Driving without wings: the effect of different digital mirror locations on the visual behaviour, performance and opinions of drivers

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Abstract

Drivers' awareness of the rearward road scene is critical when contemplating or executing lane-change manoeuvres, such as overtaking. Preliminary investigations have speculated on the use of rear-facing cameras to relay images to displays mounted inside the car to create 'digital mirrors'. These may overcome many of the limitations associated with traditional 'wing' and rear-view mirrors, yet will inevitably effect drivers' normal visual scanning behaviour, and may force them to consider the rearward road scene from an unfamiliar perspective that is incongruent with their mental model of the outside world. We describe a study conducted within a medium-fidelity simulator aiming to explore the visual behaviour, driving performance and opinions of drivers while using internally located digital mirrors during different overtaking manoeuvres. Using a generic UK motorway scenario, thirty-eight experienced drivers conducted overtaking manoeuvres using each of five different layouts of digital mirrors with varying degrees of 'real-world' mapping. The results showed reductions in decision time for lane changes and eyes-off road time while using the digital mirrors, when compared with baseline traditional reflective mirrors, suggesting that digital displays may enable drivers to more rapidly pick up the salient information from the rearward road scene. Subjectively, drivers preferred configurations that most closely matched existing mirror locations, where aspects of real-world mapping were largely preserved. The research highlights important human factors issues that require further investigation prior to further development/implementation of digital mirrors within vehicles. Future work should also aim to validate findings within real-world on-road environments whilst considering the effects of digital mirrors on other important visual behaviour characteristics, such as depth perception.

Keywords: digital mirrors, driving, visual behaviour, simulation

1 Introduction

A driver's ability to detect closing headway or possible lateral conflicts is critical when contemplating or executing lane-change manoeuvres, such as overtaking. Indeed, lack of attention to other road users has been widely cited as a causal factor in a large proportion of road traffic accidents (NHTSA, 2013). Consequently, a driver must maintain awareness of both the forward and rearward road scenes. While the forward road scene dominates a driver's normal field of view, their awareness of the rearward scene is largely dependent on glances to rear-view mirrors (internally and externally), which provide only an indirect view. Direct over-the-shoulder checks, or adjustments to a driver's seating position, may be used to compensate for the lack of visual acuity afforded by rear-view mirrors or to overcome issues of parallax that they pose (Schumann et al., 1996). However, performing additional checks, such as over-the-shoulder glances, require drivers to physically change their posture and head position, and thus may divert their full visual attention away from the forward road scene. This can result in deleterious effects on vehicle control – such as lateral instability – particularly amongst learner and novice drivers, and when travelling at speed. Furthermore, vehicle interior design (e.g. bulky head restraints on seats) can make over-the-shoulder checks difficult, and older drivers may be less able to perform these checks due to reduced mobility, especially when wearing a seatbelt (Dewar et al., 2000; NHTSA, 2006). Consequently, drivers are increasingly reliant on an indirect view of the rearward road scene via side ('wing') and internal rear-view mirrors when contemplating or executing lateral vehicle movements, particularly in the presence of other road users.

1.1 Limitations of Mirrors

In a driving context, there are a number of significant limitations associated with relying on mirrors to observe the rearward road scene. Notwithstanding potential confusion due to image reversal, relying upon planar (flat) mirrors to reflect the rearward road scene results in a blind spot, i.e. an area that cannot be seen from the normal driving position, either directly or indirectly via any of the internal or external mirrors (Rickesh and Naveen, 2011). Convex mirrors provide a more expansive reflective view and afford a greater coverage of the rearward road scene, thereby eliminating the blind spot. However, the convex surface causes image distortion, referred to as 'minification' that can lead to overestimation of the distance of following vehicles, misjudgements of speed and driver confusion (Schumann et al., 1996, Luoma et al., 2000). Consequently, in some countries (e.g. U.S.A. and Canada), a safety warning is required to be permanently engraved on the reflective surface of all convex mirrors of motor vehicles, stating "Objects in Mirror Are Closer Than They Appear" (U.S. Code of Federal Regulations, 2004). In contrast, multi-radius, or aspheric, mirrors are used throughout much of Europe. These comprise both planar and non-planar sections. Typically, the main body of the mirror surface is flat, but it curves away toward the outer edge thereby reducing the size of the blind spot area while also reducing the overall minification effect (Schumann et al., 1996).[1]

Distance/depth perception in mirrors is also affected by drivers' eye-to-mirror distance. Convex passenger-side mirrors produce a larger overestimation of the distance of a following vehicle due to larger eye-to-mirror distances in comparison with driver-side mirrors (Flannagan et al., 1997). However, there is little evidence to suggest that poor distance estimation caused by non-planar mirrors actually affects the number of lane-change crashes. In fact, the use of non-planar mirrors appears to be beneficial in some circumstances, e.g. for 'high risk' driver groups, such as novice drivers, who are yet to develop optimum visual search strategies (Konstantopoulos and Crundall, 2008) or may be unaccustomed to over-the-shoulder checks (Underwood, et al., 2002), or for older drivers, for whom these checks may be physically difficult (Dewar et al., 2000; Luoma et al., 2000; Schumann et al., 1996). Furthermore, it is suggested that drivers adapt their perception of objects in the side mirrors to automatically compensate for the minification effect (Luoma et al., 2000).

[1] The European ECE Regulation 46 used throughout most of the rest of the World permits planar, convex, and/or aspheric mirrors on either side of the vehicle; however, neither the U.S. nor the Canadian standard allows for aspheric mirrors (United Nations, 1995).

Flannagan et al. (1996) found empirical evidence of this, but it is not clear if these effects were sustained, as drivers were not tested over extended periods of mirror use.

A further limitation of using mirrors to reflect the rearward road scene is that mirrors require physical placement in the direct line of sight in order to reflect the desired image/view. This dictates that side mirrors are located externally. Even so, in some situations, the image may still be partially obscured by the rear car body or wheel arches, dirt on the windows, adverse weather conditions (e.g. rain drops on the window) or glare from sunlight (Dewar et al., 2000; Hucho and Sovran, 1993). Moreover, the quality and utility of the reflected view is determined to a large extent by the physical dimensions (primarily width in a driving context) of the mirror: bigger is most definitely better (Dewar et al., 2000). However, there are restrictions to the physical dimensions that are acceptable (e.g. there is limited space to physically attach a mirror to the exterior of a car), and there are also practical and legal limitations regarding how far an outside-mounted mirror can reasonably extend. For example, in the UK, The Road Vehicles (Construction and Use) Regulations 1986 dictates that mirrors must not project more than twenty centimetres beyond the overall width of the vehicle/trailer.

