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ORIGINAL RESEARCH

A validation study of a fixed-based, medium fidelity driving simulator for human–machine interfaces visual distraction testing

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Abstract

Studies comparing results captured in a simulator with those on road are important to validate the approach but are scarce in the context of secondary task distraction due to the potential ramifications of diverting attention away from safe driving. The authors compare distraction-related data from two studies exploring human–machine interfaces (HMI) design: one conducted in a static, medium-fidelity driving simulator with a vehicle enclosure and immersive visual environment, and one conducted on road. In both, 19 drivers undertook an identical selection of touchscreen, point-and-select tasks. The magnitude of visual distraction (defined as off-road glances directed towards the touchscreen) differed between the road and the simulator, with drivers making more and longer off-road glances when interacting with the interface on road. However, the ordering of effects in response to changes to the complexity of interface design was the same. For example, the number and duration of off-road glances increased with increasing number of interface elements, and smaller targets attracted longer off-road glances, in both the road and simulator studies. The work demonstrates good relative validity for the use of medium-fidelity driving simulators for HMI-visual distraction testing, supporting their application in this context, and adds to the literature regarding the visual demand characteristics of in-vehicle interfaces.

1 | INTRODUCTION

Driving simulators are commonly employed for conducting driving-related research, primarily due to their increased flexibility, safety, and control compared to on-road studies [1]. As such, they are an essential tool for conducting formative research, for example, in situations in which new and novel technologies, such as new in-vehicle human–machine interfaces (HMIs) and automated driver support systems, are being evaluated and their effects on driving performance and driver behaviour are unknown: such technologies may ultimately present an unacceptable risk to driver. In addition, simulators are a valuable resource in making summative evaluations of established or market ready technology, enabling highly controlled comparisons of different technological solutions in a variety of different driving scenarios or conditions.

Despite their prevalence in the driving arena, concerns are commonly raised regarding the validity of driving simulators and the results obtained therewith. These tend to centre on the extent to which the method reproduces the same behaviour that would be seen on the road, and thus, whether or not subsequent conclusions and recommendations are robust and well informed. A common argument posited is that drivers may assume riskier driving practices or engage in activities during simulated driving that they would not consider undertaking on the road. Validation studies are therefore important because they enable a controlled comparison between behaviour in the driving simulator and that seen on road. The literature offers a number of such studies in the context of driving behaviour and performance, with exemplars referenced below to provide context and illustrate the approach. However, the aim of the current research is to address the current scarcity of validation studies specifically related to the use of driving simulators for evaluating secondary task distractors, such as interactions with an in-vehicle HMI.

1.1 | Background literature: absolute and relative validity

Based on the accumulation and interrogation of relevant measures, including visual behaviour, driving performance, and secondary task performance, validation studies (for example, see [2–5]) aim to determine whether a driving simulator offers *absolute* or *relative* validity [6]. *Absolute validity* indicates that measures from the driving simulator are identical to those obtained in the real world (e.g. hold the same numerical value), and is absolutely required when evaluating results in the context of a benchmark or pass/fail criterion. In contrast, *relative validity* indicates that the results from the simulator are of the same order and direction as those obtained in the real world, enabling decisions to be made about the relative benefits of different technological solutions, for example, if one interface is *more* distracting than another, although the magnitude of distraction for each and the numerical difference between them may differ in each context [7]. However, it is important to note that absolute or relative validity may only hold true in the context of the specific task or activity under evaluation—demonstrating validity for a specific task or aspect of driving is not necessarily sufficient to demonstrate the validity of that simulator for all tasks and aspects of driving [8]. Thus, determining validity for the intended context of use (e.g. HMI distraction testing) is vital.

1.2 | Behavioural differences

In practice, reported findings from validation studies are mixed. For example, medium-fidelity driving simulators (see below regarding a discussion on what constitutes fidelity) have shown both relative and absolute validity for visual behaviour during routine driving [2, 5]. Nevertheless, driving performance measures (in particular, drivers' lateral control, and speed selection and maintenance) have shown much greater variability and inconsistency in driving simulators, compared to on-road studies [4, 5].

