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ABSTRACT

Current powertrains in vehicles offer a broad spectrum of driving modes that shape the driving experience. One crucial factor for determining the human factors aspects of this driving experience is the perception and evaluation of acceleration - a complex, multisensory process that integrates auditory, vestibular, and visual input. Two important questions that need to be answered in order to better characterize this percept include: How do individual sensory inputs influence acceleration perception? and How does acceleration perception change at different acceleration levels? To address these questions, here we used a unique setup based on a cable-robot simulator that allowed us to manipulate the different modalities at different levels of acceleration with real-world, in-car data for maximum realism. Specifically, we measured the just noticeable differences (JNDs) of acceleration perception in five different modality combinations with the same set of participants. Our results showed that auditory acceleration perception was less sensitive compared to other modality combinations. In addition, we found evidence for the validity of Weber's law with JNDs increasing linearly with increasing acceleration level. Interestingly, the multisensory data showed little evidence for effective cue integration of auditory information in this setup. These findings lay the groundwork for a better understanding of how different modalities work together in acceleration perception.

Introduction

Present-day vehicles are equipped with a variety of powertrains, including internal combustion engines, electric, or hydrogen options. These all have very different dynamic responses, and even within the same vehicle model, manufacturers typically include several drive modes that are able to change the engine's response curve linked to the brake, steering, or acceleration input of the driver. In all of these developments, the most important factor that manufacturers try to optimize is the driving experience evaluated by the driver. Driving experience is a multidimensional construct [1-3], which from a human factor's perspective is shaped by many different aspects, including driving performance[4], driving experience [5], age [5,6], personality traits [5], as well as fatigue [7], emotions [8], behaviors [8], and intention [9]. Importantly, however, the first step for any of these aspects consists of the various perceptual inputs generated by the driving environment and processed via the different sensory modalities.

In the present work, we specifically focus on the perception of acceleration as one of the core factors determining the driving experience [1,10,11]. Investigating acceleration perception has traditionally been done with experimental methods from the field of psychophysics [12-14]. Important parameters that are determined in such experiments are the so-called absolute or difference thresholds, with the former indicating the smallest acceleration that is perceptible and the latter indicating the minimum difference between two stimuli that is noticeable (also called *just noticeable difference*, or JND).

Although previous research has uncovered several important parameters of acceleration perception [15-23], several core limitations still exist: if studies have been done in real, in-car environments, they have mostly focused on absolute acceleration thresholds [16]. Most importantly, however, as such environments do not support selective manipulation of individual sensory inputs, they were not able to explicitly investigate multisensory aspects of acceleration perception in detail. In contrast, the few experiments conducted with driving or motion simulators that tried to study such multisensory aspects by selective manipulation (e.g., [22,23]), did not use realistic motion profiles due to physical simulator restrictions. In the present study, we address these limitations by employing in-car data recordings of accelerations from a real vehicle rendered on a unique motion simulator setup that is capable of reproducing fine-grained motion details. This simulator setup allows us to

(1) manipulate every aspect of the acceleration profile
(2) control for side effects
(3) selectively manipulate sensory modalities
(4) measure difference thresholds at several base acceleration levels

Related Works

Investigating perception in the context of human factors of driving has seen considerable interest over the past decades. As examples, Braun [5] have tried to optimize in-car visual information systems for automotive user interfaces using perceptual principles. In the context of driving simulations, Shi [8] measured driving performance, physiological data, subjective evaluations, and emotional states depending on the visual level of detail of the simulation, showing that visual fidelity, indeed, has a broad impact on the driving experience. One of the earliest studies investigating acceleration perception is that of Rockwell and Snider, who determined the absolute threshold of linear acceleration for linear acceleration with automotive vehicles to between 0.01 and 0.02g [24]. In a follow-up study they found that these thresholds only minimally depended on the base driving speed with thresholds of 0.012g at 35mph and of 0.0115g at 50mph [15]. Several further studies since then [15,24] have confirmed absolute thresholds for linear acceleration to be between 0.006g and 0.01g.

