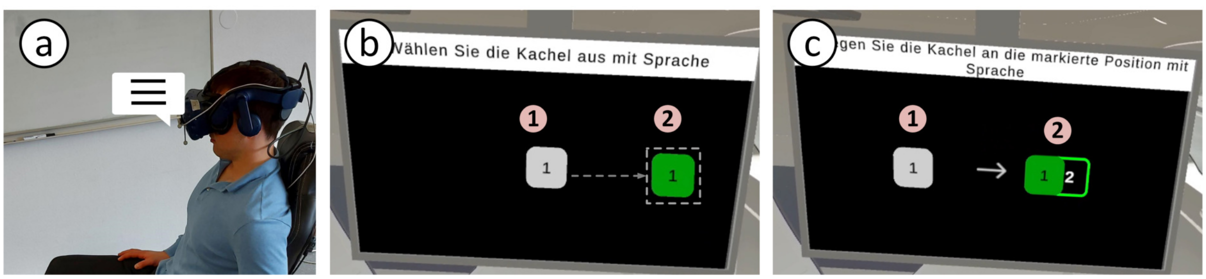


Fig. 7. (a) User employs speech command. (b) Speech-based selection: (1) saying the predefined speech command *"Select object 1"*, and (2) a recognized command triggers the selection. (c) Speech-based movement: (1) saying the predefined speech command *"Move 1 to 2"*, and (2) a recognized command triggers the automated movement to the target.

## 5 EVALUATION

A user study was conducted to evaluate the effects of the implemented motion platform on the interaction quality of input modalities.

### 5.1 Virtual Simulation Environment

In a user study by Pettersson and Karlsson [59], participants could freely rotate four chairs within a vehicle-like setup finding that they increasingly opted for rotated chairs. Jörlov et al. [28] found that for longer trips, most participants envisioned the AV as an extended living room and seating configuration with freely rotating seats. In the context of car-sharing or cabs, swivel car seats could allow different seating configurations depending on the passengers, e.g., face-to-face for a group of friends or all front-facing for a group of strangers. Additionally, simulations found increased safety for backward-facing occupants [26]. Besides, the vehicle center's space becomes usable due to the rear-facing seat configuration that alleviates the placement of large screens or a table. Such screens are needed to perform the interaction tasks in this user study. Therefore, the participant sits in a rear-facing position on a virtual swivel car seat during the entire virtual ride. Finally, this arrangement limits the ability of participants to anticipate movement. This is likely the case in more ecologically valid scenarios, for example, when being distracted by work. Additionally, this limits the biases induced by participating in a study via the reduction of anticipation possibilities. One possible disadvantage, however, could be an increased chance of simulator sickness.

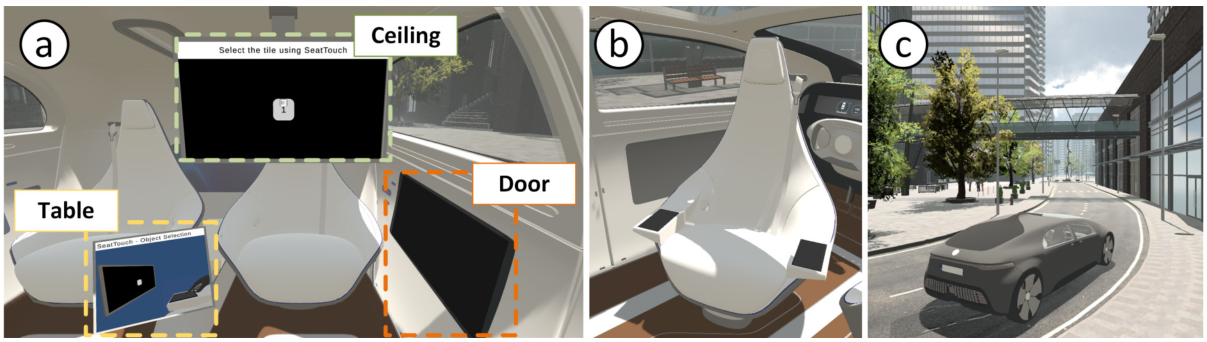


Fig. 8. (a) The three in-vehicle screens. The Table displayed the current modality and task. The Ceiling monitor was used as interaction display. The Door monitor was not used. (b) Virtual representation of the *SwiVR-Car-Seat*. (c) Screenshot of the virtual city environment.

The Mercedes-Benz *F015* concept car was selected as an exemplary AV (see Figure 8 a) and adapted to our needs (seat, screens, etc.). As participants wear a VR HMD, they cannot see the real *SwiVR-Car-Seat* and, therefore, need a visual representation. As participants can still feel the real seat, the visual representation must confirm the haptic feeling to increase the immersion and convey more realistic vehicle motion simulations. For this reason, the 3D model of an *F015* seat was modified with two added armrests.Therefore, the 3D models used for 3D printing the armrests were combined with the virtual model of the seat (see Figure 8 b).

The virtual simulation environment builds upon a predefined test track shown in Figure 9. The test track is supposed to simulate a typical North American city center and is, therefore, surrounded by skyscrapers, office buildings, and plazas (see Figure 8 c). The test track's total length is 550 m and is traversed at an average vehicle speed of **20 km/h** in 100 seconds. This velocity was chosen based on the motion simulation capabilities of the *SwiVR-Car-Seat* (see also Appendix A). Each of the five zones described in Section 3 occur once in each variant (left/right combination of curves and chicane) or at least twice (roundabouts and acceleration/braking zones) to ensure that the study participants do not evaluate the vehicle motion simulation exclusively for one type (e.g., only left curves). Each force simulation zone has a straight road connector in between without any force simulation. The connectors' length was set to 30 m to provide a short break between seat rotations, enabling a more distinctive force perception of different simulation types (e.g., curve or roundabout) while not unnecessarily lengthening the overall test track.

## 5.2 In-Vehicle Displays

This work examines a scenario in which a study participant sits on a virtual swivel car seat in a rear-facing position. The three screens *Table*, *Ceiling*, and *Door* are located at such a distance from users that they cannot touch them directly. Thus, remote interaction is required, as described in Section 4.2.

