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Usefulness and satisfaction of take-over requests for highly automated driving

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Abstract

This paper summarizes our results from survey research and driving simulator experiments on auditory, vibrotactile, and visual take-over requests in highly automated driving. Our review shows that vibrotactile take-over requests in the driver's seat yielded relatively high ratings of self-reported usefulness and satisfaction. Auditory take-over requests in the form of beeping sound were regarded as useful but not satisfactory, and it was found that the beep rate corresponds to perceived urgency. Visual-only feedback (LEDs) was regarded by participants as neither useful nor satisfactory. Augmented visual feedback was found to support effective steering and braking actions, and may be a useful compliment to vibrotactile take-over requests. The present findings may be used in the design of take-over requests.

Keywords

Highly Automated Driving; Human Machine Interfaces; Human Factors

1. Introduction

If a highly automated car reaches its operational limits, the driver must take over control within a certain time buffer. The time buffer (also called lead time, transition time, or time budget) may range from long (non-urgent situations) to short (high-urgent situation, such as an impending collision) [1]. Prior research has measured drivers' behaviour in take-over situations involving time buffers ranging between 2 and 10 seconds (for a review see [2]).

The design of take-over requests (TORs) is a crucial factor in the safety of automated driving systems, because a late or wrong response may lead to incidents and accidents. If the time buffer is short, the driver could benefit from receiving a take-over request (a warning) that conveys a high level of urgency. On the other hand, if the automated vehicle can anticipate when a transition to manual control will be needed, a take-over request can be issued well in advance in a more discretionary manner.

New types of in-vehicle feedback, such as take-over requests, can be rated along two orthogonal dimensions: (1) usefulness (quality) and (2) satisfaction (pleasure) [3, 4]. Both dimensions are regarded as important. That is, the feedback should be useful in that it supports drivers in making a safe and timely response, and it should be satisfactory: if it is not, then drivers may become annoyed and disable the feedback system altogether [5].

Within the project HFauto (Human Factors of Automated Driving), we have investigated how drivers perceive and respond to different visual auditory, vibrotactile, and visual take-over requests for highly automated driving. The aim of the present paper is to summarize our contributions regarding the effects take-over request modality on drivers' perceived usefulness and satisfaction, and driver response.

2. Auditory take-over requests

Beeps are an often used type of auditory feedback in automated driving [6]. In a crowdsourcing study with 1,692 participants, we replicated previous experimental results by showing that there exists a clear monotonic relationship between perceived urgency and inter-beep duration [1], see Figure 1.

Auditory take-over requests can also be provided in the form of speech [7, 8]. In the same large-scale international online survey, we found that the female and male voice ("Please take over!") were rated as more urgent and more preferred than beeps [1]. In another large-sample crowdsourcing study, 2,669 participants from 95 countries listened to a random 10 out of 140 take-over requests, and rated each take-over request on urgency, commandingness, pleasantness, and ease of understanding. We found that differences in speech intelligibility and perceived urgency between take-over requests in male versus female voice are generally small. Additionally, in agreement with earlier findings by Hellier et al. [10] we found that the spoken phrase (e.g., "Note, take over" versus "Take over now") affects perceived urgency. Furthermore, it was shown that an increase of speech rate yielded increased self-reported urgency (Figure 1).

In an experiment in a driving simulator (Experiment 1), we found that drivers responded effectively (i.e., average steer initiation times of about 2.0 s, which was well within the 7 s time buffer) to an auditory take-over request (double beep) [11]. However, *directional* auditory feedback provided via the car's speakers on either the left or the right was not noticed by drivers. Drivers who received directional feedback almost always steered to the left in a scenario where a stationary car blocked the middle lane (Figure 2), just as did drivers who received non-directional feedback (i.e., TOR provided via the left and right speakers simultaneously).

