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In-car speed estimations with real, virtual, and no view[☆]

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ABSTRACT

Car handling, and hence, safety, is affected by the way we estimate speed. Speed, however, is often underestimated in degraded visual environments, including virtual environments such as driving simulators. In simulators the visual and physical motion are typically incongruent as limited by quality and amplitude, respectively, which may cause a negative transfer of training. To improve the (training) quality of simulators and make them feel more real, it would be helpful to fill a knowledge gap on in-car speed perception as affected by real and virtual views, within a single group of subjects. We did so by testing whether estimations of speed in terms of km/h could be a valid metric for that purpose.

We therefore exposed 17 subjects, seated as passengers in the front of a car on a straight road to four experimental conditions: (1) driving with a real out-the-window view, (2) driving with a live video view, (3) standing still watching pre-recorded video's, and (4) driving with eyes closed. Field-of-view was made equal in all conditions. Speeds tested ranged between 20 and 60 km/h.

On average, speed was estimated 5 km/h less than actual, while we did not find a statistically significant difference between the four conditions tested.

These results seem to contradict previous observations on motion perception, in particular in simulators, that have been ascribed to the quality of the visuals used. This finding may yet be explained by the assumption that speed estimations in terms of km/h are dominated by (conscious) cognitive processes, while visual-vestibular coherence between visual and physical motion, is dominated by (unconscious) sensorial driven perceptual processes. This disqualifies perceived speed as a valid metric for studying motion perception related to the optimisation of simulators.

1. Introduction

Car handling, and hence, safety, is affected by the way we estimate speed. Speed, however, is often underestimated in degraded visual environments like foggy conditions (see, e.g., [1,2]). In some sense, virtual environments, like driving simulators, can also be regarded as degraded visual environments. Causing factors are, among other things, limitations in field of view, spatial and temporal resolution, contrast, missing motion parallax, and the use of mono versus stereo images, the latter including accommodation-convergence conflicts. Moreover, these simulators are typically affected by incongruent visual and physical motion. To be judged as coherent, for example, linear physical simulator motion generally requires less amplitude than the artificial visual motion, the discrepancy typically increasing with reducing image quality [3]. These simulator limitations may therefore cause a negative

transfer of training, and given the increasing use of simulators for driving lessons, this casts a doubt on the validity of their use for training.

To improve the validity of simulators for training needs and make them feel more real, it would be helpful to also learn more about how we perceive motion in real world conditions. Although the ratio between visual and physical motion may be anticipated being unity in real world conditions, the validation thereof is hampered by manipulation of the experimental ratio. Alternatively, perception of motion might be assessed the perception of speed or acceleration. However, the visual system is not sensitive to acceleration cues [4], and it has been doubted whether we do (consciously) perceive acceleration at all (different from making inferences about different velocities in time) [5]. As shown by [1], for example, absolute speed estimations in terms of km/h can be used, even in in-car real world conditions. As a result, [1] showed that

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the effect of contrast as related to fog, was only marginal, while overall they observed an average estimated speed of about 5 km/h less than actual.

The study by [1], however, did not include virtual views as relevant for simulators. Although simulators have extensively been used for studying speed, these studies typically concerned speed as controlled by car drivers [6–13]. The control of speed, however, is likely affected not only by perception, but by higher order cognitive functions such as avoiding risks, and the results of these studies often vary¹. Several of the visual factors mentioned have been studied too, which results, do vary as well [1,2,14–17]. Field of view (FoV), however, seems to be an exception, larger FoV consistently having been shown to yield a better performance in several ways [3,18–23].

Overall we therefore conclude that there is a lack of consistent data on self-motion perception and the perception of speed in particular, within subjects exposed to both real, and virtual views in otherwise equal conditions. Therefore we aimed at elaborating on the question whether estimating speed in terms of km/h as used by [1] can be an appropriate metric for making distinctions between real and virtual views as would be required to improve the quality of simulators and make them feel more real.