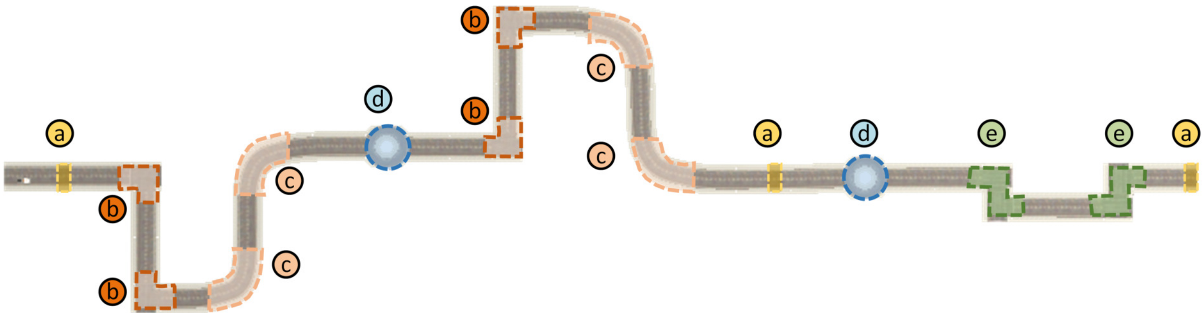


Fig. 9. The virtual test track driven by the simulated AV in Unity. (a) acceleration/braking zones, (b) sharp-curve zones, (c) long-curve zones, (d) roundabout-curve zones, and (e) chicane-curve zones.

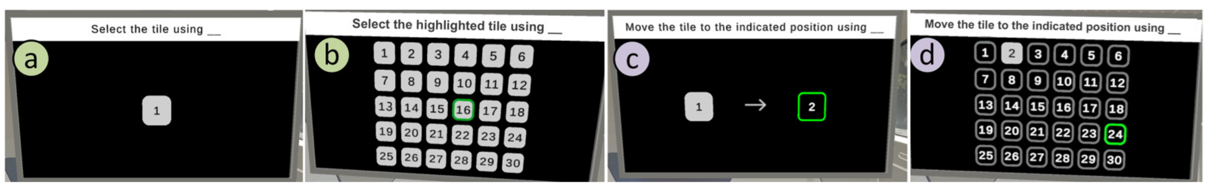


Fig. 10. (a) Selection task training stage, and (b) task stage containing 30 tiles, the tile to be selected is highlighted in green. (c) Movement task training stage, and (d) task stage with highlighted target in green.

In the *Table* area, there is a retractable, rotatable, and tiltable screen (see Figure 8 a). Due to its small size and impractical position below waist level, the table screen serves as an auxiliary information screen. In the *Ceiling* area, there is a ceiling-mounted screen that can be retracted and extended (see Figure 8 a). The ceiling screen is based on an expert workshop conducted by Sun et al. [81]. They report that a ceiling-mounted screen's usability was advantageous in an AV with a swivel seat.

## 5.3 Interaction Tasks

As described in Section 2.4, this work focused on the *atomic interaction tasks* selection and manipulation. These two tasks served as the basis for the interaction tasks employed in the user study. The study interaction task designs were inspired by a Fitts' Law [16] task similar to [40, 55].

The selection task consists of several tiles in this study, where the highlighted tile must be selected (see Figure 10 b). A tile has a dimension of 70x70 pixels on the main screen, which has a virtual resolution of 1920x1080 pixels. The selection task consists of two stages, the training stage, and the task stage. Once the training stage is completed, the vehicle commences the test track, starting the task stage. Here, 30 tiles are displayed in a 5x6 matrix, with a space of 30 pixels between the tiles. Whenever a tile is selected (correctly or incorrectly), a new target is randomly chosen from the set of tiles, which repeats until the vehicle stops.

Manipulation refers to modifying object properties, for example, affine transformations (translate, rotate, scale, or alignment) and the modification of other parameters (e.g., color or shading) [23]. Movement (also called translation) was employed in the study to represent a manipulation task. In the study implementation, object movement consists of three steps (see Section 4.2), (1) a selection to activate the object, (2) the actual movement, and (3) another selection to deactivate the object. Analogous to the selection task, the movement task displays the same 5x6 matrix containing 30 tiles (see Figure 10 d). Again, there was a training stage and a task stage. Whenever a movement is completed, a new pair of tiles (move tile and target tile) is selected.

## 6 USER STUDY

As we were interested in the effects of motion simulation on interaction quality, we designed and conducted a within-subject study with $N$=18 participants. The independent variables were *input modality* with four levels: touch, gesture, gaze, and speech, *force simulation* with two levels: force and no force, and *task* with the two levels selection and movement. This resulted in a $4 \times 2 \times 2$ design. The setup is described in Section 4.1.

The following research questions guided the exploratory study:

(1) *How realistic is the feeling of the simulated forces of vehicle motion?*
(2) *How do simulated vehicle motion forces impact task performance (e.g., time, accuracy, error rate) when using one of the four input modalities (touch, gesture, gaze, speech)?*
(3) *How do the simulated forces affect the subjective perception of interaction quality and usability of input modalities?*
(4) *What are considerations for the design of vehicle UIs and input modalities so that effects of vehicle motion-induced forces can be reduced or prevented altogether?*
(5) *What impact does the simulation of vehicle forces have on the feeling of presence in the virtual environment?*

### 6.1 Procedure

Each session started with disinfection, a brief introduction, agreeing to the consent form, and answering a demographic questionnaire on a separate laptop. We presented the combination of *input modality* and *force simulation* (8 combinations) counterbalanced (e.g., *gesture-no force*, then *touch-force*, then *speech-no force*, then *touch-no force*, etc.). We did not include the *task* in the counterbalancing. The participants performed the selection task first, followed by the movement task. This order was chosen as the selection task is easier for first-time users than the movement task that consisted of two selection tasks besides the actual object movement. The introduction was given as follows:

*You will drive through a city in a VR environment in a highly automated vehicle. The vehicle takes over all driving tasks. Therefore, you do not have to take over any tasks nor monitor the ride. You will sit on the driver's seat, which is rotated by 180° facing the rear area throughout the ride. In this area, you will see two screens, a large screen hanging from the ceiling and a smaller screen to the left at table height. The large screen is the main screen on which the tasks are displayed, and the small screen is the auxiliary screen displaying short instructional videos for the respective task. You are supposed to carry out the displayed task with the designated input modality. Each time before the actual task starts, there will be a training task. You could take your time and ask questions about the task or input modality to the experimenter. The vehicle will begin to drive only if the training task is completed.*

Besides, participants were informed that the seat would occasionally rotate to simulate the forces while driving, similar to real-life experiences, e.g., driving in a curve, accelerating, or braking.

Participants sat in the simulated vehicle for 300 s per combination (100 s for each task plus about 100 s for answering the questionnaire). They answered a repeating VR questionnaire after each task and after each combination. A VR questionnaire was used so that participants would not have to take off the VR HMD, thereby preventing immersion loss and reducing the overall study duration. At the end, participants answered a final questionnaire on a laptop and were asked about general feedback. On average, the session lasted 80 min and participants were compensated with 15€. The hygiene concept regarding COVID-19 for studies (ventilation, disinfection, wearing masks) involving human subjects of our university was applied.