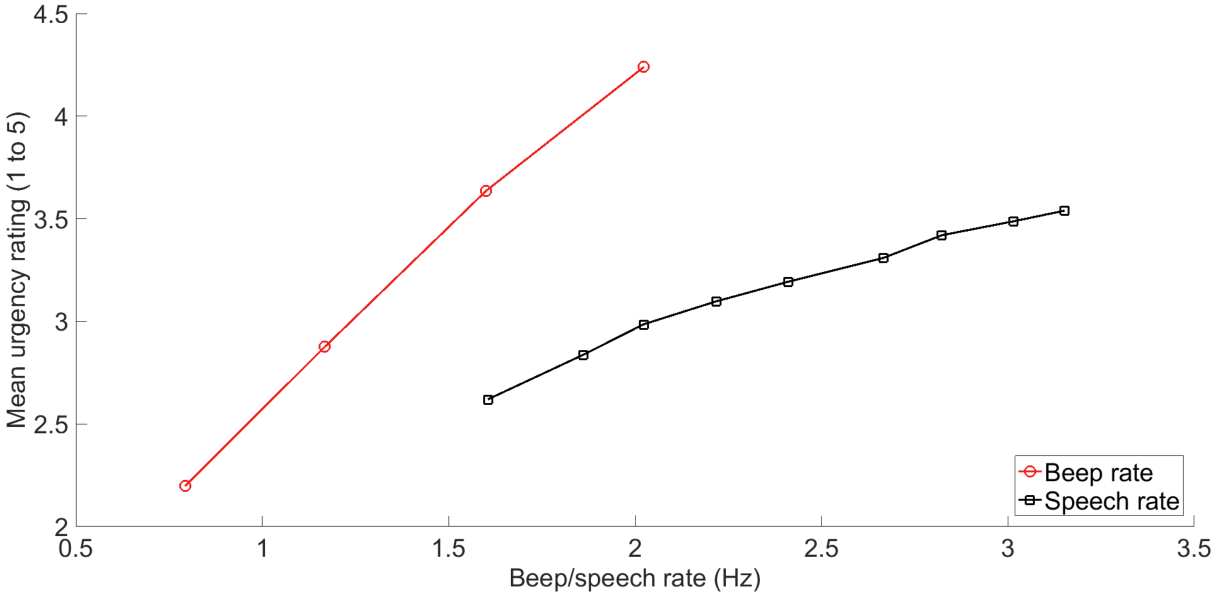

Figure 1: Relationship between self-reported urgency and beep rate / speech rate [1, 9] . The beep rate is the number of beeps per second (beeps were presented in pairs, with a 0.11 s pause in between); speech rate is expressed in syllabi per second for the uttered phrase "*take-over please*" (i.e., 4 syllabi). Participants respondent to the statement 'I consider such a sound as urgent' or 'The message is urgent' on a scale from 1 = Disagree strongly, 5 = Agree strongly.

Figure 2: A take-over scenario. Participants could avoid the stationary car by steering left or right [11].

3. Vibrotactile take-over requests

Vibrotactile messages can be perceived even in the presence of auditory distractions such as a phone call or radio music [12]. In a driving simulator experiment involving take-over situations with 7 s time buffer, we found find that vibtrotactile-only warnings in the driver seat are effective for ensuring that drivers reclaim control of the steering wheel in time (Experiment 1) [11]. However, *directional* vibrotactile cues embedded in the take-over request did not elicit a directional response in uninstructed drivers [11]. In a follow-up study (Experiment 2) [13], it was evaluated how well drivers recognized directional cues presented via the vibrotactile seat, when they were explicitly instructed about the meaning of the directional cues. Here, the participants received a static (i.e., left or right) or dynamic (i.e., moving left or right) take-over request and were asked to change lane according to the directional cue. Results showed that participants did not accurately detect the directional vibrotactile cues (correct response rates of about 80%). Furthermore, it was found that static take-over requests yielded faster reaction times than dynamic ones. In summary, vibrotactile take-over requests are useful for alerting a driver, but the amount of information that can be communicated via a vibrotactile seat may be limited [12].

