A preliminary simulator study to investigate the effects of digital mirror failures on driving and glance behaviour, situation awareness, criticality and trust

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Abstract: Camera-based 'rear-view' displays within vehicles can improve aerodynamics and the field of view. However, digital technology may fail. Specifically for lane change situations, malfunctions may result in insufficient visual information and unsafe manoeuvres. Moreover, a degraded source may lead to distraction, compromised trust and thus lower acceptance. A driving simulator experiment aimed to determine the impact of a digital mirror failure on driving and visual behaviour, situation awareness (SA), criticality ratings and trust. Therefore, the existing 'wing mirrors' were replaced with in-vehicle LCD screens. In three drives in a UK motorway scenario, 19 drivers were instructed to perform ten lane-changes. During the second drive, the right (offside) digital mirror failed immediately after the instruction to move from the middle to the right ('fast') lane. Results show that the failure led to larger speed variation, more rear-view-mirror and slightly more over-the-shoulder checks, but increased observations of the right (failed) mirror, indicating distraction. Cumulative SA was not affected, but ratings for instability, complexity and variability increased. Drivers also recognised the heightened criticality. Unsurprisingly, trust decreased, potentially motivating the compensatory behaviours. In the third drive, which was free from failures, behaviours, criticality and trust returned to pre-failure levels, indicating no persistent long-term effects.

1. Introduction

The concept of mirrorless cars involves the replacement of traditional side mirrors with camera-based displays placed within vehicles, thereby improving vehicle aerodynamics and improving the field of view. Technological advancements mean that modern in-vehicle electronics are generally robust and highly reliable, with current systems able to successfully replace or augment aspects of vehicle control, such as braking and steering [1]. Nevertheless, digital technology may fail. A failure is defined as "an event that occurs when the delivered service deviates from correct service" [2, p. 2]. Hence, a failure constitutes the situation in which a system is not doing what it is intended to do. Besides faults related to the software and electronic circuits, camera-based systems are also susceptible to environmental factors that may limit the camera's vision, such as rain, dirt and ice, sun glare, or image distortions in low sunlight conditions. Despite the most diligent efforts to ensure the correct functioning of digital mirrors, designers need to envision scenarios in which a failure occurs. In the case of digital mirrors, it could potentially cause a frozen, blank or otherwise incorrectly displayed image. Specifically, for situations in which drivers' awareness of the sides and back of their car depends on digital mirrors, malfunctions (or excessive dirt / sun glare) may result in insufficient visual information and unsafe manoeuvres. Moreover, display failures may lead to significant levels of distraction, as drivers may (repeatedly) attempt to extract information from a degraded or even misleading source. In order to measure the impact of failures, Neukum and Krüger [3] developed a criticality scale, assessing the subjectively experienced degree of disturbance, ranging from imperceptible to uncontrollable, along with an 11-point scale, shown in Table 1.

Ultimately, negative experiences can compromise trust, which is "…the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability" [4, p. 54]. Driving provides many such uncertain situations, in which drivers depend on mirror images to build sufficient awareness before making decisions. Decreased trust can then impact on the acceptance of technology [4-6]. For instance, numerous accounts of railway and aviation accidents resulting from the ignorance of alarms [cf. 7] illustrate how a lack of trust can lead to dangerous disuse. In addition, it is evident that trust is inversely related to the extent a device is monitored [6]. Hence, trust is particularly important for systems that provide a substitute for well-established, essential devices (such as a side mirror for a vehicle).

Table 1 Criticality rating scale

uncontrollable	dangerous			unpleasant			harmless			imperceptible
10	9	8	7	6	5	4	3	2	1	0

1.1. The current study

The current study aimed primarily to determine whether drivers responded to a digital mirror failure with compensatory behaviours and changes in self-reported trust. In terms of the former, they could change their speed and adjust their visual search such as using the rear-view mirror or conducting over-the-shoulder checks. Moreover, in order to better understand these effects, the research also aimed to investigate impacts of a failure on further subjective measures including situation awareness (SA) and criticality ratings. Because of the low likelihood of a digital mirror failure, repeated occurrences were not included in the present study.