These results were all obtained in real vehicles - whereas this represents the most realistic context for investigating acceleration perception, a key limitation of in-car settings is that it is exceedingly difficult if not impossible to manipulate individual factors contributing to acceleration perception. When judging acceleration, the brain will receive and integrate input from several sensory modalities, including vestibular, proprioceptive, visual, and auditory input [15-20,25]. Previous studies on velocity or acceleration perception have shown, for example, that visual and vestibular inputs are integrated in statistically optimal fashion, which holds even true for conflicting inputs [19]. This was also studied in another case for auditory and vestibular input for the perception of self- rotation [21].
If one is interested in the contribution of each of these cues to the final percept, in-car studies are not possible as they do not afford safe manipulation of individual sensory modalities. Similarly, detailed control over the aspects of the acceleration profile is only possible to a limited degree in in- car studies. For these reasons, studies on multisensory and dynamic aspects of acceleration perception have solely been conducted with driving simulator setups. One example of this is a study in which participants had to rate the intensity of different motion profiles varying in velocity, acceleration, and jerk on a hexapod motion simulator [26] - here they found that this intensity is largely determined by acceleration cues. Similarly, in [16] longitudinal acceleration profiles were run on a hexapod simulator for absolute thresholds, yielding thresholds (JND) for acceleration of 4.25% and for jerk of 13.89% for one comparison baseline. In [22], a six-degree-of-freedom motion platform was used to study multisensory aspects of acceleration perception with vestibular heading thresholds shown to depend on ego-centric rather than allocentric movement direction. An advanced hexapod motion simulator was used for perception of deceleration in [27], which combined equal deceleration values ($-0.8\ m/s^2$) with five tilt/translation conditions, showing that a higher translation resulted in a stronger braking perception.

Again, none of these previous works has investigated multisensory aspects of acceleration perception as a critical first step in shaping the driving experience. With this motivation, we here build on our earlier study, in which we showcased the potential of a unique, cable-robot-based simulator setup for investigating motion perception [28] and present several experiments aimed at investigating multisensory aspects of acceleration difference thresholds across different acceleration levels and sensory combinations with real-world, in-car motion trajectories

Results

JNDs for each acceleration category were determined as the average of the acceleration differences for which participants answered incorrectly in each trial. To investigate differences across acceleration categories, non-parametric Wilcoxon tests were employed on the JNDs. For comparisons across experiments in the same acceleration category, a Friedman test was used. Fig. 1 plots all JNDs across the different experiments and acceleration levels.

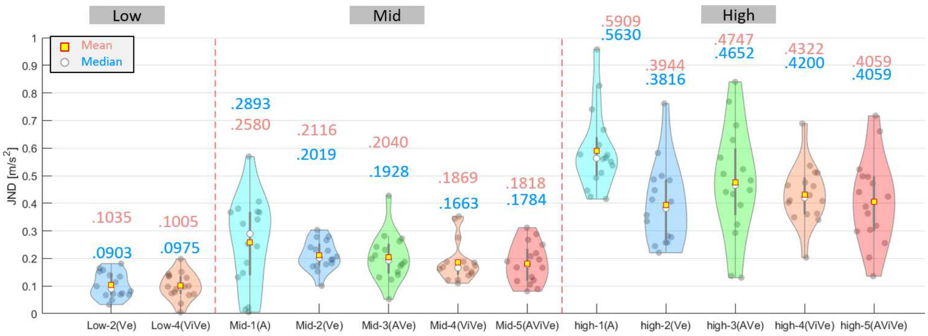

Figure 1. Violin plots of the JNDs in each acceleration level (low, mid, and high) across experiments (sensory modality combinations). Plots also indicate mean (red) and median (blue) values. Colors code the different experimental conditions - note that for low accelerations, experiments with auditory input were not run.

Analysis within each acceleration level

For the low acceleration category, JNDs were measured in two experiments with average values of JND_{Ve} = 0.103 m/s^2 and JND_{ViVe} = 0.103 m/s^2. The difference between the two modality conditions was not significant (W = 74.0, p = .756, z = 0.3103), indicating that the additional visual information did not "help" participants in discriminating accelerations better.