## 6.2 Measurements

*6.2.1 Objective Dependent Variables.* During each session, the system logged the tasks' mean completion times, accuracy (distance to the target in cm), and error rates. The system created a new log entry every time interaction was completed (e.g., a tile was selected).

*6.2.2 Subjective Dependent Variables.* After each task, a self-developed 7-point scale was used to assess participants' self-perceived task performance ("I found the previous task very challenging"; *1=completely disagree, 7=fully agree*) and the perceived influence of vehicle motion on the task performance ("The vehicle motions influenced my performance in the previous task"; *1=completely disagree, 7=fully agree*). Additionally, the cognitive load during each task was administered using the German version of the NASA-TLX [22] on a 20-point scale.

After each combination (*input modality* × *force simulation*), the participants' simulator sickness levels, perception of self-motion, and presence in the virtual environment were assessed. The sickness during the session was assessed using a single-item question from [71]: "On a scale from 1 to 10, 1 is how you felt before the test, 10 is that you wanted to stop, how did you feel during your time in the virtual world?". Before and after the entire session, the SSQ [31] was used. To measure vection, participants should rate their feeling of self-motion on a 4-point Likert scale from 1="no feeling of self-motion" to 4="very strong feelings of self-motion". This was also asked for acceleration and braking. In addition, participants should state how much they agree with the following statement on a 7-point scale: "I felt a physical acceleration/braking". Moreover, the participants should state how realistic the perception of acceleration and braking was ("The feeling of physical acceleration(/braking) felt realistic"). Due to the majority of force simulation areas being curves, participants' should also rate whether "The feeling of driving in a curve felt realistic". For the statements, 7-point scales were used from *1=completely disagree* to *7=fully agree*. Participants' presence in the virtual environment was assessed after each combination (*input modality* × *force simulation*) using Slater, Usoh, and Steed's (SUS) presence questionnaire [79].

After all conditions, participants rated their input modality preferences from highest (*ranking=1*) to lowest (*ranking=4*), and assessed the usefulness of the input modalities ("I think the interaction with [*modality*] is useful") using single-item ratings on 7-point Likert scales (*1=completely disagree, 7=fully agree*). Finally, participants could provide open feedback.

# 7 RESULTS

For the factor analysis in the case of non-parametric data, a non-parametric ANOVA (NPAV) by Lüpsen [45] was used. For post-hoc tests, Bonferroni correction was used. Effect sizes were calculated using the formula proposed by Rosenthal [74]. R in version 4.0.5 and RStudio version 1.4.1106 was used. All packages were up to date at the time of the analysis (May 2021). The results of one participant were excluded from the analysis since the participant had to abort the study due to simulator sickness symptoms.

## 7.1 Participants

For the user study, a total of $N$=18 participants (3 female, 15 male) were recruited via participant recruitment mailing lists of our university and online media (WhatsApp, ad-hoc sample). Participation was voluntary. Participants were on average 25.71 ($SD$=3.51) years old, and 17 participants hold a driving license, most of them for at least three years (16 participants). 13 participants are students and 5 employees.

On a 5-point Likert scale (*1=strongly disagree, 5=strongly agree*), participants reported a high interest interest in AVs ($M$=4.38, $SD$=.84) and agreed that such a system would ease their lives ($M$=4.11, $SD$=.90). The participants were not sure whether AVs could become a reality by 2031 (10 years from today; $M$=3.00, $SD$=1.23). The Propensity to Trust subscale of the Trust in Automation questionnaire [35] was administered once before and after all conditions. Propensity to Trust was moderate ($M$=3.08, $SD$=.72) prior to the experiment. A Wilcoxon signed-rank test revealed that, after the simulation, the values for Propensity to Trust were significantly higher (*M*=3.39, *SD*=.82; $p<.01$, *Z*=-2.88, *r*=-.48).

The participants rated their Susceptibility to Motion Sickness on a 7-point Likert scale (*1=not at all, 7=very strong*), with a mean of 2.65 (*SD*=1.11) and their Susceptibility to Simulator Sickness with a mean of 1.65 (*SD*=1.27). While on average, participants are not susceptible to motion sickness, 5 participants reported that they get at least moderately motion sick (*response >= 4*), e.g., when reading in a moving car. Only one participant reported being prone to strong simulator sickness symptoms (*response > 4*).

## 7.2 Perception of Vehicle Motion

The NPAV showed a significant main effect of *force simulation* on vection (*F*=63.85, *df*=1, $p<.001$, *r*=-.43). Vection in conditions with *force* enabled (*M*=2.79, *SD*=.74) was perceived significantly stronger compared to conditions with *no force* (*M*=1.62, *SD*=.71). The perceived realism of acceleration and braking (*F*=68.25, *df*=1, $p<.001$, *r*=-.44) was increased significantly with *force* enabled (*M*=4.35, *SD*=1.44) compared to *no force* (*M*=2.43, *SD*=1.41). The perceived realism of driving in a curve (*F*=130.89, *df*=1, $p<.001$, *r*=-.50) was also increased significantly with *force* enabled (*M*=5.16, *SD*=1.29) compared to *no force* (*M*=2.46, *SD*=1.53).

All mean ratings of the self-developed items (feeling of physical acceleration/braking, realism of acceleration/braking, and realism of curve driving) were used to calculate an average *perception of vehicle motion* score. A high score indicates that participants perceived the vehicle motion as realistic. The NPAV revealed a significant main effect of *force simulation* on the *perception of vehicle motion* score (*F*=572.46, *df*=1, $p<.001$, *r*=-.64). The score with *force* enabled (*M*=4.65, *SD*=1.14) was significantly higher compared to *no force* conditions (*M*=2.36, *SD*=1.29).

## 7.3 Simulator Sickness and Presence

Regarding sickness symptoms during the session (measured using the single item), the NPAV showed a significant main effect of *input modality* on simulator sickness (*F*=4.85, *df*=3, $p<.01$, *r*=-.24). However, a pairwise comparison using Dunn's test revealed the differences to be non-significant.

Additionally, the simulator sickness questionnaire (SSQ) was included to measure the symptoms at the beginning of the session before the participant sat down and after the session in the final questionnaire. The SSQ score for each participant is the sum of the sixteen ratings that can range from 0 (= no symptoms) to 48 (=severe symptoms). SSQ sickness symptoms before the session were very low (*M*=3.33, *SD*=5.97). SSQ sickness symptoms after the session were still rather low (*M*=9.17, *SD*=10.15). A Wilcoxon signed-rank test showed a significant increase in sickness symptoms ($p<.05$, *Z*=-2.52, *r*=-.42) after the session.

The average score of the SUS presence questionnaire was calculated. The NPAV showed a significant main effect of *force simulation* on presence (*F*=42.77, *df*=1, $p<.001$, *r*=-.39). In conditions with *force* enabled (*M*=4.68, *SD*=.99), participants rated to have a significantly higher presence than in *no force* conditions (*M*=3.70, *SD*=1.22).