1.2 Digital Mirrors

Based on these concerns, and notwithstanding current legislation[2], it would seem prudent to consider utilising an alternative method to capture and display details of the rearward road scene to drivers that could overcome some of the limitations of using traditional reflective mirrors. For example, the rearward scene could be captured utilising rear-facing cameras and relayed to video displays that serve as digital mirrors, in a similar fashion to existing camera-based parking-assist systems that warn drivers of unforeseen objects, pedestrians or other vulnerable road users (VRU) in the path of their vehicle when reversing. In this situation, there would no longer be a requirement to reflect the

[2] For example, in the UK, The Road Vehicles (Construction and Use) Regulations 1986 dictates that a typical passenger car must have, "at least one mirror fitted externally on the offside, one mirror fitted internally, unless a mirror so fitted would give the driver no view to the rear of the vehicle, and at least one mirror fitted externally on the nearside of the vehicle, unless a mirror which gives the driver an adequate view to the rear is fitted internally."

desired view, so digital mirrors need not be physically mounted outside the car. The absence of externally protruding fixtures will naturally improve vehicle aerodynamics, thereby providing the additional benefit of increased fuel economy or, in the case of electric and hybrid vehicles, extended range (Hucho and Sovran, 1993).

Digital mirror displays may also be used to provide richer, driver-centric information. For example, it would be possible to augment the image by digitally highlighting hazards, VRUs etc., though care would need to be taken to ensure that drivers are not distracted or overloaded by any additional information presented. Furthermore, many of the aforementioned concerns could be ameliorated. For example, digital image processing could be used to present a wider field of view, thereby eliminating blind spots without image distortion (Rickesh and Naveen 2011), and image clarity could be enhanced, e.g. to remove glare/improve night-time visibility (Hollnagel and Källhammer, 2003).

While it might appear tempting to thus argue that external mirrors should be replaced by in-vehicle digital mirror displays forthwith, there are nevertheless inherent problems using camera/video-based systems to relay information to drivers. For example, camera-based systems are equally susceptible to environmental factors that may limit the camera’s effectiveness, such as rain, fog or other inclement weather. Even in clear daytime conditions, the visibility of objects viewed on the monitor may be impaired due to sun glare (NHTSA, 2006) or ‘blooming’ (an effect whereby over-exposure lowers the contrast and distorts the image) (Hogervorst and De Vries, 2010). The size of the internal display is equally important – for a rear-view camera-based parking assist system, NHTSA (2006) found that in addition to limiting the field of view, smaller screens appeared to complicate the judgment of the distance to rear objects.

Utilising in-vehicle displays also disrupts drivers’ normal visual scanning behaviour, diverting their attention away from the road, and may lead to situations of ergonomic discomfort and extend primary task-completion times (Lamble, et al., 1999; McLaughlin, et al., 2003; Mohamed Ali and Fatin Bazilah, 2014). McLaughlin, et al., (2003) discovered that when presented with a rear-video parking assist system, participants' visual behaviour changed to include more in-vehicle glances to the video display rather than externally, thereby resulting in an increase in total off-road glances. Participants also took longer to park when using the camera-based parking aids, though interestingly evaluated the quality of their parking and their ability to judge the distance to other objects as higher when using the video display (McLaughlin, et al., 2003). As with digital mirrors, one could argue that the additional in-vehicle glances directed towards the displays were still fundamentally associated with primary task activities. Nevertheless, there are many concerns, such as distraction, deteriorations in driving performance and increases in cognitive load, that are inherently associated with increased in-vehicle visual scanning (De Waard, 1996; Bao et al., 2002; Noy et al., 2004).

1.3 Image Mapping

A more fundamental concern presented by replacing mirrors with in-vehicle video displays is that it can displace and reformat a driver's view of the road scene. Indeed, existing rear-view mirrors are currently located in standardised, well-understood locations (that are highly familiar to experienced drivers), where there is a clear one-to-one mapping with the outside road scene. When utilising digital mirrors, drivers are required to consider the road scene from an unfamiliar perspective that may be incongruent with their mental model of the outside world. This is likely to impose additional cognitive load and visual demand on drivers as they attempt to relate/re-orientate the video display with the real world *before* they act on the information it provides. The performance of camera-based video systems is therefore also likely to be dependent on a number of human factors that limit performance, such as the ability of drivers to interpret the information presented, the time taken to decide what to do, and the appropriateness/timeliness of drivers' responses. In the current context, it is expected that these factors will be influenced by the location/configuration of the in-vehicle displays.

1.4 Display Location

Relevant literature regarding the placement of displays in vehicles recommends that those which have high attentional demands, or that are frequently accessed by drivers, are located as close as possible to the driver's normal line of sight. This dictates that such displays are typically positioned on top of the dashboard or to the side of the steering wheel (Lamble et al., 1999; Wittmann et al., 2006). Spatial proximity to the outside road scene significantly minimises the detrimental effects on driving, indicated by reduced lane departures and improved reaction times and braking responses (Lamble et al., 1999; Wittmann et al., 2006). Moreover, improvements in lateral and longitudinal vehicle control and response times to hazardous signals are associated with reductions of in-vehicle display eccentricity (Burns et al., 2000; Summala et al., 1996). The studies conducted by Lamble et al. (1999) and Wittmann et al. (2006) focussed on displays used for secondary in-vehicle tasks. While it is tempting to argue that the findings are therefore equally applicable when locating digital mirror displays, it is recognised that the successful deployment of digital mirrors is also incumbent on drivers' ability to reconstruct the real world driving scene from the virtual/digital images presented. Consequently, the optimal location of digital mirrors may differ to that recommended for secondary displays and care should be taken with the unsolicited application of this guidance.

Existing research in the application and integration of digital mirrors within vehicles (e.g. Mohamed Ali, 2014) has tended to employ exploratory investigations/discussions into the feasibility of the mirrorless car concept, rather than quantitative evaluations. Furthermore, this research has tended to consider only a single configuration/location of the displays, albeit guided by popular ergonomic wisdom. Although revealing, it is suggested that the successful integration of 'digital mirrors' within vehicles is not only determined by physical ergonomics, but also by the driver's ability to accommodate the digital representation of the rearward road scene within the real-world driving situation. This is also likely to be influenced by the layout of the digital displays within the vehicle, and thus further research is required to determine the performance associated with different candidate configurations.

1.5 The Study

This paper reports a driving simulator study designed to investigate the effect of different locations and configurations of digital side ('wing') and internal rear-view mirror displays during lane departure and overtaking manoeuvres. During the study, the traditional reflective mirrors (rear, offside and nearside) were replaced by three digital mirrors, in five different locations/configurations.

It is anticipated that digital displays would initially replace current reflective mirrors within existing or next generation cars rather than complimenting revolutionary new vehicle designs. As such, the possible locations and configurations are naturally limited and constrained by existing cabin space/equipment and current legal obligations (such as adherence to defined 'vision zones'). Thus, the locations and configurations used during the study, although inspired by the aforementioned literature, were chosen in collaboration with industry experts. The configurations were intended to provide varying degrees of 'real-world' mapping, ranging from individual displays situated in existing mirror location (one-to-one mapping), to a digital mirror cluster mounted in the centre console (providing an integrated 'behind you' source of information rather than any discernible mapping to the real-world).

Given that digital mirrors are most likely an enhancement to existing/next generation vehicles, driver expectancy is also important. Consequently, only experienced and active drivers were recruited to take part in the study. It is therefore not intended to compare the behaviour and opinions of novice and experienced drivers, although it is recognised that conducting the study using a cohort comprising only new or novice drivers, less accustomed to or constrained by the current mirror set-up, may reveal additional insights.