For the middle acceleration category, results were obtained in all five modality combinations. Overall, all conditions that contained physical motion had similar thresholds: JND_{Ve} = 0.211 m/s^2, JND_{AVe} = 0.204 m/s^2, JND_{ViVe} = 0.186 m/s^2, JND_{AViVe} = 0.181 m/s^2. Although it seemed that auditory thresholds were higher, due to large variance, the overall Friedman test showed no significant differences across experiments ($\chi 2(4)$ = 5.24, p = .263).

For the high level of acceleration, the Friedman test indicated a significant effect of modality ($\chi 2(4)$ = 16.04, p = .003). Indeed, the auditory JNDs were significantly higher compared to most other conditions except JND_{AVi} (JND_{A} vs JND_{ViVe}: W = 120.0, p = .007, JND_{A} vs JND_{Ve}: W = 126.0, p = .003 and JND_{A} vs JND_{AViVe}: W = 124.0 p = .004). Thresholds on average were again similar across the other conditions (JND_{ViVe} = 0.432, JND_{Ve} = 0.394, JND_{AVe} = 0.474 and JND_{AViVe} = 0.405 m/s^2). Overall, this result indicates that the auditory information seems to render the task "harder" at high levels of acceleration.

Weber's law

In our previous pilot study, we found evidence for Weber's law in acceleration perception for one condition with all sensory modalities [28]. We were interested in checking whether a similar trend would hold also for the other modality combinations included in the present study. The table in Fig. 2.a shows results of Wilcoxon tests for all comparisons of acceleration categories in each of the five experiments. All pairwise comparisons were highly significant, indicating that JNDs, indeed, on average increased with increasing base acceleration. Fig. 2.b in addition plots individual JNDs and fitted trends for the two experiments, for which all three acceleration categories were tested. We found an average fit quality of linear trends of r^2 = .896 for JND_{ViVe} and of r^2 = .945 for JND_{Ve}. A paired t-test of the slopes revealed no significant differences between the two experiments (p=.195, t(15)=1.358, n.s.). As can be seen, the resulting increase in JNDs with increasing base acceleration is well explainable with an increasing (linear) trend of similar magnitude in both conditions.

a Experiment	Low vs Mid	Low vs High	Mid vs High
1: A	x	x	U = 145, p < .001, z = 4.466
2: Ve	U = 149, p < .001, z = 4.315	U = 136, p < .001, z = 4.805	U = 159, p < .001, z = 3.938
3: AVe	x	x	U = 166, p < .001, z = 3.674
4: ViVe	U = 167, p < .001, z = 3.637	U = 136, p < .001, z = 4.805	U = 142, p < .001, z = 4.579
5: AViVe	x	x	U = 157, p < .001, z = 4.013

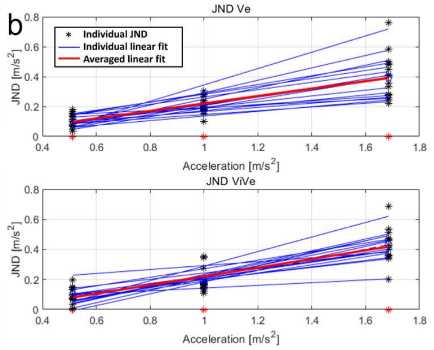

Figure 2. (a) Results of Wilcoxon tests across acceleration categories within the same sensory conditions (b) Results of the JNDs obtained for each acceleration category (indicated by red asterisks): light grey lines connect JNDs from the same participant across category; blue dots are average JNDs for each category with the solid black line being the linear fit.