Unexpected behaviour in a driving simulator, or that which is contrary to expectations, is typically, and often rather conveniently attributed to the 'lack of genuine risk' associated with the simulated driving experience, thereby bringing into question the validity of the approach and the context in which it is applied. That being the case, it can be difficult to argue to the contrary and such criticism remains inevitable. Doubtless, simulated driving presents no risk of physical harm occurring to the driver if a collision occurs in the virtual world, and it is not difficult to surmise that this could encourage drivers to adopt riskier driving styles and behaviours without the fear of retribution. Furthermore, risk perception has been specifically shown to play an important role in determining drivers' visual search behaviours and their associated head movements, and it is thus reasonable to opine that these behaviours could differ during simulated driving if risk perception differed. Indeed, in the context of driving simulator validation studies, Robbins et al. [8] found that drivers' head movements when assessing the situation at a road junction were not significantly different between the simulator and on-road, in terms of *frequency* and *range*. However, drivers demonstrated significantly *longer mean fixations* in the driving simulator compared to on-road, especially in low-demand simulated driving situations. This suggests that although drivers undertook appropriate visual checks when assessing the road situation, they lacked efficacy in their distribution and allocation of visual attention, particularly when contemplating low-demand driving situations in the simulator. The authors subsequently concluded that in order to improve validity, drivers should be presented with at least a moderate level of demand during simulated driving [8].

1.3 | Simulator fidelity and driving performance

In terms of driving behaviour and performance, Jamson et al. [9] observed that participants adopted higher speeds along straight segments of road when using a driving simulator, compared to on-road driving. Several other studies (e.g. [10, 11]) report similar findings. Differences in speed selection and maintenance are often additionally attributed to the absence (or poor fidelity) of vestibular and other motion cues which make speed perception in the virtual world difficult, not solely the aforementioned 'lack-of-risk' factors. Consequently, the fidelity of the driving simulator (i.e. the 'degree of similarity between the simulator and the equipment which is simulated' ([12], p. 9)) is also considered to influence the validity of the approach. Here, factors such as the design of the simulator itself are considered important, as they can help to encourage a sense of presence, or 'being there' [13]. For example, utilising a real vehicle enclosure located within an immersive screen, which may be described as 'medium fidelity', can help encourage participants to believe that they are actually driving on the road. In contrast, seating participants at a desk and displaying the unfolding driving scene on a single desktop monitor in front of then (a 'low fidelity' setup) may be less persuasive. These factors are referred to as the 'physical validity' of the simulator [6, 14], though it is recognised that no formal standard or certification currently exists. In contrast, 'behavioural validity' concerns the extent to which the method reproduces the same behaviour that would be seen on the road. These factors are naturally intertwined: for example, it is commonly recommended that the physical set-up (or physical validity) of the simulator should be as close to real-world equivalents as possible in order to encourage high behavioural validity [15].

Indeed, drivers' behaviour has been shown to differ significantly between simulators of different physical fidelity. For example, a comparison of driver behaviour in four different driving simulators [16] shows numerous dissimilarities, and these were attributed to the physical fidelity of the simulator and the feedback they presented to the driver. For instance, it was reported that limited motion feedback in the low-fidelity simulator led participants to decelerate unusually strongly when they were approaching a stop line from 40 and 10 m. This was attributed to drivers underestimating the distance and/or time to collision in the absence of motion feedback. Simulators with limited vestibular feedback can also cause greater speed variability and fluctuation, encouraging drivers to over-accelerate, and then correct their speed through deceleration or braking. Jamson and Jamson [3] compared a static, low-cost simulator with a high-fidelity motion-based version, both using the same software. Despite generally positive experiential results associated with the static, low-cost simulator, findings suggest reduced lateral control, shorter headways, and poorer self-reported performance ratings associated with the lower fidelity experience. Interestingly, Jamson et al. [9] reported that the lowest speeds in the driving simulator were observed in proximity to pedestrian refuges, and they concluded that, even within the virtual, simulated world, these presented a genuine threat to participants in their study, alerting them to the potential presence of pedestrians.

1.4 | Study motivation

While the literature provides several examples of simulator validity studies, these are almost exclusively concerned with validating metrics associated with driving behaviour, in other words, how drivers behave in response to the road environment and other road users (speed selection and maintenance, road position etc.). Nevertheless, driving simulators are often recommended as the preferred method of evaluation in distraction testing for in-vehicle, secondary devices (e.g. [17, 18]). In part, this is because they can appear to offer good *face validity*, particularly relevant for high-fidelity facilities. In other words, locating participants in a real vehicle enclosure and asking them to drive using authentic primary vehicle controls might encourage independent observers to believe that the method is likely to deliver what it purports to, particularly when compared to other more rudimentary distraction testing techniques, such as visual occlusion [19]. However, validation studies seldom consider the impact of a driver's decision to engage with an in-vehicle secondary task, such as making selections on in-vehicle HMI. Studies in this area are notoriously difficult to undertake on the road (and therefore severely limited), largely because, by definition, the on-road element of any comparative study bears a genuine risk of harm to participants, who will be exposed to the very risks and hazards that the simulator intentionally removes. This study reports a validation study of a fixed-based, medium fidelity driving simulator in the context of HMI visual distraction testing, thus aiming to address the current scarcity in the literature and provide evidence to support the use of such facilities in this context. The specific aims of the research are