During the study, relevant data were obtained to determine driving performance, visual behaviour and subjective evaluations of workload, distraction, situation awareness, trust and depth perception associated with the digital mirror configurations.

2 Method

2.1 Participants

Thirty-eight people took part in the study, comprising equal numbers of male and female participants (mean age, 34; range, 21 to 57 years). All participants held a valid driving licence and were experienced and active drivers, although the number of years driving ranged from one to thirty-eight (mean 14 years). Participants' current annual mileage was in the range 5,000-10,000 miles (mode). Participants were self-selecting volunteers who responded to advertisements placed on-line and around the University of Nottingham campus, and were reimbursed with £20 (GBP) of shopping vouchers as compensation for their time. All participants provided written informed consent before taking part.

2.2 Apparatus, Design and Procedure

The study took place in a medium-fidelity, fixed-based driving simulator at the University of Nottingham, comprising the front half of a 2001 right-hand drive Honda Civic car positioned within a curved screen affording a 270° viewing angle. A bespoke driving scenario was created using STISIM (version 2) software to replicate a standard three-lane UK motorway with a moderate level of traffic (see Figure 1), and was projected onto the screen using three overhead projectors. To ensure consistency in mirror demand across conditions, the same basic driving scenario was used during each drive (including road design and course, speed and location of other vehicles). However, subtle changes, such as the make, model and colour of accompanying vehicles, were made between conditions to ensure that they appeared notionally different to participants.

[INSERT FIGURE 1 HERE]

Figure 1: Screenshot of Bespoke Motorway Driving Scenario used during the Study

The study was conducted in two separate sessions, undertaken approximately one week apart. During stage one of the study, participants completed a baseline drive in the simulator using three standard mirrors positioned in conventional locations. The rear view images were captured dynamically from unobtrusive locations embedded within the projected forward-facing road scene, flipped and relayed in real-time to three 42" LED televisions positioned behind the car, such that the images completely filled participants' reflected field of view when using the existing mirrors. Prior to stage two, the mirrors were removed and replaced with three 7" LCD displays (rear-view images were captured from the projected road scene as before, but in this case relayed directly to the LCD displays).

During stage two, participants undertook five drives with the LCD displays located in different positions (see Table 1). In all digital display configurations, the left side mirror image was always displayed to the left, and the right mirror image to the right.

Table 1: Traditional (Baseline) and Digital Mirror Configurations (M=Mirror; D=Display; R=Rear-View; O=Offside; N=Nearside)

[INSERT TABLE 1 HERE]

Digital mirror configurations were changed between each simulated drive but participants only experienced one configuration during each drive. Participants were provided with a short (2½ minute) familiarisation drive before undertaking the recorded drive for each condition (which lasted approximately 6½ minutes) to ensure that they were familiar with the new display locations. The order that the five different configurations were presented to participants was counterbalanced to avoid learning effects. All participants were exposed to all conditions in a within-subjects design.

During each of the six simulated drives (using either traditional or digital mirrors), participants were instructed to perform nine prescribed manoeuvres – seven 'simple' single lane-change manoeuvres, where they were required to move into an adjacent lane to overtake another vehicle but were not required to return to the original lane (e.g. inside lane to middle lane, middle lane to outside lane, etc.) and two ‘complex’ multiple lane-change manoeuvres, representing full overtaking manoeuvres (i.e. inside-middle-inside, middle-outside-middle). All manoeuvres were road legal and appropriate, according to the UK Highway Code (Department for Transport, 2007). Directions to undertake each manoeuvre were pre-recorded sound files that were integrated within the simulator software and delivered at the same point during the scenario for each participant (e.g. at 1900, 6600 and 10000 feet). This ensured that other road vehicles within the vicinity were appropriately placed (e.g. ahead of the participant’s vehicle and in the same lane in order to allow an overtaking manoeuvre to take place), that participants were actually required to use the mirrors/digital displays before undertaking such a manoeuvre, and that the driving experience remained consistent between participants and conditions. Instructions were formatted using simple instructional language. For example, “Move into the middle lane when it is safe to do so” (simple), “Move into the outside lane and then back into the middle lane to overtake the car in front when it is safe to do so” (complex). The starting position (e.g. ‘middle lane’) of each manoeuvre was intrinsically constrained by the end of the previous manoeuvre and therefore the order of presentation remained consistent for all participants. It was not deemed appropriate or feasible to counterbalance manoeuvres. Moreover, data were combined and mean values calculated for similar manoeuvres for each participant, thereby eliminating any potential order effects.

2.3 Measures

For each mirror/digital display configuration, driving performance data were captured by the simulator software. The following measures were captured in order to determine drivers’ decision-making/distance judgement and lane change behaviour. This allowed conclusions to be drawn regarding how rapidly and succinctly drivers were able to extract the salient information from the digital representation of the rearward road scene (in each of the layouts/configurations), before deciding and executing a manoeuvre. Results were compared with the baseline reflected mirror condition. The following measures are reported:

1. Time to initiate lane-change manoeuvre (i.e. time between delivery of verbal instruction and start of manoeuvre).
2. Headway to car being overtaken at the commencement of a manoeuvre.
3. The distance in front of the overtaken car at the point at which the participant re-joins their initial lane (complex manoeuvres).

For all driving performance measures, the start/end of a manoeuvre was defined as the point at which the centre of the car crossed the dividing line between lanes.

Participants' eye movements and visual gaze behaviour were recorded using SensoMotoric Instruments (SMI) eye-tracking glasses (ETG). The following measures are reported:

1. Total duration, average duration and number of overall off-road glances (i.e. the cumulative eyes-off-road time, including all sequential fixations to and saccades between one or more of the mirrors/displays before the driver's gaze returns to the road ahead).
2. Number of transitions between mirrors (i.e. occasions where the driver's eyes move directly from one mirror to another without looking elsewhere in between).

These data are common metrics for determining the visual distraction associated with using in-vehicle electronic devices (e.g. NHTSA, 2013). They allow the determination of the type and level of visual distraction and the degree of visual demand associated with a task or activity. The number of transitions between mirrors reflects the potential requirement to extract salient information from more than one source, as well as providing an indication of the cumulative distraction effects of multiple digital displays.

Subjective data were also collected to determine participants' assessment of workload, distraction, situation awareness, trust and depth perception associated with each mirror/display configuration, and their overall preference rating. Subjective data were captured using the NASA Task Load Index

(TLX) questionnaire (Hart and Staveland, 1988), completed immediately following each condition, thereby providing subjective multi-dimensional workload assessments for each configuration. The NASA-TLX questionnaire included two additional bespoke Likert-scale questions (formatted and presented in accordance with the standard questions to avoid confusion) requiring participants to rate the 'situation awareness' and 'depth-perception' associated with each condition. The additional measures are commonly considered as factors the affect the efficiency and utility of traditional mirrors (Schumann et al., 1996, Luoma et al., 2000). Responses to the two additional questions were analysed independently from the NASA-TLX responses.