Cue Integration modeling

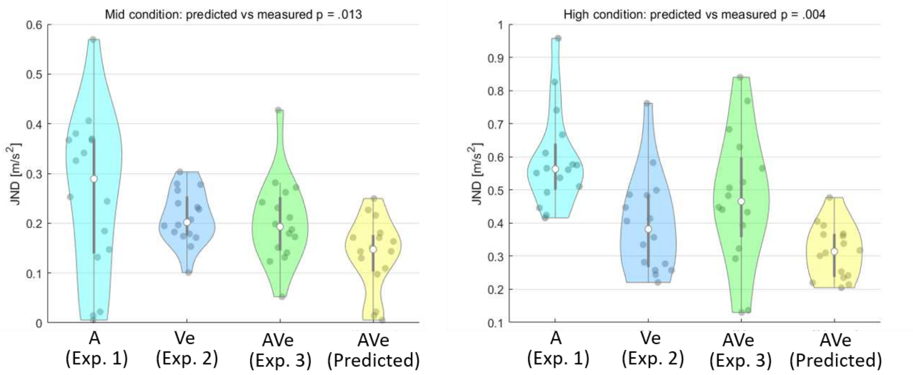

Figure 3. Plots of cue integration modelling (left – medium and right – high level acceleration) for Experiments 1-3 with the yellow plots being the predicted JND for Experiment 3 based on the JNDs of Experiments 1 and 2. Both results showed the predicted JNDs to be significantly lower compared to the measured JNDs.

To investigate the influence of auditory and vestibular information on acceleration perception, methods from cue integration modeling were used. Following [29,30], JNDs are seen as proportional to each cue's intrinsic reliability (σ). Since not all individual JNDs could be tested, here we focus on comparing the JNDs from the auditory only, vestibular only and auditory plus vestibular experiments, as we can use the JNDs from the first two experiments to try to predict the JND from the third. By setting each cue's reliability (σ_A, σ_{Ve}) to be equivalent to the measured JNDs, the optimal maximum likelihood integration (σ^2_{AVe}) can be predicted to be [31-33]

$$\sigma^2_{AVe} = \frac{\sigma^2_A \sigma^2_{Ve}}{\sigma^2_A + \sigma^2_{Ve}} \tag{1}$$

Fig. 3 shows the results of this analysis as violin plots for the middle and high acceleration categories. For the middle acceleration category, predicted JNDs were computed to be on average $JND_{Pred\_AVe} = 0.173$ m/s^2 with measured JNDs in contrast having a value of JND_{AVe} = 0.192 m/s^2. For the high acceleration category, predicted JNDs were computed to be JND_{Pred_AVe}= 0.314 m/s^2 with measured JNDs at around JND_{AVe}= 0.465 m/s^2. Statistical tests comparing predicted to measured JNDs showed significantly lower values for predictions compared to our actual measurements (mid: $W = 118$, $p = .017$, high: $W = 114$, $p = .010$). This result indicates that participants were not able to fully integrate auditory and vestibular information for acceleration perception - from the results, it rather seems as if they chose to disregard the auditory cue in favor of the vestibular one.

Discussion

In the present study, we used a unique driving simulator setup that allowed us to study multisensory aspects of acceleration perception based on real driving data. Specifically, we determined difference thresholds for linear acceleration at three levels of acceleration, varying the sensory inputs across experiments.

Our first goal was to measure acceleration thresholds across different sensory conditions at the same acceleration level. At low acceleration levels, the results of JND_{ViVe} and JND_{Ve} yielded comparable values of around 0.10 m/s^2. These results are similar to absolute thresholds determined in previous acceleration studies with in-car data [1,13,28]. For the middle and high acceleration levels, we added three more sensory conditions; JND_{AVe}, JND_{AViVe}, and JND_{A} at the middle level, JNDs were around .18 – .22 m/s^2, and we observed no significant differences among the JND_{Ve}, JND_{AVe}, JND_{ViVe}, and JND_{AViVe} except for JND_{A}. At the high level, JNDs ranged from .39 – .47 m/s^2, again at similar levels except for JND_{A}. Interestingly, only the auditory condition had different (higher) JNDs from the other modalities. Furthermore, the addition of the visual modality in Experiment 5 did not improve the acceleration thresholds beyond the values obtained with the vestibular condition (Experiment 2) alone, indicating that the perception of acceleration may strongly depend only on vestibular input.