1. To validate the use of a fixed-based, medium fidelity driving simulator in the context of HMI visual distraction testing
2. To contribute to the literature regarding the visual demand characteristics of HMI design elements (button size, layout, and number)

TABLE 1 Participant demographics

	Road	Simulator
No. of participants	19 (13 male, 6 female)	19 (10 male, 9 female)
Age	Mean: 35; range: 21–58 years	Mean: 33; range: 22–65
Years with licence	Mean: 16.1; range: 4–32	Mean: 13.6; range: 3–47
Annual mileage	Mean: 9489; range: 5000–25,000 mi	Mean: 7413; range: 1000–21,800 mi

The method and results are thus presented to outline and address each of these aims.

2 | METHODOLOGY

2.1 | Overview of experimental design

In order to compare results obtained in a driving simulator with those collected on-road, a 2 × 2 × 2 mixed design was employed, with participants either taking part in an on-road study or a medium-fidelity driving simulator study (Study: Road or Simulator). Participants were required to conduct a series of point-and-touch button selection tasks using a touchscreen interface located within the vehicle. Tasks differed with regard to the number of target buttons presented (Number: One or Four), the size of targets (Size: Small or Large) and the location of the interface (Height: High or Low), with the number of task repetitions and overall experience controlled to minimise potential effects of fatigue and motion/simulator sickness. Analysis subsequently evaluated visual behaviour and driving performance and compared this between groups (Road vs. Simulator) in order to determine the validity of the medium-fidelity driving simulator in the context of visual distraction and HMI design.

2.2 | Participants

Participant demographics are shown in Table 1. All participants were required to be over 21 years old, have held a valid UK or EU driving licence for 3 years or longer, drive regularly and own or lease their own car. For the Road group (on-road study), participants were also required to hold a valid University driving permit for car insurance purposes. All participants declared that they had no known health-related problems that might affect driving and possessed normal or corrected-to-normal vision. They participated in the study on a voluntary basis by responding to a blanket email sent to staff and postgraduate students at the University of Nottingham, and received a shopping voucher as a gesture of goodwill, commensurate with the activity—£10 (GBP) for the Simulator Study and £20 (GBP) for the Road study. The Road and Simulator studies were reviewed independently, and both were approved by the University of Nottingham Faculty of Engineering ethics committee.

FIGURE 1 Experimental setup in the instrumented car, showing the iPad fixed to the centre console and four bullet camera views (left) and driver seated in vehicle (right).

Informed consent was obtained from each participant prior to them taking part.

2.3 | Apparatus

2.3.1 | Touchscreen human–machine interface (HMI)

In both studies, a 32 GB iPad 9.7″ tablet computer running iOS 11 ('iPad') was utilised to display a generic point-and-touch 'button' touchscreen interface. The iPad was securely fixed in the centre console using a dedicated mount. The mount allowed a higher and a lower position, approximating to common positions utilised by car manufacturers. In the High position, the top edge of the iPad was in line with the top edge of the dashboard. In the Low position, the iPad was positioned approximately 10 cm below this.

2.3.2 | On-road study ('Road')

For the on-road study ('Road'), an instrumented Ford Focus with a manual gearbox and dual controls, owned and insured by the University of Nottingham, was used. Four synchronised bullet cameras were fixed to the interior of the car. The first camera was placed on the dashboard and faced the cab. This camera thus provided a view of the driver so that the driver's visual behaviour, for example, eyes-off-road, was captured. Two cameras were placed next to the front headrests and the fourth camera was fixed to the rear screen. For the on-road study, it was felt that dedicated eye-tracking equipment (glasses) would not be necessary for the measures of interest (which could be accurately obtained from the aforementioned videos); this further alleviated potential risks, such as the eye-tracking glasses interfering with the driving task or restricting drivers' peripheral vision. As shown in Figure 1, three of the in-vehicle cameras faced towards the iPad from different directions to capture the interaction between the system and the driver.