## 7.4 Objective Task Performance Measures

*7.4.1 Completion Time.* A low mean value indicates a fast interaction completion (in seconds). The NPAV revealed a significant IE of *input modality* × *task* on completion time (*F*=74.99, *df*=3, $p<.001$). Figure 11 shows that when using *speech*, there was nearly no difference in the completion times of movement and selection tasks. However, movement tasks were completed faster using *touch* (*M*=3.25, *SD*=.71) or *gesture* (*M*=4.32, *SD*=1.69) compared to selection tasks (*touch*: *M*=3.65, *SD*=.83; *gesture*: *M*=4.99, *SD*=1.00) In contrast, when using *gaze*, the movement tasks (*M*=14.29, *SD*=16.07) were completed slower than selection tasks (*M*=4.49, *SD*=3.34).

*7.4.2 Accuracy.* A smaller value resembles a more accurate interaction (in cm). The mean accuracy values for *speech* were removed from the analysis as the values are always zero due to automatic tile selection and movement when a speech command is recognized. The NPAV revealed a significant IE of *input modality* × *force simulation* on the mean interaction accuracy (*F*=3.32, *df*=2, *p*<.05). In conditions with *no force*, the interaction was more accurate when using *gesture* (*M*=3.02, *SD*=2.26) or *gaze* (*M*=3.17, *SD*=1.22) compared to conditions with *force* enabled (*gesture*: *M*=4.08, *SD*=2.91; *gaze*: *M*=4.58, *SD*=1.53). On the other hand, the interaction using *touch* was more accurate with *force* enabled (*M*=2.87, *SD*=3.46) than with *no force* (*M*=3.39, *SD*=3.90).

The NPAV also showed a significant IE of *input modality* × *task* on interaction accuracy (*F*=5.94, *df*=2, *p*<.01). Figure 13 shows that the participants performed selection tasks more accurately than movement tasks.

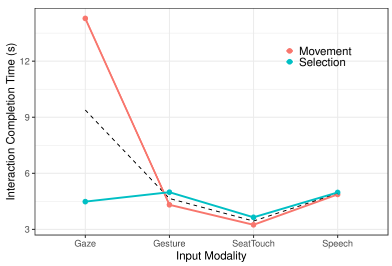


Fig. 11. IE of *input modality* × *task* on task mean interaction completion time (in s).

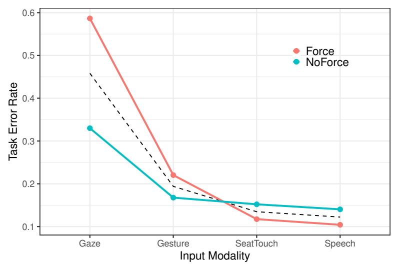


Fig. 12. IE of *input modality* × *force simulation* on task mean error rate.

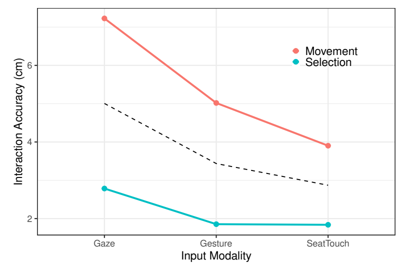


Fig. 13. IE of *input modality* × *task* on task mean interaction accuracy (in cm).

*7.4.3 Error Rate.* The task *error rate* is the number of target misses divided by the number of completed interactions. The NPAV revealed a significant IE of *input modality* × *force simulation* on error rate (*F*=7.00, *df*=3, *p*<.001). Figure 12 shows that the error rate was higher when participants used *gesture* (*M*=.22, *SD*=.30) or *gaze* (*M*=.59, *SD*=.25) while *force* was enabled compared to *no force* (*gesture*: *M*=.17, *SD*=.22; *gaze*: *M*=.33, *SD*=.27). However, the error rate was lower when participants used *touch* (*M*=.12, *SD*=.28) or *speech* (*M*=.10, *SD*=.24) while *force* was enabled compared to *no force* (*touch*: *M*=.15, *SD*=.32; *speech*: *M*=.14, *SD*=.26).

## 7.5 Subjective Task Performance Measures

The NPAV showed a significant main effect of *input modality* on the perceived challenge (*F*=30.20, *df*=3, *p*<.001, *r*=-.40; see Figure 14). Post-hoc tests using Dunn's test revealed that the tasks were perceived significantly more challenging while using *gesture* (*M*=4.06, *SD*=2.60) or *gaze* (*M*=4.79, *SD*=2.63) compared to *touch* (*M*=1.75, *SD*=1.12). Post-hoc tests further revealed that the tasks were perceived significantly more challenging using *gesture* or *gaze* than using *speech* (*M*=1.79, *SD*=1.37). The NPAV also showed a significant main effect of *task* on the perceived challenge (*F*=4.80, *df*=1, *p*<.05, *r*=-.12). The participants found the movement task (*M*=3.31, *SD*=2.46) significantly more challenging than the selection task (*M*=2.89, *SD*=2.43).

The NPAV showed a significant IE of *input modality* × *force simulation* on the perceived influence of vehicle motion on task performance (*F*=17.20, *df*=3, *p*<.001). Figure 16 shows that with *no force*, the participants did not feel that the vehicle motions influenced their task performance (on average *M*=1.44, *SD*=.08). With *force* enabled, they rated the influence of vehicle motions from weak while using *touch* (*M*=2.03, *SD*=1.17) or *speech* (*M*=1.71, *SD*=1.24) to noticeable during interaction with *gaze* (*M*=4.82, *SD*=1.80) or *gesture* (*M*=4.38, *SD*=1.79). However, the NPAV did not reveal any effects of *task* on the perceived influence of vehicle motion on task performance.

*7.5.1 NASA TLX.* Task workload was measured using the NASA-TLX. The total workload is the average of all six subscales. The NPAV showed a significant IE of *input modality* × *task* on the total workload (*F*=4.17, *df*=3, *p*<.05). Figure 15 shows that there was a higher total workload when participants performed movement tasks using *gaze* (*M*=9.50, *SD*=4.05), *gesture* (*M*=6.94, *SD*=3.10), or *speech* (*M*=4.08, *SD*=2.39) compared to selection tasks

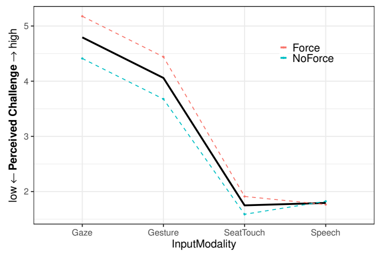


Fig. 14. Main effect of *input modality* on the perceived task challenge.