With these results, we next analyzed cue integration based solely on auditory and vestibular inputs. We calculated predicted JNDs based on optimal maximum likelihood integration, and compared predicted JND_{Pred_AVe} and actual JND_{AVe}. In accordance with our previous analysis, we found that people seemed to weigh the vestibular cue more than the auditory cue for acceleration perception. In this context, a previous study on visual-vestibular integration for self-motion perception also found a decrease in visual sensitivity during angular self-motion tasks [34] when visual and vestibular input were presented concurrently. Hence, it seems that acceleration perception for the parameter ranges tested in the present and other studies is dominated by vestibular input.

Similar to other studies of sensory perception (e.g., vision [35], touch [36], and audition [37]), we found clear evidence for Weber's law in our data. Comparing thresholds across acceleration levels, we confirmed that these were increasing linearly at similar magnitudes for two experiments testing vestibular input only versus a combination of visual and vestibular input. It will be interesting to compare other modality combinations as well in the future and to increase the number of acceleration levels beyond three to further probe the range over which Weber's law holds in acceleration perception - the latter, however, would require a different setup as we already hit the limits for the CRS setup employed in the present study.

Conclusion

In the present study, we investigated the contribution of different modality inputs to perception of linear acceleration at several acceleration levels. At these levels, vestibular inputs seemed to dominate perception. It will be interesting to extend the range of acceleration levels as well as the type of trajectory to include other types of acceleration (i.e., angular) to further probe the validity of our findings. At the same time, other factors influencing the driving experience, such as jerk, delay, driver position, driving maneuver, or dynamic acceleration curve, will need to be tested. The current setup also did not allow us to selectively manipulate the visual input, which will require a VR-enabled setup - a direction that we are currently pursuing.

Our findings can also provide input for vehicle design in terms of ensuring a satisfying driving experience in industrial applications. Given the different acceleration profiles of electric versus combustion engine cars, additional research on the dynamics of the acceleration will be an important next step.

Methods

Participants

We recruited a total of n=16 participants (8 female) without physiological impairments to visual, vestibular, or auditory processing. Their age ranged from 28 to 63 (mean: 36.1 yr) with all participants possessing a driving license. We obtained written, informed consent from all participants with all procedures adhering to the Declaration of Helsinki. The experiment received ethical approval from the ethical review board of the University of Tübingen (486/2019BO2).

Cable Robot Simulators

To present the acceleration profiles, we employed a cable-driven simulator developed by the Max Planck Institute for Biological Cybernetics together with the Fraunhofer Institute for Manufacturing Engineering and Automation [38]. The Cable Robot Simulator (CRS) consists of a parallel kinematics architecture driven by eight winches. The winch cables are connected to an icosahedron-shaped cabin with tensions ranging from 1kN to 14kN. Using a parallel-control setup, the simulator is able to achieve a maximum acceleration by 15 m/s^2 and a maximum speed of 5 m/s within its total workspace of 4 x 8 x 5 m. The fine-grained, high-speed control of the winches coupled with the relatively low weight load allows the CRS to render motion profiles with excellent fidelity [38].

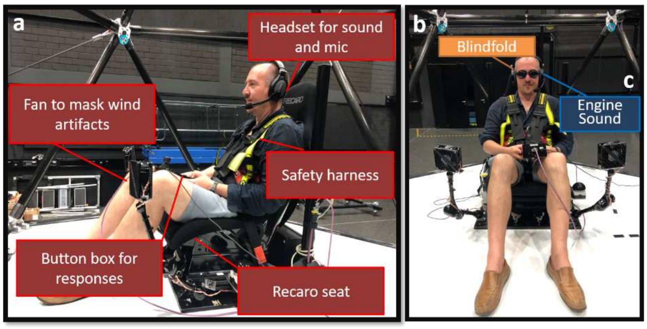

Figure 4. (a) The basic setup on the CRS, (b) Different view showing participant with blindfold and headset.

The basic setup on the CRS for all participants included a headset (for communicating with the experimenter and playing audio), two fans (to block the feeling of the air flow during movements), a button box (for operating the movements and for recording answers from participants), and a car-seat (see Figs. 4.a,b). Participants wore safety belts during all experiments.