2.3.3 | Driving simulator study ('Simulator')

For the driving simulator study ('Simulator'), participants utilised a medium-fidelity, fixed-based driving simulator, comprising a matte black right-hand drive Audi TT within a 270° curved screen setup (Figure 2). The bespoke simulator has been developed by the research team at the University of Nottingham specifically in the context of distraction testing and has been utilised in numerous studies previously. The driving scenario was created using STISIM Version 3 software and projected onto the screen using three high-definition overhead projectors; image warping and edge-blending ensured this presented a near-contiguous image to participants. The scenario aimed

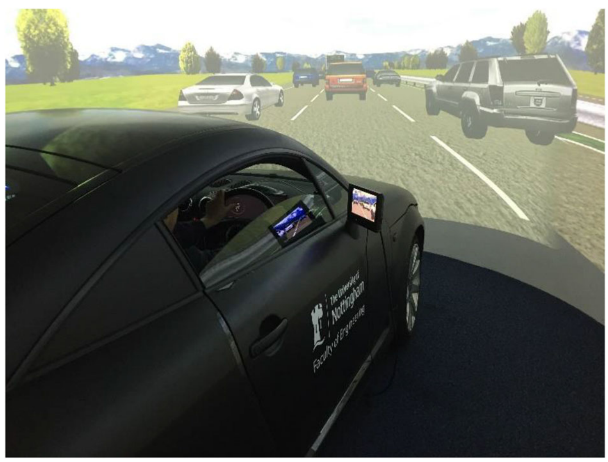

FIGURE 2 Medium-fidelity fixed-base driving simulator.

FIGURE 3 Medium-fidelity driving simulator, showing four camera views with iPad (HMI) located in centre console. HMI, human–machine interfaces.

to replicate, as far as practicable, the section of the motorway used for the on-road element of the validation study. The same iPad was placed in the driving simulator buck, in equivalent locations to the Ford Focus. In addition, four inobtrusive cameras captured the driver's face and their interactions with the iPad (Figure 3). The first camera was placed on the dashboard facing the driver to capture the driver's visual behaviour (i.e. eyes-off-road). The other three cameras captured other interior views of the driver and vehicle cabin.

2.3.4 | Visual and auditory stimuli

Buttons on the touchscreen were square with two levels of Size: Small = 2.4 cm width/height with 1 cm distance between buttons; Large = 3.2 cm width/height with 1.4 cm vertical and 1.8 cm horizontal distance between buttons (Figure 4). The chosen button dimensions were based on former studies undertaken by the authors, which had previously been informed by literature (see [20–24]). The results from these studies indicated that button sizes smaller than those chosen could encourage single glances away from the road lasting longer than 2 s (for some drivers) and were thus considered potentially too distracting to undertake in an on-road evaluation (see [17]). The space between buttons was chosen to maintain the design aesthetics of the interface, that is, to appear proportionally equivalent for each button size, and was again informed by the aforementioned studies. Buttons were presented as a single target (Number = 1), or clustered in groups of four buttons (Number = 4) (Figure 4). Larger arrays (greater than four buttons) were considered too distracting, based on previous studies (see [20, 21, 23, 24]).

For each task, participants were required to correctly select a designated button. The target button was identified using a pre-recorded word, which was spoken aloud and followed by an auditory chime. The chime signalled that the button or button array had appeared on screen. Participants were then required to select the button displaying the first two letters of the spoken word. So, for example, if the spoken word was: 'ANIMAL', participants were required to select the button displaying the letters: 'AN'. After the correct button was selected, the buttons disappeared, and the word 'wait' appeared on the screen. The experimenter subsequently triggered the next button configuration, at the designated time, which appeared and was accompanied by another auditory chime.

Stimuli were presented in a pseudo-randomised order, but always alternated in Size and Number. For example, if the first trial had one small button, the second trial had one large button. The third trial then had four small buttons, and the fourth trial had four large buttons, and so on. In addition, the location of the whole button group was randomised and could be in any one of nine different locations on the touchscreen (top, middle and bottom and left, centre and right). This amounted to 16 button presses during each session. In practise, several predetermined configurations were saved, and these were randomised amongst participants. In addition, the Height of the touchscreen (High and Low) was counterbalanced between participants.

The button-selection touchscreen tasks under examination were created as a hyperlinked Microsoft PowerPoint presentation, designed to appear as a rudimentary, experimental interface, which was used in both the Road and Simulator studies. This was deployed using the Microsoft PowerPoint app for iPad, ensuring this was available offline for the Road study. A screen protector was also added to prevent distracting sun glare during the Road study.