Finally, after completing all conditions, participants were asked to rank the configurations in order of their preference and provide comments to support/elucidate their rankings, where appropriate.

3 Results and Analysis

Unless otherwise stated, for all measures the data were averaged across all nine manoeuvres for each participant/configuration and then compared across the six configurations using a one-way ANOVA. Planned comparisons were used to compare each of the digital mirror conditions with the baseline condition.

3.1 Driving Performance

A significant effect of mirror condition ($F(5, 185) = 4.11$; $p<0.01$), revealed that drivers initiated manoeuvres earlier in all five digital mirror conditions than in the baseline condition (max. $p<0.05$) (see Figure 2).

[INSERT FIGURE 2 HERE]

Figure 2: Mean Time to Initiate Lane-Change Manoeuvres for Traditional (Baseline, B) and Digital Mirror Configurations

There were no significant effects of mirror condition revealed for headway at the start of an overtaking manoeuvre ($F(5, 185) = 1.80$; $p=0.115$). Neither were there any significant effects of mirror condition revealed for the distance in front of the overtaken car when the participant re-joined their initial lane position at the end of the overtaking manoeuvre ($F(5, 185) = 0.78$; $p=0.566$), although there was generally greater variability when using the digital mirrors compared with the baseline.

3.2 Visual Gaze Behaviour

A significant effect of mirror condition on total off-road glance duration ($F(5, 185) = 5.27$; $p<0.001$), revealed that display configurations one ($p<0.001$), two ($p<0.05$) and three ($p<0.001$) resulted in drivers spending less time looking away from the road towards the digital mirrors compared with the baseline condition (see Figure 3).

The effect of mirror/display configuration on mean off-road glance duration and number of off-road glances was also significant ($F(5, 185) = 3.34$; $p<0.01$; $F(5, 185) = 22.19$; $p<0.001$, respectively) (see Figure 3). Configurations one and two resulted in fewer off-road glances than the baseline condition ($p<0.001$), but mean off-road glance duration was not found to be significantly different for these configurations. Configuration three also resulted in fewer off-road glances than the baseline, but these glances were also significantly shorter than those in the baseline condition ($p<0.01$). In contrast, configuration four resulted in significantly more, shorter glances than the baseline condition ($p<0.01$). Condition five did not significantly differ from the baseline using this measurement.

[INSERT FIGURE 3 HERE]

Figure 3: Visual Gaze Behaviour for Traditional (Baseline, B) and Digital Mirror Configurations

The number of transitions between mirrors were calculated for each participant and then compared across mirror conditions using a one-way ANOVA. Planned comparisons were used to compare each of the five digital mirror conditions with the baseline condition. Significant effects are shown in Table 2.

Table 2: Mean Number (Standard Deviation) of Mirror-to-Mirror Transitions with Significant Differences Highlighted (R=Rear-View; O=Offside; N=Nearside)

[INSERT TABLE 2 HERE]

3.3 Subjective Data

There was evidence to suggest that participant's subjective responses were influenced by the quality and resolution of the reflected images used during the baseline condition (see discussion). Therefore, for the analysis of the subjective measures, digital mirror configuration one (traditional mirror locations, but with digital mirrors rather than actual mirrors) was treated as the baseline condition and all other digital mirror configurations were compared with it using non-parametric analysis of variance.

Total workload was calculated as the sum of all individual NASA-TLX ratings for the six subscales, in line with common practice. A significant effect of configuration on total workload ($\chi2$ (4) = 19.59, $p < 0.005$), revealed that participants reported higher levels of workload in configuration five compared with the baseline condition (configuration one) ($Z = -4.126$; $p<0.05$) (see Figure 4).

There were also similar, significant effects revealed for distraction ($\chi2$ (4) = 9.87, $p < .05$), situation awareness ($\chi2$ (4) = 10.11, $p < .05$), trust ($\chi2$ (4) = 21.99, $p < .001$) and depth perception ($\chi2$ (4) = 23.47, $p < .001$). These indicated that participants felt more distracted (Z = -2.16; p<0.05), experienced significantly lower levels of situational awareness (Z = -4.126; p<0.05), lower levels of trust (Z = -3.47; p<0.005) and poorer depth perception (Z = -2.87; p<0.005) while using configuration five compared with the baseline (configuration one) (see Figure 4).

To analyse participant's overall preference ratings, a one-way non-parametric ANOVA was performed comparing all five digital mirror configurations with the original reflected mirror baseline. Further comparisons were made between configurations two to five and configuration one. A significant effect of configuration on preference ranking ($\chi2$ (5) = 74.51, $p < 0.001$), revealed significantly less favourable rankings for configuration five than for the mirror baseline (Z = -5.06; p<0.01). Furthermore, rankings were significantly less favourable for configuration five than for configuration one (the digital mirror baseline) (Z = -5.00; p<0.001) (see Figure 4).

[INSERT FIGURE 4 HERE]

Figure 4: Mean Subjective Ratings for Traditional (Baseline, B) and Digital Mirror Configurations (for Workload, Distraction, Situation Awareness and Trust, ratings of 0 = 'low')

4 Discussion

4.1 Driving Performance

The driving performance data appear to provide evidence for reduced decision time with digital mirrors when compared with the reflected mirrors baseline condition. In particular, drivers initiated overtaking manoeuvres 0.6-0.9 seconds earlier in all of the digital mirror configurations. However, in the current study, it is important to note that the data revealed no differences between configuration one (in which the digital mirrors retained the same traditional mirror locations) and the other four (in-vehicle) display configurations. A possible explanation is that the digital mirrors enabled drivers to more rapidly pick up the salient information from the rearward road scene (e.g. the presence of a vehicle in a particular lane, time gap to vehicle, etc.) when compared with a reflected image. Some support for this hypothesis is provided by user comments in which drivers noted that they did not need to move their head to bring an image into view for the digital mirror as they would have expected to have done when using traditional mirrors (i.e. there were no issues of parallax). In this respect, the results may be compared with studies conducted with camera-based digital parking aids. However, the current results are notably in contrast to McLaughlin, et al. (2003) who observed apparent retardation in information uptake, i.e. participants took longer to manoeuvre while using the digital parking aids compared with normal visual acquisition techniques (traditional mirrors/over-the-shoulder checks).

An alternative explanation for the extended decision times during the baseline mirror condition concerns the reflected image quality/resolution. The baseline condition constituted reflected images from large televisions located behind the driver. Consequently, participants were relying on the reflection of a monoscopic two-dimensional projection of the three-dimensional world. This is unlikely to have provided a realistic view and basis for comparison. Moreover, the rear-view mirror images were captured from small inset mirror displays in the projected road scene and were therefore of limited resolution. Scaling these images to fill a large television screen resulted in a noticeably poorer quality image (as noted in the analysis of subjective data section in the results section). The difference in resolution may explain slower information uptake in the reflected mirror baseline when compared to all of the digital mirror configurations. Road trials would enable an understanding of whether such positive or negative explanations are appropriate.