In-car data - multisensory acceleration profiles

To measure in-car acceleration data, a high-resolution accelerometer ('ASC 3521-002', ASC GmbH, Pfaffenhofen, Germany; range=+/-2g, Sensitivity = 1000 mV/g, frequency response (+/-5%) = 100Hz) and a high-resolution microphone ('SQuadriga II', HEAD acoustics, Herzogenrath, Germany) were fitted to an experimental car that was controlled via an instrumented acceleration pedal. In this study, we focused on JNDs of typical driving accelerations, parametrized as percentage of pedal depression. In-car acceleration data was thus measured with pedal depressions ranging from 5% to 40% in 5% steps.

From the resulting accelerometer data, a total of 201 trajectories were computed by means of linear interpolation of fixed time intervals. These 201 trajectories were divided into three acceleration categories: low (trajectory 1-67, 0.51-0.99 m/s^2), mid (trajectory 68-134, 1.00-1.67 m/s^2), and high (trajectory 135-201, 1.68-2.79 m/s^2). The CRS was used to render these acceleration profiles, which were augmented such that they fit into its workspace using suitable deceleration phases. Importantly, each acceleration category included the same deceleration phase (low: -0.5 m/s^2, mid: -0.8 m/s^2, high: -2.5 m/s^2) to avoid distinguishing JNDs based on deceleration alone. Additionally, each motion profile traversed the same total distance in the simulator workspace.

In addition to the accelerometer in-car data, the engine sounds were also recorded at each pedal depression level. These sounds were cleaned, cut, interpolated into 201 profiles, and finally time-synced to each of the acceleration profiles.

Experimental design

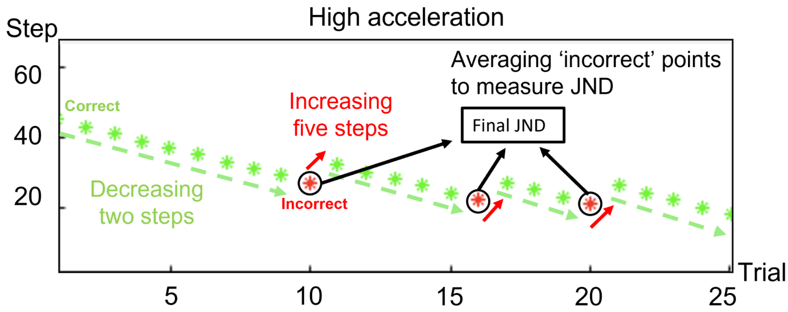

Figure 5. An example of the staircase procedure in the "high" condition. The initial step difference was set to 45. Every time the participant answered correctly, this step difference was decreased by 2 steps (green dots). If participants answered incorrectly, the difference was increased by 5 steps (red dots). The final JND estimate was determined as the average of all reversal points within all trials, amounting to roughly 20 steps for this staircase.

To investigate individual just-noticeable-differences (JNDs) for acceleration, participants conducted a 2-interval-forced-choice task, in which they were to decide which of two subsequently-presented acceleration profiles on the simulator contained the higher acceleration. JNDs were determined separately for each of the three acceleration categories and in each of several sensory conditions (see below).

In each acceleration category, one profile was determined to be a fixed baseline with the other profile - the comparison stimulus - varied according to the participant's answer. The comparison profile started from 15, 30, and 45 acceleration steps higher in the low, middle and high category as these differences resulted in clear perceptual differences overall (one step referring to the difference between any two subsequent of the 201 trajectories). The order of baseline and comparison profiles was randomized, as was the acceleration category during all tasks.

Depending on the participant's answer, the difference between the baseline and comparison trajectory of a next step was adjusted as follows: if the answer was incorrect, the difference of two trajectories was increased by 5 steps, otherwise it was decreased by 2 steps – a so-called staircase procedure [39,40]. Each of the three independently-tracked staircases ended, if the difference reached 0, or when a maximum of 25 trials was reached. The final JND point in each acceleration category was calculated as the average of the reversal points (that is, the incorrect answers, see Fig. 5). Overall, this resulted in one JND for each acceleration category.