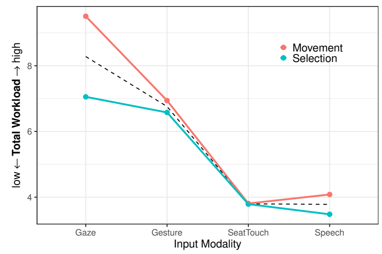


Fig. 15. IE of *input modality* × *task* on the total NASA TLX workload.

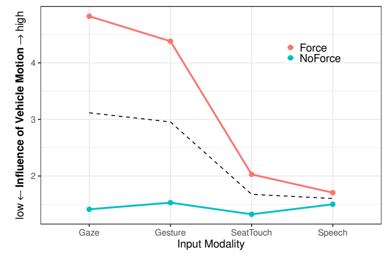


Fig. 16. IE of *input modality* × *force simulation* on the perceived influence of vehicle motion on task performance.

(*gaze*: *M*=7.05, *SD*=3.29; *gesture*: *M*=6.58, *SD*=3.09; *speech*: *M*=3.48, *SD*=2.48). However, there was no difference between the two types of tasks regarding *touch*.

In the following, the results for each NASA-TLX subscale are reported.

*Mental Demand.* The NPAV showed a significant main effect of *input modality* on mental demand (*F*=10.68, *df*=3, *p*<.001, *r*=-.26). Pairwise comparisons using Dunn's test revealed that mental demand was rated significantly higher for *gaze* (*M*=6.69, *SD*=5.28) or *gesture* (*M*=5.26, *SD*=3.50) compared to *touch* (*M*=3.18, *SD*=2.63). The NPAV also showed significant main effects of *force simulation* (*F*=6.51, *df*=1, *p*<.05, *r*=-.14) and *task* (*F*=23.92, *df*=1, *p*<.001, *r*=-.23) on mental demand. Mental demand was rated significantly higher in conditions with *force* enabled (*M*=5.15, *SD*=4.27) compared to *no force* conditions (*M*=4.47, *SD*=3.60). Besides, the mental demand was rated significantly higher for movement tasks (*M*=5.40, *SD*=4.21) compared to selection tasks (*M*=4.23, *SD*=3.60).

*Physical Demand.* Regarding physical demand during task interaction, the NPAV showed a significant main effect of *input modality* (*F*=46.98, *df*=3, *p*<.001, *r*=-.46). Pairwise comparisons using Dunn's test revealed that physical demand was significantly higher using *gesture* (*M*=9.51, *SD*=4.55) compared to using *touch* (*M*=3.87, *SD*=2.65), *gaze* (*M*=6.03, *SD*=4.90) or *speech* (*M*=2.78, *SD*=2.63). In addition, task interaction using *gaze* was rated significantly more physically demanding than *speech*.

*Temporal Demand.* The NPAV showed a significant main effect of *input modality* on temporal demand (*F*=17.47, *df*=3, *p*<.001, *r*=-.33). Pairwise comparisons using Dunn's test revealed that temporal demand was rated significantly higher using *gaze* (*M*=7.31, *SD*=4.81) compared to *touch* (*M*=3.10, *SD*=2.74) or *speech* (*M*=3.06, *SD*=2.77). Besides, it showed that temporal demand was significantly higher using *gesture* (*M*=4.85, *SD*=3.17) compared to *touch* or *speech*.

*Performance.* Regarding performance, the NPAV showed a significant main effect of *input modality* (*F*=3.59, *df*=3, *p*<.05, *r*=-.14). A high rating for this means a low self-perceived performance in the task. Pairwise comparisons using Dunn's test revealed that the performance was significantly lower for *gaze* (*M*=10.74, *SD*=5.60) compared to *touch* (*M*=6.04, *SD*=6.31), *gesture* (*M*=7.16, *SD*=4.70), or *speech* (*M*=6.85, *SD*=6.94).

*Effort.* The NPAV showed a significant main effect of *force simulation* on effort (*F*=7.40, *df*=1, *p*<.05, *r*=-.15). The effort was rated significantly higher in conditions with *force* enabled (*M*=6.63, *SD*=5.02) compared to *no force* conditions (*M*=5.68, *SD*=4.51). The NPAV also revealed a significant IE of *input modality* × *task* on effort (*F*=5.30, *df*=3, *p*<.01). Figure 17 a shows that the effort was rated higher when the participants performed movement tasks using *gaze* (*M*=11.15, *SD*=5.27), *touch* (*M*=3.71, *SD*=2.57), or *speech* (*M*=3.47, *SD*=2.58) compared to selection tasks

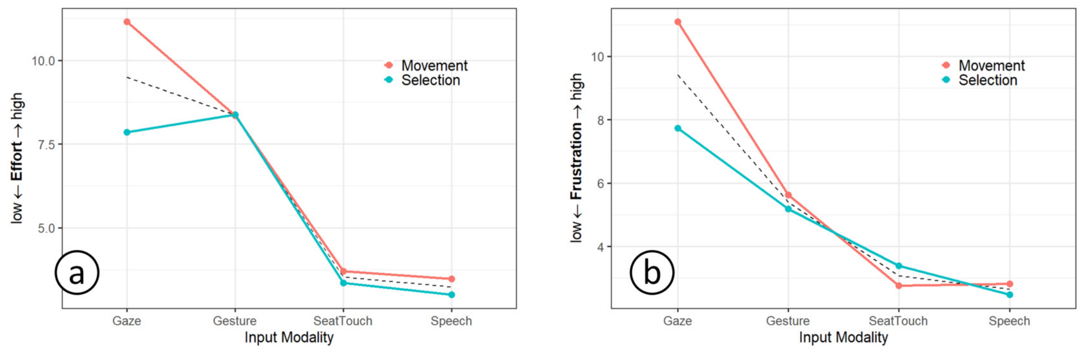


Fig. 17. IE of (a) *input modality* × *task* on effort and (b) of *input modality* × *task* on frustration.

(*gaze*: *M*=7.85, *SD*=5.08; *touch*: *M*=3.35, *SD*=2.62; *speech*: *M*=3.00, *SD*=2.56). However, for *gesture* there was nearly no difference in the effort ratings between movement (*M*=8.35, *SD*=4.28) and selection (*M*=8.28, *SD*=4.36).

*Frustration.* Regarding frustration, the NPAV showed a significant IE of *input modality* × *task* (*F*=3.78, *df*=3, *p*<.05). Figure 17 b shows that the participants were more frustrated when they performed movement tasks using *gaze* (*M*=11.09, *SD*=5.07), *gesture* (*M*=5.61, *SD*=4.67), or *speech* (*M*=2.82, *SD*=2.43) compared to selection tasks (*gaze*: *M*=7.74, *SD*=4.87; *gesture*: *M*=5.18, *SD*=4.22; *speech*: *M*=2.47, *SD*=2.19). In contrast, the participants were more frustrated when they performed selection tasks using *touch* (*M*=3.38, *SD*=3.51) compared to movement tasks (*M*=2.76, *SD*=2.37).