For the other two driving performance variables there were no significant differences between all of the conditions. Specifically, the type and layout of the mirror displays did not influence how close drivers got to the lead vehicle before they initiated an overtake manoeuvre, nor did it affect how far past a vehicle they travelled before moving back into their original lane. These data therefore provide evidence that the use of digital mirror displays does not appear to change how drivers as a whole undertake an overtake manoeuvre when compared with reflected images. Moreover, the layout of the displays themselves has no appreciable effect on overtaking driving behaviour. However, it is important to note that there was generally more variability in some behaviour when using the digital mirror display configurations compared with the baseline – for example, concerning the distance after an overtake manoeuvre that drivers returned to their original lane. This is potentially important as it highlights the individual differences present in response to the different novel digital mirrors.

4.2 Visual Gaze Behaviour

It is also tempting to conclude from the analysis of visual gaze behaviour that drivers are able to extract salient information more quickly from certain digital mirror configurations, i.e. those in which the displays were positioned in locations that were most similar to the expected mirror layout. For example, in terms of total eyes-off-road time, configurations one, two and three resulted in drivers spending less time looking away from the road towards the digital mirrors than during the baseline condition – between six and seven seconds across all nine manoeuvres.

These results appear to be in contrast with current guidance on the placement of displays in vehicles (e.g. Lamble et al., 1999; Wittmann et al., 2006), which recommends that those that have high attentional demands, or are frequently used by drivers, are located as close as possible to the driver's normal line of sight, typically on top of the dashboard. In the case of digital mirrors, it would appear that the most appropriate locations, in order to minimise total eyes-off-road time and accelerate information capture, are those that preserve, as far as practicable, aspects of real-world mapping.

It is also possible that the results obtained in the current study may be due to the highly automated nature of glances to mirrors which resulted in the more 'radical' layouts demanding additional eyes-off-road time as drivers attempted to locate the appropriate digital mirror and relate/re-orientate the video display with the real world. However, as before, the result may also be influenced by the difficulties experienced with the lower resolution baseline displays, resulting in extended glances to the traditional mirrors.

In some respects, it is more enlightening to consider the distribution of glances (i.e. glance duration and frequency) across the different conditions. Configurations three and four were associated with shorter off-road glances – interestingly, in these configurations, the displays were positioned closest to the driver's natural line of sight. This result is important given the increased emphasis being given in government organisations (e.g. NHTSA, 2013) towards the glance duration measure, especially the need to avoid long off-road glances in excess of two seconds.

For glance frequency, the higher number of glances made to configuration four is of particular interest. For this configuration, the increase in the number of in-vehicle glances is consistent with the research presented by McLaughlin, et al., (2003). A possible explanation why configuration four is particularly problematic for drivers, is because the displays are separate enough in space to require individual glances for each location and the configuration is appreciably different to the traditional layout, thus requiring additional 'exploratory' glances to extract information – especially in regard to the lowered rear view mirror location. Indeed, there were some residual, misplaced glances to the original rear view mirror location made by participants while using this configuration. Additional in-vehicle glances are typically associated with increased distraction, increased cognitive load and decreases to driving performance (De Waard, 1996; Bao et al., 2002; Noy et al., 2004). However, there was no evidence of these effects associated with configuration four in the current study.

Although several specific differences are apparent in the analysis of transitions between different mirrors, the most consistent set of effects were associated with configuration five, in which the mirror displays were integrated into the centre console. This configuration notably also presented the right wing mirror information to the left of the driver and as such is not expected to conform with regulations currently being prepared for camera monitoring systems. Nevertheless, these two aspects clearly had a significant effect on drivers' visual search patterns. In particular, it is felt that peripheral vision had a role in behaviour, as drivers are potentially able to acquire information from multiple digital mirror displays within a single glance. In addition, the presentation of the right mirror information to the left of the driver is likely to have created some confusion, making it difficult for drivers to relate/re-orientate the information presented by the digital mirror with the real world (this is also clearly apparent in the subjective data). Consequently, there were significantly more mirror-to-mirror transitions apparent in configuration five. Moreover, there were, again, several erroneous glances made by participants to the traditional mirror locations – particularly the right (offside) mirror – during this condition.

4.3 Subjective Data

The subjective data were equally perspicuous in revealing the shortcomings of configuration five. Indeed, it was evident from the post-study questionnaire that configuration five was consistently viewed negatively related to other layouts. This pertained to issues of workload, trust, situation awareness, distraction and depth perception. The fact that participants rated so consistently across all scales suggests a negative halo effect in which users developed an overall poor impression of this configuration and rated accordingly for all scales. In this respect, participants' comments are perhaps more illuminating. These cited familiarity issues, as the layout was felt to be too distant from prior experiences ("felt unnatural to focus on all screens at once", "this one is all kinds of wrong"), as well as obscuration problems (“steering wheel blocking view of right mirror”). This highlights the increased importance of user anthropometry in the design of digital mirrors and layouts, as well as other general concerns, such as the need to overcome prevailing expectations regarding mirror locations, which may be exposed empirically while testing different layouts and configurations. Participants also indicated a perceived increase in workload associated with configuration five – “had to concentrate a bit more on this one.”

For specific ratings, participants appeared not to distinguish between configurations two, three and four. However, when asked to provide a preference, configuration two was consistently ranked highest in comparison to others. In contrast, configurations three and four received mixed opinions. Again, participants’ comments were particularly insightful – configuration two was deemed to be, “easy to get used to” and “natural… similar to standard configuration”. In contrast, when using configuration three, participants remarked, “moving the rear view mirror to a lower position feels wrong” and “odd to have right screen where it should be but not left.” Comments regarding configuration four reflected other concerns: “screens were too distracting… too close together” and “fear of confusing ‘in front’ and ‘behind’”. Overall, the preference ratings and user comments support drivers’ desire for a digital mirror layout that is closest to the existing status quo.

In addition to the prevailing familiarity concerns, several other issues were raised by users, which have clear implications for driver acceptance of this technology and should be considered in further development work. For instance, drivers were conscious of the impact of alternative layouts on their need to move their head to view information, not only due to the physical position of displays, but also because of the removal of parallax afforded by two-dimensional displays, and their comments reflect this. For example, “Less effort to rotate my head… with new setup,” “required less movement and felt comfortable” (both comments related to configuration two); “loved this one… very easy to glance and check” and “nice to have mirrors on same level” (regarding configuration three); “not natural to look down for rear view mirror” (in response to configuration four).

Issues of trust ("Was hard to trust and judge screens"), depth-perception ("Some difference in distance perception") and validity ("Displays feel a bit artificial compared to mirrors…") were also apparent when participants were asked to comment on how their experience of using the digital mirrors compared with using traditional mirrors during normal driving. In this respect, comparisons can be made with other existing in-vehicles 'display' systems, such as GPS navigation devices, which also present a digital representation of the road scene, typically the forward scene augmented with route guidance advice. Using navigation devices can create a blurring between the digital (virtual) representation and the real world environment, resulting in a loss of engagement with the physical world (Leshed, et al., 2008). In the case of digital mirrors, drivers may become more engaged with and reliant on the technological environment afforded by the digital mirrors, and less so on their direct perception of the material environment, particularly with the more 'radical' layouts. There was evidence of this effect during the study, particularly associated with configuration five: "Forgot to use the windscreen."