To investigate the influence of different sensory modalities on the JNDs, we included five different experiments in this study that varied three sensory modalities: vestibular, visual, and auditory. Experiment 1 used only auditory input, Experiment 2 only vestibular input, Experiment 3 combined auditory and vestibular inputs, Experiment 4 combined visual and vestibular inputs, and Experiment 5 combined all three sensory modalities (see Table I).

Experiment	Modality	
1: A	Audition	
2: Ve	Vestibular	
3: AVe	Audition + Vestibular	
4: ViVe	Vision + Vestibular	
5: AViVe	Vision + Vestibular +Audition	

Table 1. Table of experiments varying sensory modalities. Experiment 1 (A) only uses auditory input, Experiment 2 (Ve) only vestibular input, Experiment 3 (AVe) both vestibular and auditory inputs, Experiment 4 (ViVe) both visual and vestibular inputs, and Experiment 5 (AViVe) uses all three modalities with visual, vestibular, and auditory input

All experiments used the CRS setup in different ways: in Experiment 1 (abbreviated with "A" in the following), participants were seated on the driving seat, wearing a blindfold. The simulator was not switched on during this experiment. The different sound profiles were played via a high-quality headset. In Experiment 2 (Ve), participants wore a blindfold, and the headset played white noise to mask any outside sounds. The simulator presented the motion trajectories. Experiment 3 (AVe) was the same as Experiment 2, except that the headset played the sound profiles. Experiment 4 (ViVe) was the same as Experiment 2, except that participants did not wear the blindfold. Finally, in Experiment 5 (AViVe), participants experienced all three sensory modalities.
Experiments 1, 3, and 5 did not include the low acceleration category as the engine sound was too quiet to be heard reliably.

Trial procedure

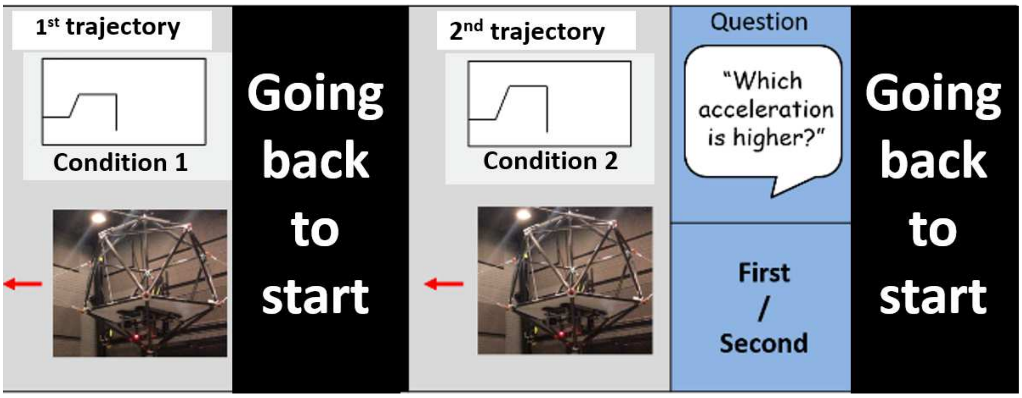

Figure 6. The trial procedure. In each trial, a baseline and comparison stimulus are presented in random order, and the task for the participant was to judge which of the two forward accelerations was higher

In every trial, the CRS was first driven to a fixed start position. Participants were then able to initiate each trial using a button press, after which the CRS played back two acceleration trajectories. After each trajectory was played, the CRS slowly moved back to the start position. After finishing the second trajectory, participants judged which motion was felt as the stronger acceleration (see Fig. 6). To make participants focus on the forward acceleration phase, voice instructions ('start' and 'stop') were played via the headset to inform participants of the duration of the acceleration phase during trajectories. In addition, participants were instructed to disregard the deceleration phase for their judgments.
Each trajectory took roughly 10s, and the whole trial with re-positioning and answering took around 30s. The

total experiment time was therefore around 50min including ample break time.

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Data availability statement

Data is available from the corresponding author upon reasonable request.

Competing interests

The authors declare no financial or non-financial competing interests.

Informed consent statement

Informed consent for publication of identifying information/images in an online open-access publication has been obtained from the individual shown in Figure 4.

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