*7.5.2 Input Modality Preferences.* The input modality *touch* received rankings indicating the highest preference, i.e., the lowest mean (*M*=1.41, *SD*=.62). The remaining ranking was as follows: *speech* (*M*=1.94, *SD*=.66), *gesture* (*M*=2.94, *SD*=.75), *gaze* (*M*=3.71, *SD*=.77). A Friedman's ANOVA showed a significant difference in the mean rankings ($\chi^2(3)$=32.08, *p*<.001). Post-hoc tests revealed that, compared to *touch*, *gesture* and *gaze* were rated significantly worse. Besides, *gaze* was rated significantly worse compared to *speech*.

Participants also ranked their preferred input modality for the selection task. *Touch* received the highest preference rankings (*M*=1.47, *SD*=.72). The remaining ranking for selection tasks was as follows: *speech* (*M*=2.00, *SD*=.94), *gesture* (*M*=3.06, *SD*=.66), *gaze* (*M*=3.47, *SD*=.87). A Friedman's ANOVA showed a significant difference in the mean rankings ($\chi^2(3)$=26.15, *p*<.001). Post-hoc tests showed that, compared to *touch*, *gesture* and *gaze* were rated significantly worse regarding selection tasks. *Gaze* was also rated significantly worse regarding selection tasks compared to *speech*.

In terms of preferences for performing a movement task, *touch* received the highest ranking (*M*=1.53, *SD*=.80). The remaining ranking for movement tasks was *speech* (*M*=1.94, *SD*=.83), *gesture* (*M*=2.71, *SD*=.77), *gaze* (*M*=3.82, *SD*=.39). A Friedman's ANOAV showed a significant difference in the mean rankings ($\chi^2(3)$=31.09, *p*<.001). Post-hoc tests revealed that, compared to *touch*, *gesture* and *gaze* were rated significantly worse regarding movement tasks. Besides, *gaze* was rated significantly worse regarding movement tasks compared to *speech*.

The usefulness of each input modality was assessed on a 7-point Likert scale. Participants rated the modality *touch* as most useful (i.e., the highest mean *M*=6.82, *SD*=.39), followed by *speech* (*M*=5.76, *SD*=1.03), *gesture* (*M*=4.35, *SD*=1.93), and *gaze* (*M*=3.59, *SD*=1.73). A Friedman rank-sum test showed a significant difference in the mean rated usefulness of the input modalities ($\chi^2(3)$=29.27, *p*<.001). Post-hoc tests showed that, compared to *touch*, all other modalities except *speech* were rated significantly less useful.

## 8 OPEN FEEDBACK

In general, participants liked the precise [P1, P3, P4], intuitive [P2, P9, P12], and fast [P5, P14, P17] interaction using the *touch* modality. While the modality *gesture* was perceived as a relatively neutral way to interact [P10, P12], some participants liked the physical engagement [P6]. Regarding *gaze* input, they positively emphasized the low level of physical activity required [P1, P8, P15] and found the hands-free interaction advantageous [P7, P12, P14]. Participants were also surprised how well the speech recognition worked [P4, P5, P6] and liked the low physical activity required for *speech* input [P2, P9, P16].

For both *gesture* and *gaze* inputs, most participants wished for more accurate recognition [P3, P7, P9]. Some participants further mentioned that they got tired after using *gesture*s and *gaze* [P1, P13]. Regarding *speech* input, most participants had no negative feedback. However, some perceived the interaction as cumbersome after a while [P1, P17] and disliked that *speech* interaction may limit the communication with passengers [P12].

Participants also mentioned general feedback during or after the session. Regarding the realism of the vehicle motion simulation, [P14] stated: "An additional "shaking motor" or vibration would be desirable to, for example, simulate the unevenness of the ground/road." [P14] further mentioned an increased feeling of realism of the vehicle motion during demanding task interactions: "The fact that you had to concentrate fully on the task made the motions feel especially realistic since you cannot concentrate on them as much." This was also highlighted by [P1]: "One was constantly concentrating on the task, barely noticing what the virtual world looked like, not even paying much attention to the car interior." [P1] further stated an increased perception of time pressure during *gaze* interactions: "With *gaze*, one felt more time pressure than with the other modalities because the circle was filling up, and one absolutely had to wait because otherwise, one would have to start again. In the other modalities with a cursor, the circle was not really noticeable."

## 9 DISCUSSION

Overall, the concept of vehicle motion simulation using the *SwiVR-Car-Seat* increased the participants' perception of vehicle motion (see Section 7.2). This is in line with studies [71, 93] which showed that the feeling of self-motion is increased by presenting a vestibular stimulus orthogonal to a visual one (see Section 2.1). Regarding the SSQ, a significant increase of simulator sickness after the experience compared to before was measured (see Section 7.3). However, according to a categorization of SSQ scores by Kennedy et al. [30], the sickness symptoms were minimal after the experience. Because of this low rating, it is assumed that the sickness symptoms were dominantly caused by the prolonged usage of the VR HMD (80 min) instead of the simulator experience itself.

Applying rotational stimuli (*force* enabled) significantly increased the feeling of being present in the virtual world (see Section 7.3). Therefore, it is assumed that this concept of vehicle motion simulation using rotation is a natural way of simulating vehicle motion in VR. Still, there are some points to discuss.

### 9.1 Fidelity of Vehicle Motion Simulation

The results showed that the concept could induce the feeling of vehicle motion forces, and participants also rated them as moderately realistic (see Section 7.2).

The perceived realism of vehicle motion in both acceleration/braking and curve zones was significantly higher when force simulation was enabled compared to only visual stimuli in VR. However, the simulation of acceleration/braking was perceived as less realistic than the simulation of driving in a curve. For acceleration/braking, the principle of vection is challenging to apply [71, 93]. An explanation for this may be that in curve zones, the simulated forces' directions nearly match a real-world scenario's force directions. Another explanation could be that the turn velocity, while being tested beforehand, was not adequate for some participants during braking/accelerating. Additionally, personality traits can alter vection [15].

However, there was no significant difference between the rated realism of both zone types, so it is assumed that the simulation of acceleration/braking also worked sufficiently well.

Further research is necessary to determine the required simulation fidelity by comparing motion platforms with different degrees of freedom (e.g., 2 DoF or 3 DoF).

Although the 1 DoF motion platform cannot perfectly simulate vehicle motion forces (see Section 3), the advantages are that acceptable results can be achieved for low cost and relatively low effort compared to high-fidelity motion simulators (e.g., [50]). Therefore, such a system may be helpful in (rapidly) prototyping new concepts and technologies in automotive research.