On a more positive note, drivers mentioned that they expected digital mirrors could alleviate current problems experienced with glare on mirrors ("…easier to see screens than mirrors") – assuming an appropriate camera solution is achieved (NHTSA, 2006). This is likely to be particularly significant during night-time driving, and reference should therefore be made to existing night-vision enhancement systems during further work (e.g. Hollnagel and Källhammer, 2003).

It is also interesting to note that most participants were generally amenable to the concept of digital mirrors, and felt that they would be able to adapt to the different configurations given sufficient exposure ("The positions may work better once you get used to them."). In this respect it is worth noting that similar adaptation effects have been observed in response to the minification effect associated with convex mirrors (Flannagan et al., 1996; Luoma et al., 2000).

Finally, it is recognised by the authors that there may be further potential issues associated with removing traditional mirrors, yet to be highlighted by the research. For example, the internal rear-view mirror is often utilised by drivers who are parents and carers to monitor the activities of their children or charges in the back seat or may be used to achieve eye-to-eye contact during conversations with rear-seat passengers (Laurier, et al., 2008). Although these activities may not be driving-related, per se (and clearly should be discouraged during actual driving as they redirect drivers' attention away from the road scene, both visually and cognitively), their prevalence in the 'ordinary organisation of car travel' (Laurier, et al., 2008), and the fact that they will no longer be possible when using digital mirrors displaying external camera-based content, suggests that such activities should be considered when contemplating replacing traditional reflective mirrors with digital displays.

5 Conclusion and Further Work

The results indicate reductions in decision time and eyes-off road time while using digital mirrors, suggesting that such technology may enable drivers to more rapidly uptake salient information from the rearward road scene. However, care should be taken when drawing this conclusion, particularly given some of the issues presented in the discussion. It is perhaps of greater value to take away the fact that drivers clearly preferred configurations that most closely matched their expectations of existing mirror locations, where aspects of real-world mapping were preserved. Moreover, participants associated the more radical layouts with increased workload, lower levels of trust, reduced situation awareness, greater distraction and poorer depth perception. In the real world, these factors are likely to affect a driver's ability to interpret the information presented, particularly when contemplating or executing lane-change manoeuvres.

It is noteworthy that only experienced and active drivers took part in the study. This was an intentional part of the experimental design in an attempt to preserve the ecological validity of the results, particularly given the likelihood that digital mirrors would initially replace traditional reflective mirrors within existing or next generation cars rather than adorning innovative new vehicle interiors. However, it is acknowledged that results from a similar study conducted with a cohort of novice or infrequent drivers, who may be less accustomed to the real world mapping associated with the current mirror set-up, may be significantly different. Thus, it is unclear whether the current results would be generalizable to new drivers, who may have a higher tolerance for novel designs. Equally, it is possible that experienced drivers' responses could be enhanced as they gain familiarity with and adapt to a digital mirror system.

Nevertheless, it remains clear that the effective adoption and utilisation of digital mirrors within cars will depend upon how the images are provided to the driver and how well that information is processed. The research highlights important human factors issues that require further investigation prior to the development/implementation of digital mirrors within vehicles. Future work should include on-road investigations of the different digital mirror configurations, especially focussing on driver acceptance and usage over time, as well as considering the implications of using digital mirror displays for distance judgements and speed perception.