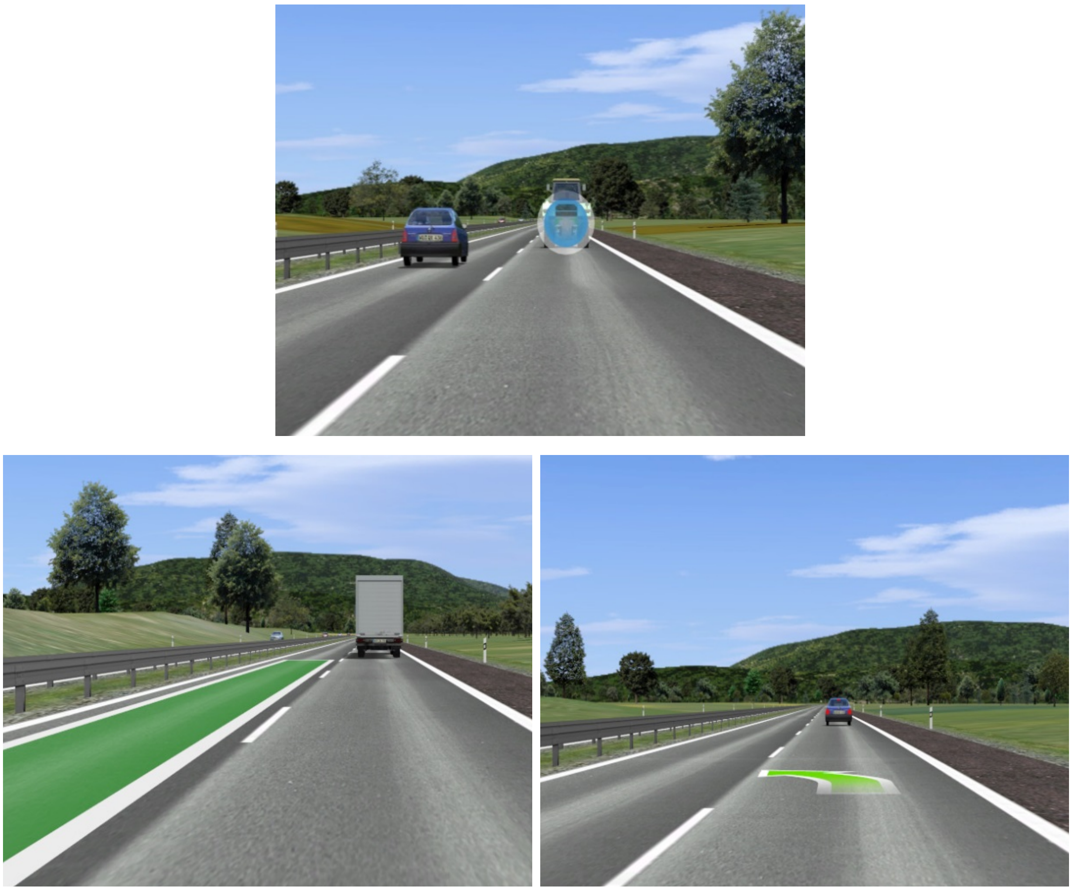

Figure 3. The visual interface in [14]. Top middle (sphere): a sphere highlighting the slow-moving vehicle ahead in both scenarios. Bottom left (carpet): a green carpet in the left lane for the lane change scenario. Bottom right (arrow): a green arrow pointing left for the lane change scenario.

4. Visual augmented feedback and visual take-over requests

In a driving simulator study (Experiment 3) [14] we assessed the effectiveness of visual augmented feedback for supporting vibrotactile take-over requests. Figure 3 shows four types of visual feedback that were used during lane change and braking scenarios: (1) a baseline condition without visual support, (2) a sphere highlighting a slow-moving vehicle ahead in both scenarios, (3) a green carpet in the left lane for the lane change scenario and a red barrier covering the lane markings for the braking scenario, and (4) a red arrow pointing backwards, for the braking scenario. We found that the carpet feedback and arrow feedback facilitated accurate braking and lane changing behaviour compared to the baseline condition, whereas the sphere feedback appeared to cause confusion in that drivers showed unnecessary braking in a scenario in which they only had to change lanes.

In another driving simulator study (Experiment 4) [15], we measures driver response times to take-over requests provided via (1) a vibrotactile seat, (2) auditory beeps, and (3) visual LEDs surrounding the secondary task display and above the steering wheel while drivers were performing different types of secondary tasks (watching a video, reading, or performing an simulated hands-free phone task). The results of this study showed that the initial steering response times were about 0.6 s slower for the visual take-over requests than for the vibrotactile and auditory take-over requests. It was concluded that visual warnings convey a low sense of urgency or may go unnoticed even when in the driver's visual field of view. In summary, visual messages are prone to be overlooked, especially during highly automated driving in which drivers will be allowed to take their eyes off the road and engage in non-driving tasks.

5. Comparing auditory, visual, and vibrotactile take-over requests

Figure 4 summarizes the results of the same usefulness and satisfaction questionnaire [3], for all four diving simulator experiments reviewed above. All experiments were performed with the same driving simulator software (SILAB) and with equivalent simulator hardware (i.e., full passenger vehicle with surround projection).

Several findings stand out: visual-only feedback (i.e., the LEDs) was not regarded as useful by participants (Experiment 4) [15]. These subjective findings mirror the objective take-over response times, which were found to be slower than the response times to vibrations-only and auditory-only take-over requests [15]. Furthermore, auditory-only feedback (Experiments 1 & 4; [11, 15]) was not useful, but not satisfactory. In our experiments, the auditory take-over request consisted of a loud beep. Vibrations were overall regarded as both useful and satisfactory (Experiments 1–4). However, vibrations combined with ambiguous visual information (Sphere) reduced overall usefulness and satisfaction as compared to vibrations-only take-over requests (Experiment 3) [14].