Of interest to this analysis were the lane changes in which failures occurred, as well as the corresponding lane changes in the drives without failures. This was decided in order to measure effects of failures on subsequent mirror use when the mirror is functioning correctly.

2. Methodology

2.1. Mirror Failure Condition

In order to measure the effects of digital mirror failures, the drivers were subjected to a failure condition of the right (offside) digital mirror. The failure occurred at a dedicated but unpredictable time, immediately after being instructed to move from the middle into the right hand (‘fast’) lane, followed by subsequent lane change instructions. The failure always occurred during Drive 2 and involved the mirror turning blue for approximately 1 second followed by a frozen image with a road clear of traffic being presented, shown in Fig. 1.

Fig. 1. *Frozen image displayed in the right-hand mirror when the failure occurred*

2.2. Design

The study was conducted with a repeated-measures design, with one factor, Drive. This factor consists of three levels, Drive 1 to 3. The first Drive was a baseline Drive, where no failures occurred. During the second Drive, the failure occurred at a dedicated, but for the participant unpredictable time and remained until the end of this Drive. During the third Drive, no failures occurred, to measure whether the participants displayed any residual behaviours and attitudes that reflect carry-on effects after experiencing failure.

2.3. Apparatus

The experiment was conducted using a busy UK motorway scenario in a medium-fidelity driving simulator at the University of Nottingham. The simulator is normally equipped with external LCD wing mirrors, but for the current study these were replaced with separate LCD panels inside the vehicle, as shown in Fig. 2. The rear-view mirror remained unchanged. The right-hand screen was connected to an HDMI switch, so the experimenter was able to change the screen input. This meant the screen briefly flashed blue due to the temporarily missing signal, followed by an image emulating a frozen motorway scene, as shown above.

Fig. 2. *University of Nottingham driving simulator* **(a)** Fixed-base driving simulator **(b)** Digital mirror setup

2.4. Participants

Participants were recruited via an advertisement email to the staff and postgraduate students at the university as well as personally contacting colleagues and friends. In total, 19 regular drivers participated in the study, ranging from the age groups 18-29 to 60-69, and an average annual mileage of 3,516 miles (SD = 3,059 miles). As a gesture of appreciation, the participants were handed £10 shopping vouchers.

2.5. Procedure

At the beginning of the session, the participants were briefed on the study, without being informed about the failures, to avoid expectation. The drivers were then asked to fill in a consent form and a demographic questionnaire. The experiment involved three separate Drives (each approximately 10 minutes long). In each Drive, the participants were instructed to perform several lane-change manoeuvres while being surrounded by ambient traffic. These were delivered by voice instructions, which had been pre-recorded and were automatically played at specified distances down the road. The failure was triggered manually by the experimenter with a button press. Due to expected different speeds of the participants, it was not possible to closely control the location of the cars in the adjacent lane in relation to the participant vehicle. The lane change manoeuvres and the location of the mirror failure are illustrated in Fig. 3. Before the completion of the session, the participants were debriefed and it was explained to them that the purpose of the study involved the digital mirror failures.

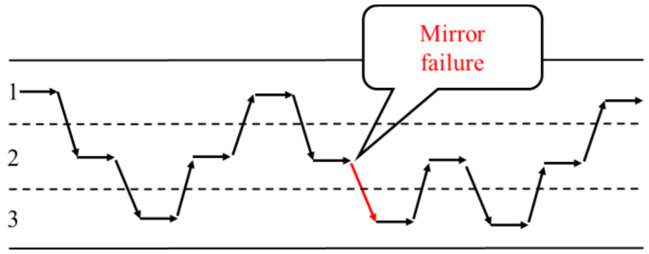

Fig. 3. *Plan view of the motorway with lane changes, showing the placement of the mirror failure within Drive 2*

2.6. Measures

Participants' reactions were recorded by the driving simulator software, operationalised as the speed and speed variation and lane position, as well as cameras inside the vehicle. The video recordings were then coded to identify glances into the digital mirrors, the rear-view mirror and over-the-shoulder checks. SA was measured with a 12-item questionnaire by Taylor and Selcon **[8]**. Trust was measured with a questionnaire by Jian et al. **[9]** and criticality with the criticality rating scale **[3]**.