To that end we ran an experiment in a real car, making a distinction between driving with a real out-the-window (OtW) view, driving with a live video view presented by a head mounted display (HMD), viewing a pre-recorded video with the same HMD while standing still, and driving with eyes closed. The motives underlying these conditions is explained below. The dependent variable studied in this experiment was a verbal quantitative estimate of speed in terms of km/h. Analogous to the observations by [3], we hypothesized that, on average, estimated speed would be less than actual, the discrepancy being least when driving with a real OtW view, and largest with eyes closed.

2. Materials and methods

2.1. Materials

The test vehicle used in this experiment was a 2002 1.8 turbo Volkswagen Passat station wagon with automatic transmission, driving on an almost straight private road with a length of approximately 1 km. During the experiment this road was deserted, which allowed to accelerate, decelerate and stop at any time without putting a risk to the experimental car and its occupants nor to that of other traffic.

As an intermediate for computer generated simulator images, we used video recordings for practical reasons, in particular for allowing a real-time low-delay interaction with the real world. Showing real time video in most popular VR glasses, however, an additional delay is introduced by the image processing required to compensate for lens distortions. We therefore used a Fatshark Dominator HD2 head mounted display (HMD), which allowed for a direct feedthrough of video recordings. This device had a FoV of approx. 40 degrees (h) × 30 degrees (v), a resolution of 800(h) × 600(v) per eye and a total weight of 152 g. To record and play live video images, a small light weight KPC-E700PUB colour camera with a resolution of 700TVL and PAL 976(h) × 582(v) was mounted to the HMD positioned in between the eyes (see Fig. 1a). It had a 6 mm lens with a horizontal FoV of approx. 40 degrees too.

In total 7 men and 10 women participated in the experiment, with an average age of 26 years (SD = 4.6). All subjects were without any disease known by themselves possibly affecting their driving abilities,

and did not wear glasses (which could obstruct wearing the HMD).

To prevent confounding by engine noise, possibly being indicative for speed, subjects were presented with white audio noise through headphones, while maintaining communication with the experimental leader.

2.2. Independent variables

Four main visual conditions were used: (1) driving with real OtW view, (2) driving with live video, (3) standing still viewing pre-recorded videos, and (4) driving with eyes closed. Of these conditions, (1) and (2) are included as the two primary conditions of interest. To account for the known effects of FoV on perception of speed, we used dummy goggles in condition (2) as shown in Fig. 1b right, that limited the horizontal FoV to 40 degrees, equal to that of the HMD as used in conditions (2) and (3). Conditions (3) and (4) were added to learn whether mere visual and/or vestibular² effects could explain part of the results to be found. In condition (3) pre-recorded videos were streamed from a laptop. These recordings were made in advance of the experiment for all speeds tested, by having a test subject wearing the HMD/camera combination and using the track as in the other conditions. In condition (4), the HMD was worn but inactive. The order of these four conditions was balanced over the subjects.

To minimize vestibular effects, we chose to have our subjects estimate speed during intervals in which the actual speed was constant. To that end, each of the four main visual conditions were driven with five different speeds: 20, 30, 40, 50, and 60 km/h. The lowest speed was determined by the lowest speed allowed by the cruise control, the highest speed was limited by the length of the test track and safety issues. The five speeds were presented once in each condition in a random order. In total, each subject therefore experienced 4 (conditions) × 5 (speeds) = 20 trials. These trials were realised within two half-hour intervals with a half-hour break in between. Changes in actual speed preceding each test varied between −40 km/h (decelerating from 60 to 20 km/h) and +60 km/h (accelerating from standstill) and were all realised with an acceleration or deceleration of approximately 1 m/s². This implies that a larger change of speed also took more time to be accomplished. Depending on the combination of the change of speed and test speed, one or two speeds could be tested in a single stretch, before turning the car at the end of the track and starting the next stretch. Because accelerations from zero speed were over-represented in the otherwise random distribution of actual speeds, the final distribution of speed changes was not uniform.

2.3. Dependent variable

The single dependent variable studied here was the subjects' estimates of their speed in terms of km/h.