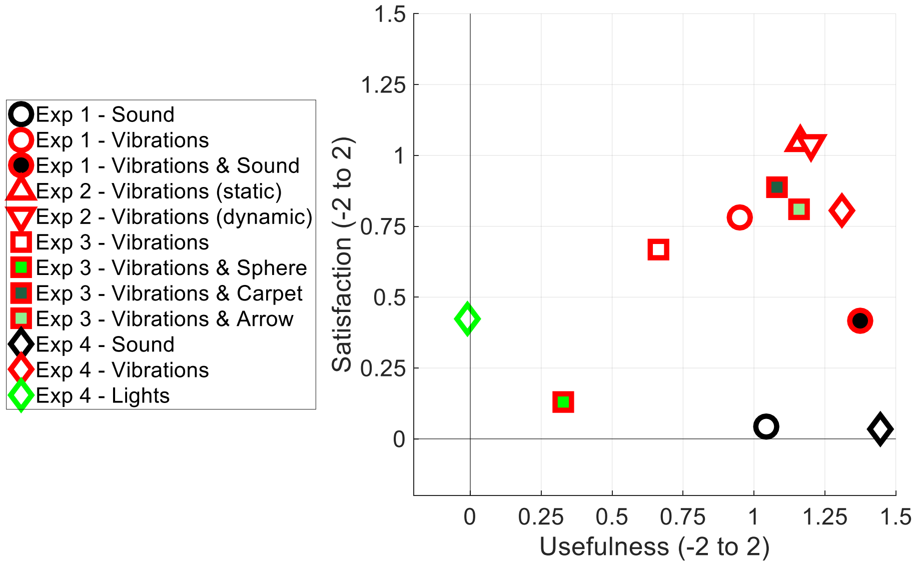

Figure 4: Self-reported satisfaction and usefulness for take-over requests tested in four driving simulator experiments.

6. Discussion

We designed and evaluated various auditory, visual, and vibrotactile take-over requests. Results showed that visual-only take-over requests in the form of LEDs yielded low ratings of usefulness and high steer-touch response times compared to sound-only and vibration-only take-over requests. Augmented visual feedback (Carpet, Arrow) has the potential to enhance decision making (e.g., whether the driver appropriately implements a steering or braking action), but should be implemented with care. Visual feedback tends to be dominant over feedback in other modalities, and if augmented visual feedback does not provide semantically meaningful information (cf. Sphere), then the driver may respond inappropriately and self-report ratings of usefulness may be impaired. It should be noted that the present results do not necessarily generalize to all types of visual feedback. For example, recently the use of ambient light was regarded as promising as take-over request [16].

Vibrotactile take-over requests feedback were found to be useful for getting the driver back into the loop, even when presented in isolation. However, the effectiveness of directional (left vs. right) vibrations in the driver seat may be limited as compared to non-directional vibrations. Another limitation of vibrotactile feedback is that the driver and the source of vibrations have to be in physical contact with each other [12].

The beeps yielded low satisfaction ratings, and were less preferred than speech-based take-over requests. However, beeps may be an effective channel for conveying a sense of urgency, and the inter-beep interval is a useful moderator variable in this regard (cf. parking sensors). It is possible that speech-based take-over requests yield higher satisfaction and a higher sense of urgency than beeps [1, 7, 8, 17, 18].

In order to counteract the limitations of unimodal take-over requests, the use of multimodal take-over requests may be promising. Multimodal feedback increases the redundancy of the warning and consequently reduces the probability of misses, as compared to unimodal feedback. By means of a crowdsourced online questionnaire, we asked the opinion of 1,692 people on auditory, visual, and vibrotactile take-over requests in highly automated driving [1]. The survey included recordings of auditory messages and illustrations of visual and vibrational messages. The results of the survey showed, consistent with the literature, that multimodal take-over requests were the most preferred option in high urgency scenarios. Furthermore, in a driving simulator experiment [11], we found that drivers showed a faster initial response to multimodal (i.e., auditory & vibrotactile) than vibrotactile-only take-over requests.

Future research should seek ways to maximize the usefulness and satisfaction of take-over requests by finding the right combination of auditory, vibrotactile, and visual feedback. Here attention should be paid to temporal and semantic congruence.

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