2.7. Analysis

Of interest to this analysis was the lane change in which the failure occurred (Drive 2), as well as the corresponding lane changes in the Drives without failures (Drives 1 and 3). The time window for data gathering was from the onset of the failure until the successful completion of the lane change manoeuvre. If no lane change occurred, the data window lasted until the following lane change instruction.

The analysis was conducted with SPPS, using multivariate ANOVAs with Drive as within-subjects factor. In case the assumptions of parametric tests were violated, a Friedman test was performed instead, with Wilcoxon signed-rank tests for pairwise comparisons. All pairwise comparisons were Bonferroni-corrected.

3. Results

3.1. Driving measures

When the mirror right failed, six drivers did not perform the lane change that was instructed at that time. One of these drivers then also omitted the corresponding lane change in Drive 3. Generally, the drivers did not change their mean speed following the failure ($p = .150$). However, the analysis of the standard deviation of speed produced a main effect [$F(2, 36) = 3.45$, $p = .043$], which was due to larger speed changes in Drive 2 (mean = 10.22 m/s, SD = 4.08 m/s) compared to Drive 3 (mean = 7.16 m/s, SD = 3.01 m/s, $p = .025$). There was a main effect for the lateral variation [$F(1.234, 22.217) = 4.41$, $p = .040$], but post-hoc comparisons did not flag up significant differences.

3.2. Glance Behaviour

Only 4 of the 19 drivers performed a check over their shoulder in Drive 2, when the failure occurred, which was still more compared to 2 participants in Drives 1 and 3. However, due to the small numbers, this variable was not statistically analysed. Friedman tests of the mirror glances identified main effects for the number of glances to the right [$\chi2(2, N = 19) = 20.48$, $p < .001$] and rear mirrors [$\chi2(2, N = 19) = 21.26$, $p < .001$]. Pairwise comparisons showed an increase of glances into the right mirror by 113% from Drive 1 to 2 ($p = .003$), followed by a 51% decrease in Drive 3 ($p < .001$). Glances into the rear-view mirror increased by 184% from Drive 1 to 2 ($p < .001$) and then lowered by 63% in Drive 3 ($p = .003$). There were no significant pairwise differences between Drives 1 and 3.

3.3. Subjective SA

The cumulative SA score was higher on average in Drive 2 compared to the Drives without failure, but the effect was not significant ($p = .059$). When comparing the separate items, it was found that, from Drive 1 to 2, there were increases in instability ($p = .036$), complexity ($p =.024$) and variability ($p = .003$). Then, complexity decreased in Drive 3 ($p = .036$). No item produced a significant difference in SA between Drive 1 and 3.

3.4. Criticality

In Drive 1, the average critical rating was 2.79 and thus within the range of 'harmless'. An ANOVA of the criticality ratings produced a significant main effect [$F(1.21, 21.76) = 18.69$, $p < .001$]. Pairwise post-hoc comparisons assigned this effect to an increase in criticality ratings by 79% from Drive 1 to Drive 2 ($p = .004$) into 'unpleasant' as well as a subsequent decrease to 2.47 ('harmless', $p < .001$).

3.5. Subjective Trust

An ANOVA of the cumulative trust score resulted in a significant main effect [$F(2, 36) = 15.92$, $p < .001$]. Pairwise comparisons assigned this effect to a lowered trust score, by 67% from Drive 1 to 2 ($p < .001$), and a subsequent 141%

increase in Drive 3 (p = .001). Trust did not differ between Drive 1 and 3 (p = .359).

When considering the separate questionnaire items, pairwise Wilcoxon signed-rank tests showed that ratings worsened from Drive 1 to 2 for wariness (p = .021), harmfulness (p = .006), confidence (p = .003), dependability (p = .012), reliance (p = .001) and trust (p < .001). Answers then improved in Drive 3 for wariness (p = .033), harmfulness (p = .003), integrity (p = .042), reliance (p = .012) and trust (p = .001). Box plots of results are provided in Fig. 4.