6 Acknowledgements

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Figure

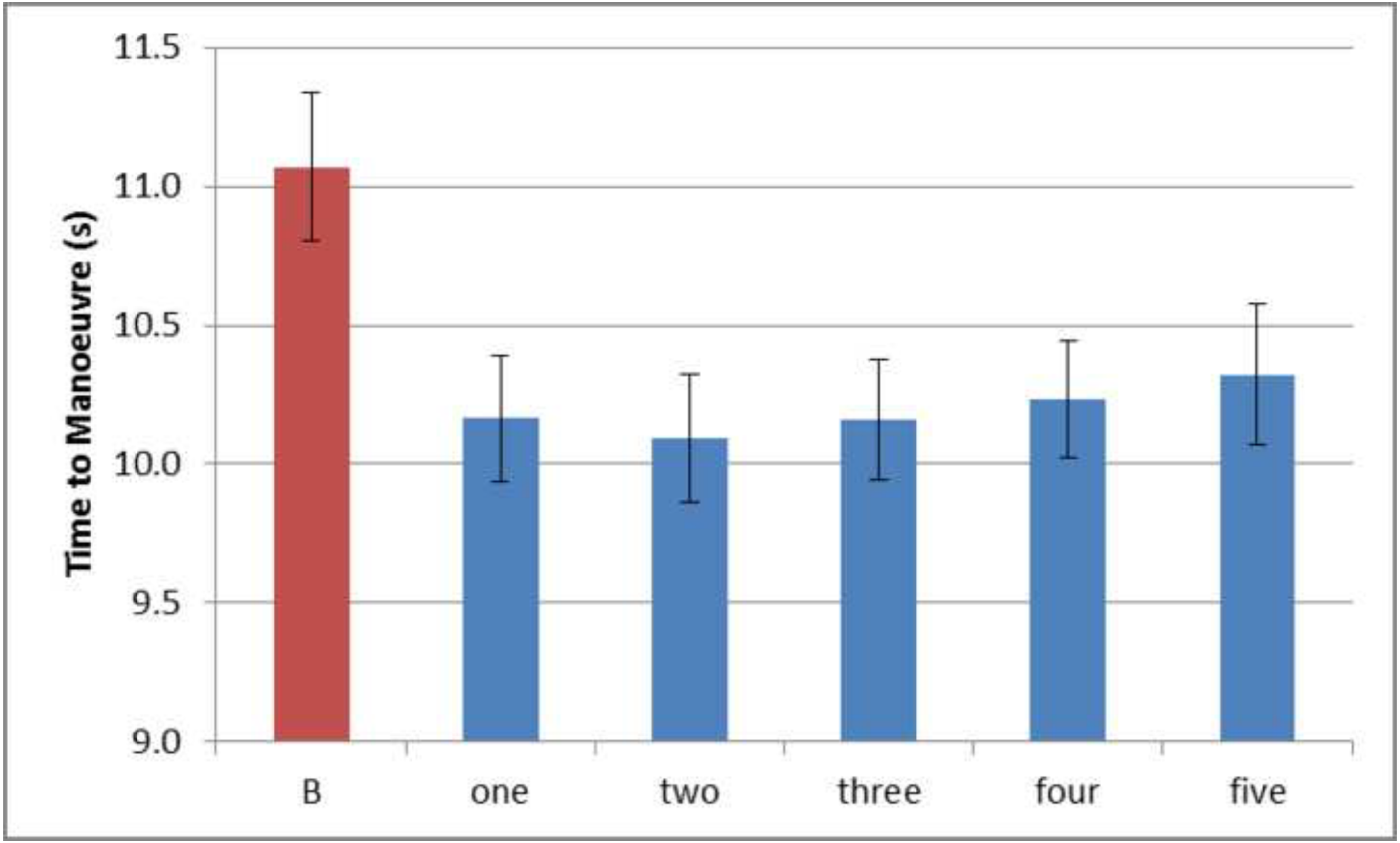
Time to Manoeuvre (s)
11.5
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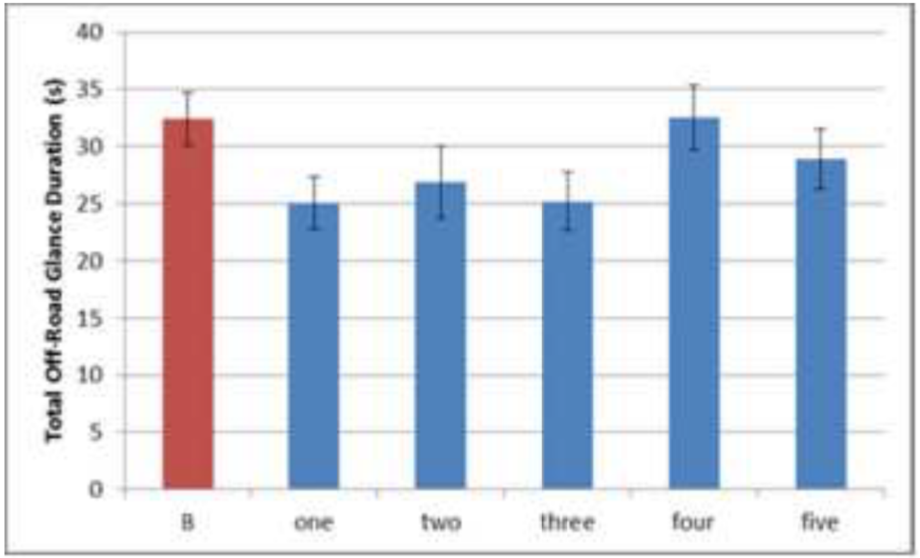
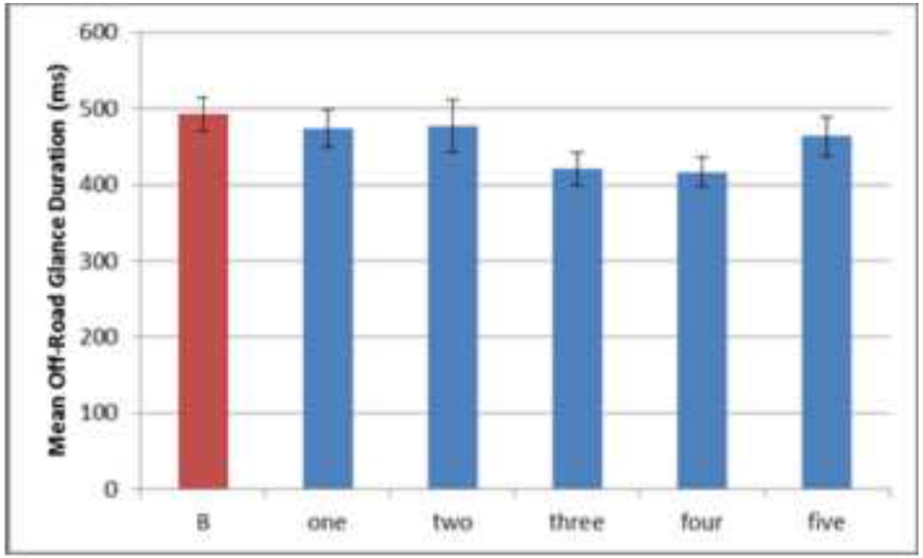
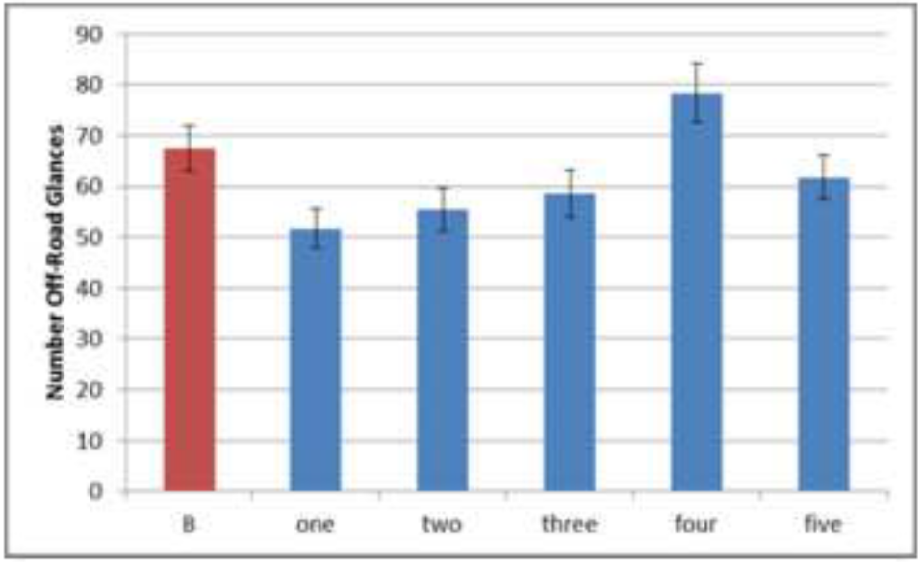
Figure