## 9.2 Impact of Vehicle Motion on Interaction Quality

A significant difference was observed between the input modalities for simulated vehicle motions. *Touch*-based interactions were completed the fastest, more than twice as fast as *gaze*-based interactions, which were the slowest modality (see Figure 11). In between were *gesture* and *speech*, with which the interaction was almost equally fast. Using *speech*, participants always had to pronounce a command thoroughly to trigger the desired interaction. Therefore, the task completion time is linked to the speaking time, which may explain the relatively slow completion time compared to, e.g., *touch*.

*Gaze*- and *gesture*-based interactions were less accurate when *force* was enabled than with *no force*. It is assumed that for *gaze*, this was not only due to vehicle motion but was also strongly influenced by the implementation of the gaze interaction and the need to familiarize with the technique. Besides, the *gaze* approach suffered from the Midas touch problem as described by Mohan et al. [49] and also mentioned by [P1]. Regarding *gesture*, it is assumed that the results were caused by the greater physical demand required for *gesture*-based interaction. Surprisingly, an opposite effect was observed for *touch*-based interactions, as they were less accurate in conditions with *no force*. Although the technical implementation had a noticeable influence on the respective interaction accuracy, a trend is still visible, suggesting that physically demanding input modalities (e.g., *gesture* or *gaze*) become less accurate during vehicle motion.

Overall, the participants perceived the movement task as more challenging than the selection tasks. This is in line with studies [6, 80] that found an increased total workload in complex/more difficult interaction tasks than simple/easier tasks. Participants also felt the simulated vehicle motions influence their task performance. However, the influence was rated as rather weak when using *touch* and *speech*, compared to *gesture* and *gaze*-based interaction (see Figure 16).

Similarly, *gaze* and *gesture*-based interaction were rated as more mentally demanding than *touch*-based interaction (see Section 7.5.1). This might be caused by the unfamiliar interaction with *gaze* and *gesture* (see [62]) or the lower robustness of the eye-tracking implementation.

The *gesture*-based interaction was perceived as more physically demanding than *touch*-based interaction (see Section 7.5.1 and gorilla arm effect/fatigue [25]). *Gaze*-based interactions were also perceived as physically demanding, which can be explained by eye fatigue, which can occur in eye-based interactions [38].

[P1] reported that time pressure was perceived as more intense when using *gaze* compared to the other input modalities (see Section 8). The results regarding Temporal Demand showed a similar effect. On average, *gaze*- and *gesture*-based interactions were perceived as more temporal demanding than *touch* or *speech*. This may be because participants felt they had to complete as many interactions with *gesture* or *gaze* as with *touch* or *speech*.

Participants perceived the effort to carry out a task as greater in the conditions with *force* enabled compared to the conditions with *no force* (see Section 7.5.1). This indicates that the simulated vehicle motions made the interaction more difficult and that participants had to exert more effort to compensate them.

Based on the results in this study, it is concluded that the simulated vehicle motions impact the interaction quality depending on two main factors: (1) the input modality characteristics and (2) the technical implementation of the interaction concept. Regarding the modality characteristics, it was observed that interactions with high physical demand are more susceptible to be negatively influenced by simulated vehicle motion. Furthermore, the implementation of an input modality's interaction concept may negatively influence task performance. However, a well-designed interaction could mitigate the negative effects of vehicle motion on interaction quality.

### 9.3 On the Importance of Including Vehicle Motion into Interaction Research

Numerous studies were conducted in fixed-base low-fidelity simulators [11, 19, 64, 72, 73]. Our results showed noticeable effects of vehicle motion on the interaction quality. This means that some results of previous works that did not include vehicle motion may be distorted and even be invalid. This problem is also recognized by some authors such as Roider and Gross [72] who mentioned that their driving simulator did not support motion feedback, but real vehicle motion is likely to degrade the user's performance during interaction with their gesture concept. In line with previous research and based on this work's results, it can be concluded that including vehicle motion in interaction research is of great importance, as motion effects may critically influence the results of an evaluation and even render some results invalid.

### 9.4 Considerations for Interaction Design

One factor relevant for interaction quality is an input modality's characteristics (e.g., involved body parts, required effort, or mental demand), which contribute to its suitability during vehicle motion. Based on the assessed Input Modality Preferences (see Section 7.5.2), participants would prefer *touch*. These results align with the subjective and objective task performance measures. However, these cannot be tested in non-motion driving simulators (e.g., [56, 81, 91]). The results also showed that there was a significant difference between the interaction task selection and movement).

Another factor is the (technical) implementation of an input modality, containing the interaction procedure, the semantics, and UI design. In Section 5.3, it was explained that the study task UI was intentionally designed to be not ideal towards each input modality and thereby posing a challenge for some interactions. In this approach, the challenge was mainly caused by the small space (1 cm) between the interactable elements (tiles). In combination with a tile diameter of approximately 4.5 cm, incorrect input was provoked, reflected in the Accuracy results. Therefore, sufficient space between the interactable UI elements is recommended to prevent erroneous input during vehicle motion. Analogous, the size of the UI elements could be adjusted to increase their hit area. In this implementation, the tiles' size was 70 pixels (≈4.5 cm). Based on the results, this size can be seen as a minimum to mitigate the vehicle motions' influence at least equally as in this study. However, these considerations are strongly dependent on the interaction concept. In this case, they are intended for cursor-based interaction, but other interaction concepts are also suitable in AVs. For example, users may interact with symbolic gestures (e.g., moving the hand in a specific way to signalize a lane change, see [11, 72]), which do not require accurately aiming at a target or controlling a cursor. In the future, the effects of vehicle motion on interaction quality should be assessed when using such concepts.

## 10 LIMITATIONS & FUTURE WORK

The number of participants in the study was of moderate size (*N*=18). As mostly a younger male participants (on average 25 years old, only three women) took part, it is not clear whether this work's findings are transferable to other age groups. Regarding gender impacts, we only found outliers in Simulator Sickness caused by one female participant. However, there were also outliers for men. While this study should, therefore, be repeated with a more diverse set of participants (e.g., to contemplate the decreased motor abilities of older adults [87]), our study results at least seem not to be strongly influenced by the low number of female participants. It is also unclear what impact the settings had on the perception of vehicle motion (acceleration/braking and curves). While these were chosen carefully, specific adjustments (e.g., rotation speed, duration, or timing) could have improved the simulation's realism. Transferability to a real-world scenario is restricted due to the usage of a relatively long (80 min) VR simulation. Additionally, as the used motion platform in this work is only 1 DoF, the study should be repeated with a more-dimensional motion platform (e.g., 3 DoF) that may improve the motion simulation and still be low-cost and low effort. Finally, a comparison to the effects of motion in a real vehicle with regards to fidelity and validity [67, 70] is necessary. While the results obtained with our implementation should be more externally valid compared to a static setup, we emphasize that this simulator is primarily intended for exploration, not validation. This is especially necessary if driving-related tasks are concerned as differences for simulators and real-world driving have been found, for example, for steering requests [70].