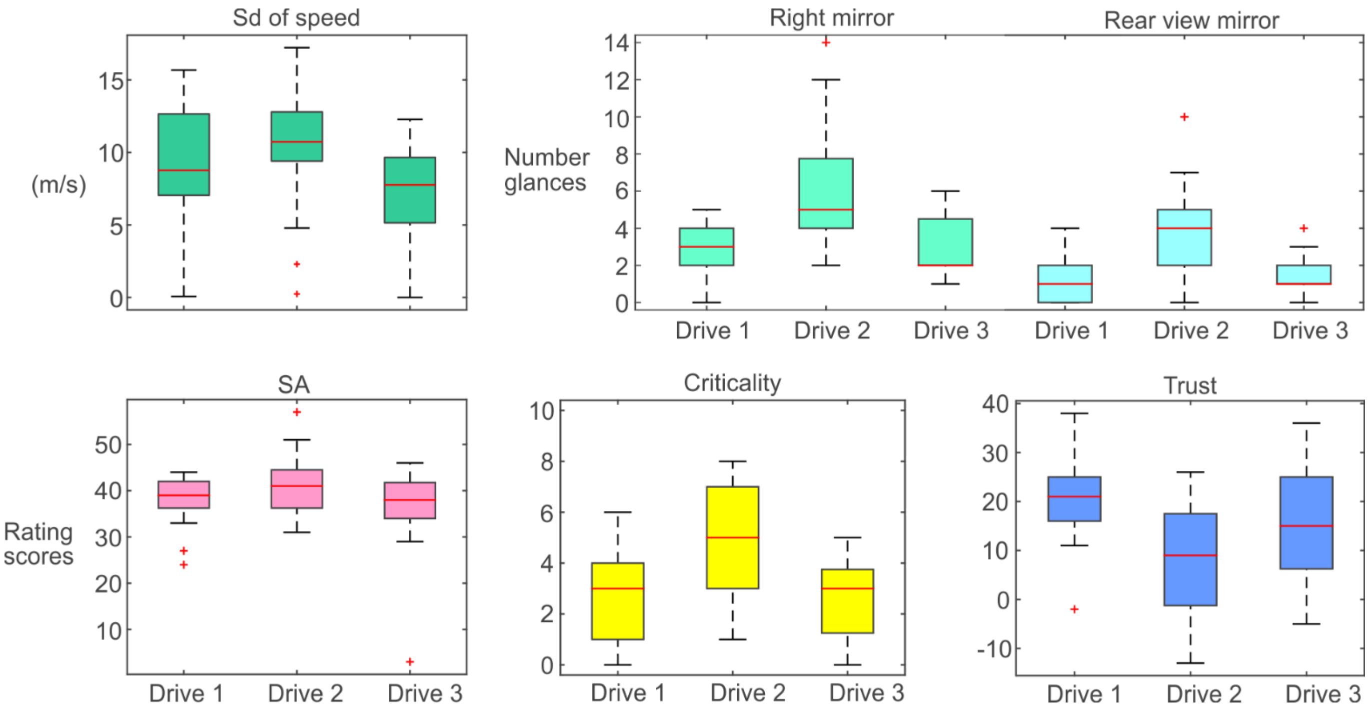

Fig. 4. *Box plots of summary measures*

4. Discussion

The present study investigated the effects of a ‘frozen-image’ failure of the digital mirror system on driving and visual behaviour, SA, criticality ratings and trust, measured in a driving simulator study supplemented with video recordings and questionnaires. Results show that the failure led to significant changes in behaviours. Although mean speed and lateral variation were not significantly affected, speed variation was higher following the failure (leading to non-significant decreases in mean speed). The drivers also compensated by looking more often into the rear-view mirror. Using the centre mirror seemed to have been the first course of action for the drivers, once they realised the failure. A slight increase in over-the-shoulder (blind-spot) checks could also be observed, but the number was generally unexpectedly low. It is a possibility that the driving simulator environment did not provide the visual experience that is realistic enough to support such checks, even during a mirror failure. However, an analysis of lane changes during a naturalistic driving study in the US [10] supports the observation that drivers tend to rely on rear-view-mirrors, more than on the respective side mirror, and the least on blind-spot checks. It has indeed been shown that brief rear-view-mirror checks decrease crash and near-crash risk [11]. Hence, possibly due to these compensatory behaviours, cumulative SA was not significantly affected, but the individual items: instability, complexity and variability were increased. It also appears that the drivers recognised the heightened criticality, rising from ‘harmless’ to ‘unpleasant’. The finding that the participants looked at the right (failed) mirror more indicates a potential distraction effect [12, 13]. The frozen image can be misleading, but the flashing blue screen preceding the frozen image might have mitigated that effect. The clarity of the situation was indicated by the timely increase in compensatory behaviours. In addition, when prompted by the experimenter at the end of the session, 17 of the 19 participants mentioned the failure, and none of them explicitly attributed it to the driving simulator equipment. Hence, it is suggested that a clear warning symbol, which immediately communicated the mirror’s state to the driver, could be useful in the case of such a failure. In this way, it could help the drivers build a correct mental model of the situation, which can result in potentially safer and more appropriate reactions [14, 15].

Ultimately, despite the difficulties of the situation, no collisions occurred, but the experimenter observed several ‘near-misses’, highlighting a potentially increased crash risk when failures occurred. The fact that six drivers refused to change into the fast lane with a failed mirror shows how these drivers prioritised safety, which is remarkable in the face of experimental instructions and the potentially associated social desirability [16].