TOTAL OFF-ROAD TIME



OFF-ROAD GLANCE DURATION



NUMBER OF OFF-ROAD GLANCES

Figure
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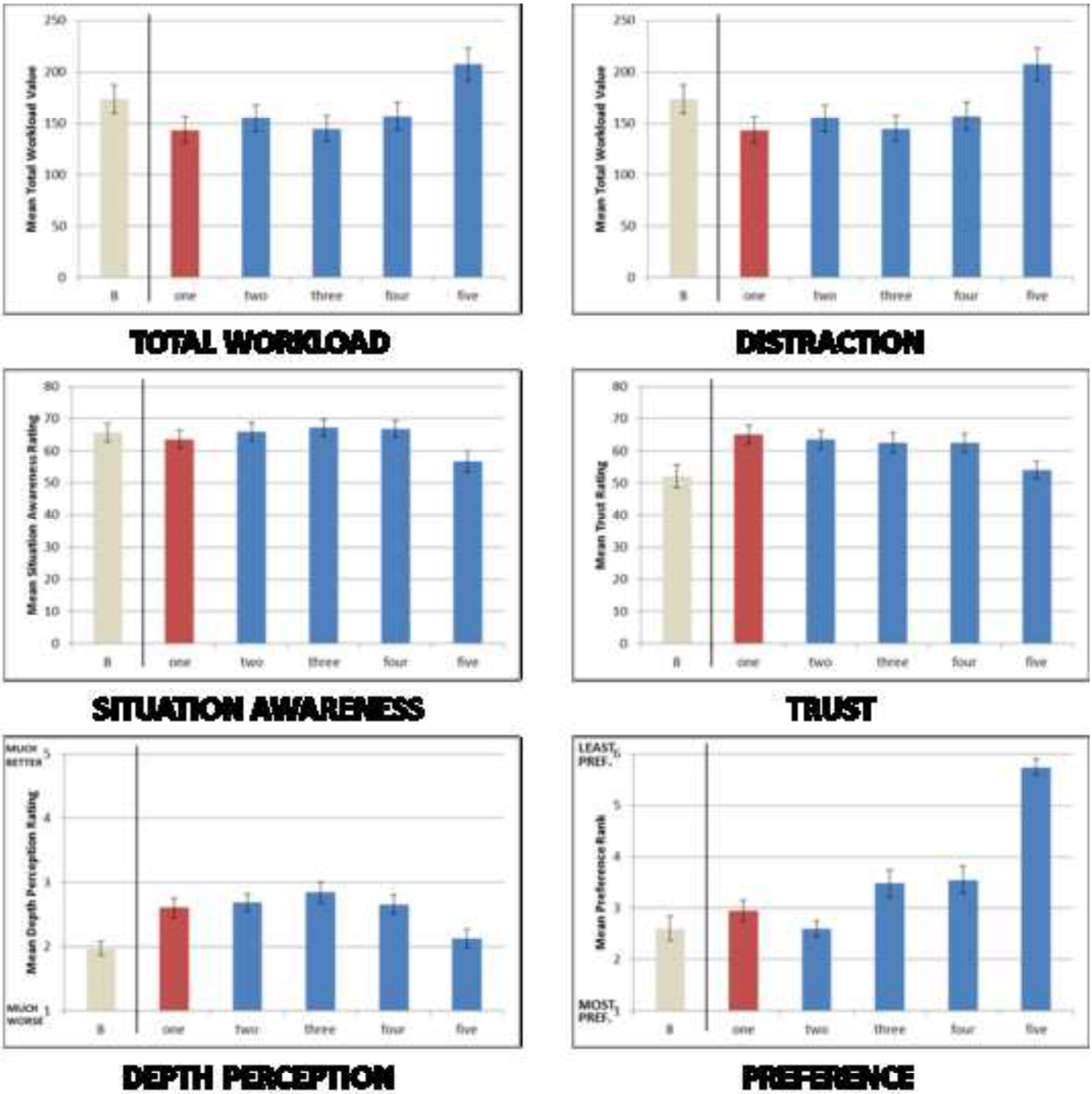
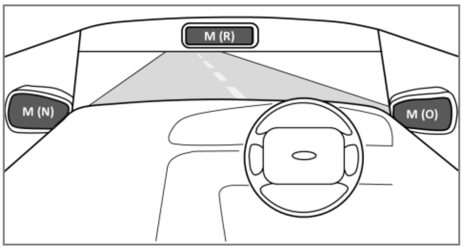
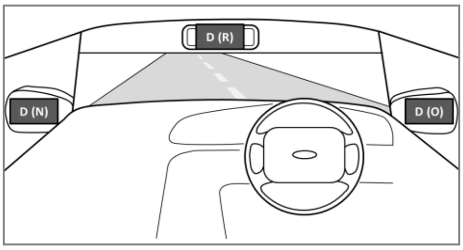
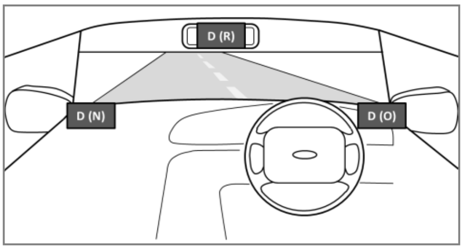
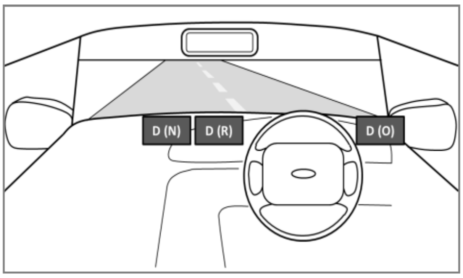
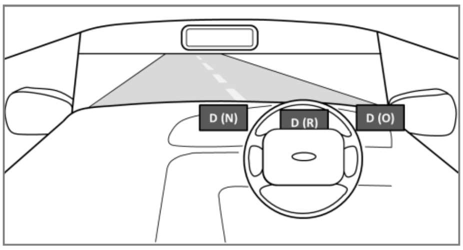
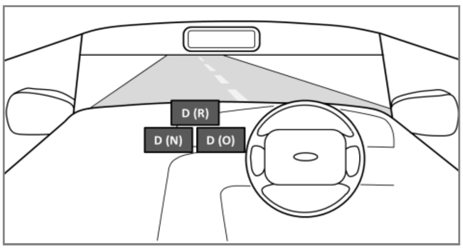


Table

Table 1: Traditional (Baseline) and Digital Mirror Configurations (M=Mirror; D=Display; R=Rear-View; O=Offside; N=Nearside)

Configuration	Image	Details
Baseline		Reflective mirrors positioned at traditional locations – internal rear-view and external 'wing' mirrors. Acts as a baseline condition for comparison.
1		Digital displays positioned in traditional mirror locations. Provides one-to-one real-world mapping and a direct comparison between display formats – traditional mirror versus digital screen.
2		Displays placed within vehicle close to their baseline locations. Maintains a significant element of real-world mapping. Also, offers a slight reduction in head movement required to locate offside mirror display, and expected benefits in vehicle aerodynamics.
3		Offside display placed as configuration 2. Rear and nearside displays integrated and situated within centre console. Provides further reductions in head movement required to locate nearside and rear-view mirror displays.
4		Nearside display located immediately to the left of steering wheel, rear view in cluster (note: speedometer is still visible), and offside display to right of steering wheel. Presents all displays close to driver's normal line of sight.
5		All three displays clustered within the centre console. Provides an integrated source of information but with negligible mapping to the real-world.

Table

Table 1: Mean Number (Standard Deviation) of Mirror-to-Mirror Transitions with Significant Differences Highlighted (R=Rear-View; O=Offside; N=Nearside)

Mirror Transition	**Configuration**					
	Baseline	**1**	**2**	**3**	**4**	**5**
N – O	0.21 (0.07)	0.21 (0.1)	0.32 (0.15)	0.05 (0.04)	0.45 (0.11)	**0.95*** (0.34)
N – R	2.26 (0.43)	2.95 (0.37)	2.53 (0.34)	3.66 (0.67)	2.66 (0.44)	3.16 (0.46)
O – N	0.16 (0.07)	0.18 (0.07)	0.21 (0.11)	0.03 (0.03)	0.50 (0.15)	**1.13*** (0.36)
O – R	1.42 (0.28)	**0.71*** (0.2)	1.16 (0.22)	1.03 (0.22)	**3.47*** (0.56)	**5.26*** (0.85)
R – N	3.89 (0.52)	3.45 (0.54)	3.66 (0.48)	3.37 (0.59)	**1.39*** (0.24)	3 00 (0.41)
R – O	2.18 (0.33)	**0.97*** (0.19)	**1.45*** (0.25)	**1.29*** (0.25)	2.58 (0.44)	**5.18*** (0.67)