2.4. Experimental procedure

The experimental protocol was approved by the institutional review board of TNO Soesterberg in accordance with the declaration of Helsinki, and included that all subjects were informed about the purpose and procedures and they signed an informed consent in advance of the experiment. The experimental leader was the driver and subjects were seated in the passenger front-seat. The subjects were instructed to close their eyes during accelerations and decelerations, until the experimental leader mentioned that they could open them again. The

¹ Here, we deliberately included a rather large list of references without going into details, because these references have been part of discussions about the results of the paper at hand, while we conclude these are not pertinent to the research question stated in the following paragraph, nor do their results contribute to the conclusions drawn at the end.

² A detail concerns the fact that with whole-body motion, not only the organs of balance are stimulated, but also the somatosensory system as a whole. Yet, it has been shown that with respect to motion perception, the organs of balance do play a major role [24,25] for which reason we here keep to mentioning the vestibular system only.

Fig. 1. (a) The HMD and camera used in this experiment. (b) Dummy goggles limiting the FoV to that of the HMD used in the real OtW view condition.

experimental leader accelerated/decelerated to the intended test speed, set the cruise control and waited for a few seconds before the subject was asked to open his or her eyes and keep looking straight ahead. After another ten seconds, subjects were then asked the following question: “How fast do you think you are driving in km/h?”. Anticipating a rounding of numbers to the nearest multiple of five, and preventing interindividual differences in this respect, subjects were instructed to round their estimates to multiples of 5 km/h. After having reported their speed estimation, they closed their eyes again and the experimental leader marked the reported speed on a form within easy reach of the steering wheel. If the remaining track stretch allowed, the experimental leader accelerated or decelerated from the current speed to a new speed condition. If there was not enough track length left, the experimental leader made a turn at the end of the track and then accelerated to a new test speed. During turns, participants were allowed to open their eyes and look out the window to reduce the chance of motion sickness. To familiarize the subjects with the procedure and to provide an equal reference for all subjects, two speeds were driven in advance of the actual experimental conditions with real OtW view, one at 10 km/h and another at 70 km/h. Although subjects were informed about these two familiarization speeds, they were not informed about the actual speeds tested.

3. Results

All participants completed the experiment. Further analyses are therefore completed using the data of all 17 participants. Fig. 2a shows the observed quantitative speed estimations depending on the actual driven speeds, separate for the four visual conditions. All estimations varied from 5 to 90 km/h. To emphasize the difference between actual

and estimated speed, Fig. 2b shows the difference between estimated and actual speeds.

A repeated measures ANOVA was made of the difference between estimated and actual speed as the dependent variable, using the visual condition and actual speed as independent variables. The analysis included an offset to account for a possible overall speed difference. This analysis did not show main effects of visual condition ($F(3,48) = 1.61$, $p = .20$) nor of the actual speed ($F(4,64) = 1.17$, $p = .33$). The interaction between condition and actual speed was not significant either ($F(12,192) = 1.57$, $p = .10$). Overall, a t -test showed that the estimated speed was 5.1 km/h less than actual ($t(339) = 8.22$, $p < 10^{-14}$, $sd = 11.5$).

To test whether these effects were affected by vestibular cues due to the changes in actual speed preceding each test, we performed linear regressions on the observed differences between estimated and actual speed, and these actual speed changes. These tests were accordingly only performed in the three driving conditions. These regressions showed that 7.7% of the variance was explained ($F(1,63) = 5.26$, $p < .05$) for the real view condition with a slope of 0.09 and 11.6% for the condition with live video ($F(1,63) = 8.26$, $p < .01$) with a slope of 0.08, but there was no effect in the eyes closed condition ($F(1,63) = 2.87$, $p = .10$). Here, a slope of zero (no significant effect found) implies that the differences between the estimated and actual speeds are independent of the actual preceding changes in speed. A slope of 0.1 would imply that, on average, the difference between estimated and actual speed increases by 1 km/h with every 10 km/h of the preceding change in speed. Note that these differences add to the observed average underestimation of 5.1 km/h. This implies that at the largest changes in speed (i.e., 0–60 km/h), there was almost no underestimation of speed in the two conditions with real and virtual views.

Fig. 2. Estimated versus actual speed (a) and the discrepancy between estimated and actual (b) per visual condition. Error bars show the between subjects SD.