The analysis of the trust questionnaire shows that trust in the digital mirrors was influenced by whether a failure occurred in a Drive or not, but only for the actual failure situation, not for the following failure-free Drive. In

Drive 2, trust in the technology decreased significantly, cumulatively and for most separate items. In summary, the mirror failure conditions significantly decreased self-reported trust. This adjustment in trust could have motivated the drivers to perform the compensatory behaviours, which were appropriate in this case.

There were no significant differences in any of the dependent variables between the first and third Drives, which were both free from failures. Hence, driving and visual behaviours, SA and perceived criticality returned to pre-failure levels when the digital mirror returned to normal functioning, but the reconstruction of previous trust levels is especially interesting. The finding that the impact on trust did not influence the later Drive can indicate that trust, in situations with a functioning mirror, is not influenced by earlier failures. However, the trust construct measured in questionnaires is considered potentially weak, and does not always translate into actual behaviour [17]. Another possible explanation for the restoration of trust involves an increased general exposure of the society to technology and therefore a higher level of initial trust [18]. In addition, even if people's expectations of a system are not met during the first uses, the expectations may be simply adjusted, so that trust is not necessarily affected [19].

5. Conclusions

The findings of the current study show how drivers may react when digital mirrors fail, particularly in critical situations such as lane changes. When a failure occurred in the simulator, the drivers performed compensatory behaviours such as changing their speed and performing more glances into rear-view mirrors, and thus maintained some degree of SA. However, the alternative mirror views do not provide sufficient information about the driver's side view of the car and the number of necessary over-the-shoulder checks was low. At the same time, increased glances into the failed mirror indicate its distracting effect. Subjectively, drivers rated the criticality of the situation as 'unpleasant' and indicated lowered trust in the technology. Behavioural and subjective measures, including trust, were restored once the mirror returned to full functionality, suggesting no lasting effects of the failure. Future research needs to investigate digital mirror failures in the real world, because a driving simulator study is only able to deliver initial indications, particularly as the graphics cannot replace a real-world view. A wider range of different manoeuvres can further aid the understanding of mirror use and responses to failures. It also needs to be considered whether a frozen image without an obviously flashing blue screen beforehand can be more difficult to realise and thus misleading and distracting. On the flipside, a permanent blue screen or clear failure symbols could mitigate distraction and motivate better compensatory actions.

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7. References

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