Regarding interaction concepts, we selected common input modalities. However, these have specific strengths and weaknesses, which makes comparability more difficult. Also, the chosen interaction tasks, while providing information about atomic interactions, potentially cannot provide sufficient information about higher-level interaction (e.g., text input) or entire applications. Finally, the movement task was loosely resembling a Fitts' law task due to the resemblance to a potential real UI. However, due to this and the random movement tasks, the distances were not equal per participant. Nonetheless, we believe these differences to be negligible because of the high number of interactions.

## 11 CONCLUSION

This work showed the effects of vehicle motion simulated in a 1 DoF simulator on the interaction quality in an AV. In total, the four input modalities touch, gesture, gaze, and speech were selected and implemented. In an exploratory user study (*N*=18), this concept was evaluated within a VR simulation, in which participants sat in a virtual AV and performed atomic interaction tasks (selection and movement) using the input modalities. Overall, the results showed that the proposed concept of vehicle motion simulation increased the perceived realism of vehicle motion in the VR environment, increased the feeling of presence, and significantly influenced participants' task performance. However, the influence on performance was not uniform across the four input modalities. While the motion simulation caused worse task performance (objective and subjective) for gesture and gaze input, there was little impact on touch- and speech-based interaction. This highlights that input modalities are differently affected by vehicle motion, which future automotive UI designs should consider. This work further enhances the body of knowledge on interaction design in automotive UI and provides a low-cost tool for quick interaction design and evaluation.

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## A EXEMPLARY FORCE CALCULATION

The average human body weighs 70 kg, and the average human hand is around 0.58% of total body weight; therefore, the average hand weighs 0.406 kg[1].

### A.1 Centrifugal Force

For an overview of the scenery, see Figure 18.

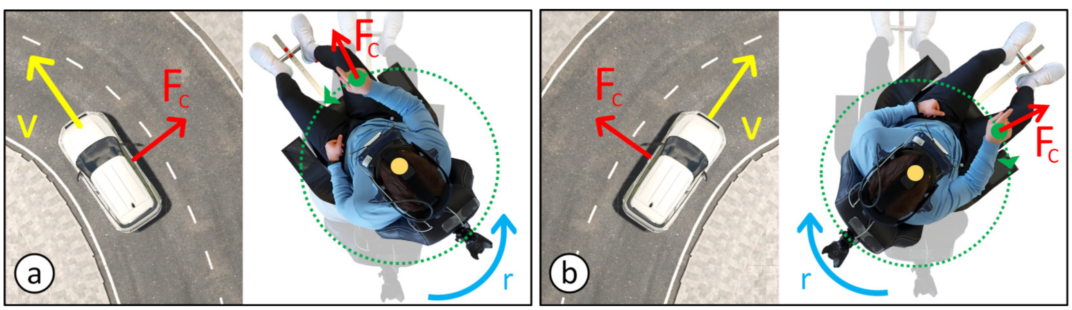


Fig. 18. Centrifugal force $\vec{F_C}$ acts on passengers in a vehicle with velocity $\vec{v}$ and on the user's hand while on the *SwiVR-Car-Seat* displayed for left and right curves. Arrow magnitudes/directions are only included for clarification and do not exactly match real forces.

The centrifugal force $F_C$ acts on the hand in a rotating frame of reference, e.g., while being a passenger in a vehicle that is driving in a curve. The formula is $F_C = (mv^2)/r$, where $m$ is the mass of an object rotating with velocity $v$ at a distance $r$ from the origin of a frame of reference.

Driving with a (real) vehicle in a curve:
$m = 0.406kg$; $v = 5.556m/s$ $(= 20km/h)$; $r = 25m$ (the radius of a long-curve zone employed in the user study).
Result: The centrifugal force $F_C$ that acts on the user's hand is $\mathbf{0.501}$ $N$.

[1] https://exrx.net/Kinesiology/Segments; Accessed: 12.05.2021

Rotating on the *SwiVR-Car-Seat*:
$m = 0.406kg$; $v = 0.785m/s$ (4$s$ for one rotation); $r = 0.5m$.
Result: The centrifugal force $F_C$ that acts on the user's hand is **0.500** $N$.

## A.2 Inertial Force

For an overview of the scenery, see Figure 19.

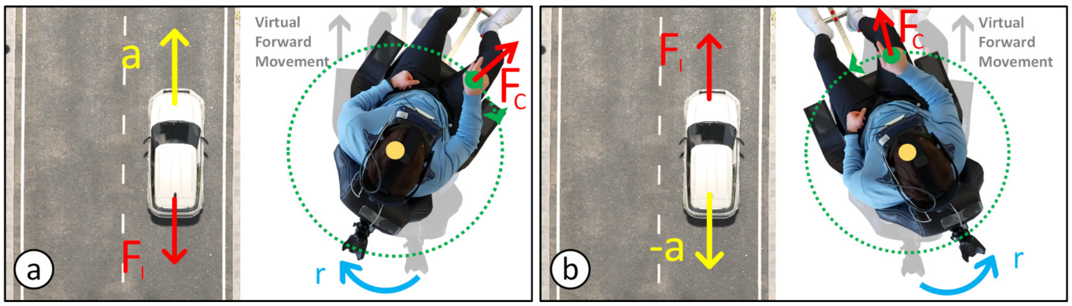


Fig. 19. Inertial force $\vec{F_I}$ acts on passengers while a vehicle is accelerating with $\vec{a}$. Centrifugal force $\vec{F_C}$ acts on the user's hand while the *SwiVR-Car-Seat* is rotating with a distance of $r$; meanwhile, forward movement is presented in VR. Arrow magnitudes/directions are only included for clarification and do not exactly match real forces.

The inertial force $F_I$ acts on passengers' hands in an accelerating or braking vehicle. The formula is $F_I = -ma$, where $m$ is the mass of an object accelerated with $a$.

Accelerating in a (real) vehicle:
$m = 0.406kg$; $a = 6.667m/s^2$.
Result: The inertial force $F_I$ that acts on the user's hand is **2.710** $N$.

Rotating on the *SwiVR-Car-Seat*:
The formula for $F_C$ is used because the seat can only exert a centrifugal force on the user's hand.
$m = 0.406kg$; $v = 1.571m/s$ (2$s$ for one rotation). This is faster compared to the curve driving example as a higher velocity was chosen to simulate accelerating/braking; $r = 0.5m$.
Result: The centrifugal force $F_C$ that acts on the user's hand is **2.004** $N$.