4. Discussion and conclusions

To test whether estimating speed in terms of km/h can be an appropriate metric for making distinctions between real and virtual views as would be required to improve the quality of simulators and make them feel more real, we exposed subjects to four different combinations of physical self-motion and visual information: (1) driving with real OtW view, (2) driving with live video, (3) standing still viewing pre-recorded videos, and (4) driving with eyes closed. Contrary to our expectation, the differences between the speeds estimated and actually driven did not differ significantly between these four conditions. We therefore conclude that under the conditions as studied, speed estimation in terms of km/h is not a valid metric for the purpose aimed at. Our not having been able to validate our assumption, the findings may be understood by reckoning a number of issues.

First we did observe an average underestimation of speed by about 5 km/h, equal to the difference observed before by [1]. This observation can therefore in part be considered a validation of the results we found.

Second, we used a limited FoV in all conditions, while FoV was already known to be a dominant factor in estimating speed [3,16,18–23]. One factor then concerns the role of peripheral view, which has been shown to be dominant forvection, i.e., our sense of self-motion induced by mere visual optic flow [26,27]. If the reduced FoV would have played a major role in our experiment, this would also have caused a reduced accuracy of the speeds estimated. However, we did observe that these speed estimations were quite close to the actual speeds, which also held for the stand still condition in particular. In combination with the first argument given above, this disqualifies FoV as the explanatory factor of our not finding an effect of the visual conditions on the speed estimations.

Third, the condition with no view (eyes closed or vestibular only), did not yield statistically different estimations of speed as compared to the other conditions. Because the test intervals were driven with constant velocity, and the vestibular system is known to be sensitive to acceleration and hence not to constant velocity [28], this result can only be understood by path integration and the effect of road rumble. Road rumble typically increases with increasing car speed, and may hence serve as a cue for the speed estimations. Path integration refers to the assumption that sensory afferents coding for acceleration are integrated by our central nervous system over time to obtain a sense of speed as yet [29]. These factors, however, cannot be decisive in explaining the lack of difference in speed estimations between the other conditions. First, the speed estimations in the standing still condition were comparable to those observed while driving. Second, the difference between estimated and actual speed did vary with the preceding actual speed in the two visual conditions. Our not finding an effect of the visual conditions on the speed estimations therefore requires yet another explanation.

As referred to in the introduction already, there is a large amount of literature dealing with motion perception in virtual or simulator environments. In most of this literature, however, the dependent variables related to human behaviour, in particular the speed as controlled by the driver. In this literature, the speed controlled is implicitly assumed to be directly related to the speed perceived [2,6,7,9–17,19,21,23]. Control of speed, however, concerns a complex process, not only affected by perception, but by other higher order cognitive factors in addition, such as the avoidance of risks. Here, perception typically refers to intuitive “feelings” or “sensations” largely determined unconsciously by sensory cues. Perception therefore does not require conscious reasoning. Cognition typically refers to “thoughts”, i.e., a mental process involving (conscious) attention, memory and reasoning. It therefore makes sense to assume that cognition plays a major role in estimating speed. Moreover, the estimation of speed in terms of km/h, requires a conceptual notion of the unit used, which, in this case, includes reasoned knowledge about distance in kilometres and time in hours. Estimating

speed, furthermore requires memory about previously experienced speeds, typically a cognitive function in addition. Coherence, as rated by [3] for example, concerns an instantaneous “feeling” largely determined by multiple senses, in their case being visual and vestibular. Coherence may therefore be assumed to be largely a perceptual issue. Yet, because perception of coherence does require memory too, i.e., about previously experienced natural motion, perception and cognition cannot be considered mutually exclusive concepts, but do show at least some overlap and interaction [30].

Overall we therefore assume that quantitative speed estimations in terms of km/h are dominated by cognitive inferences. Moreover, because cognitive processes are realized by different neural structures in the brain as compared to perceptual and sensory processes, this can also explain that quantitative speed estimations as observed here do show a different dependency on visual and vestibular cues, as compared to judging a perceptually dominated coherence between these cues. This distinction between perception and cognition therefore supports the understanding of why speed estimation in terms of km/h is not a valid metric that is generally applicable in research aiming at making simulators feel more real.

Declarations of interest

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