2.4 | Risk assessment and ethical approval

Gaining approval to conduct the on-road study was contingent on a number of factors that are shared here with the

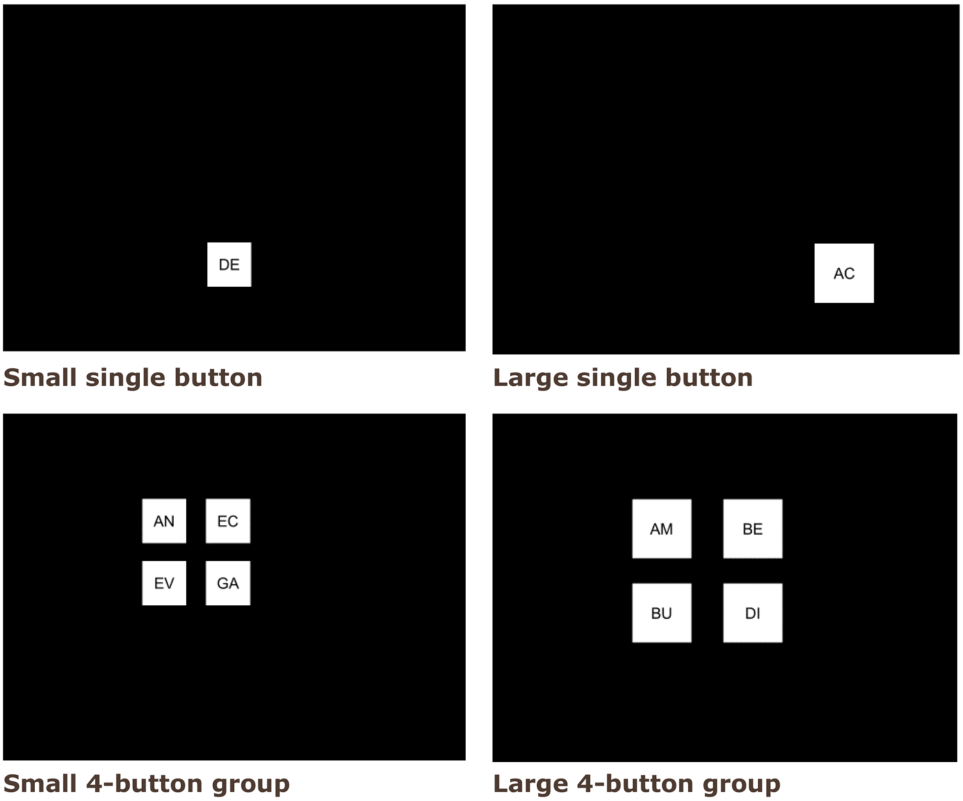

FIGURE 4 Examples of the experimental interface, showing button and group sizes.

aim of informing future on-road, HMI distraction studies. First and foremost, all participants were made aware that their primary task remained the safe control of the vehicle, as would be expected, and that they should behave as they would during routine driving with safety as their first prerogative. Therefore, in order to manage the potential distraction associated with the secondary tasks (i.e. interactions with the touchscreen), tasks were carefully selected, based on aggregated data from previous studies, to conform with NHTSA's recommendations [17], which are widely accepted as best practice. These stipulate that in-vehicle secondary tasks should, on average, be successfully completed in less than 12 s and require individual off-road glances no longer than 2 s. Corroborative data were compiled from the University of Nottingham's extensive corpus of HMI driving simulator studies (e.g. [23, 24]). In practise, this restricted testing to interface designs comprising larger buttons (≥ 2.4 cm) and small, structured arrays (≤4 buttons).

In addition, the vehicle used for the on-road study was fitted with dual controls and an additional rear-view mirror, meaning that the front-seat passenger (in this case, a researcher, who accompanied all participants) could take control or stop the vehicle in an emergency. To facilitate this, the researcher in question received bespoke driver instructor training provided by a local driver training school, aiming to impart the necessary knowledge, skills, and awareness to identify where, when and how to safely assume control of the vehicle, if required.

Finally, the on-road study was scheduled to take place outside of peak driving hours and utilised a straight section of a nearby motorway. During the study itself, participants were specifically instructed to remain in lane one (i.e. the left, or inside lane) of the motorway and drive at a constant speed, unless their passage ahead was blocked. They were only asked to commence a task when the researcher was confident that there were no nearby vehicles (ahead or next to the ego vehicle) or any other imminent hazards (such as a nearby slip road/exit).

2.5 | Procedure

2.5.1 | On-road study ('Road')

For the Road study, participants entered the instrumented car. A researcher (the 'experimenter') was also present and remained so for the entire journey in the front passenger seat. Their role was to relay experimental details, change hardware configuration (e.g. location of iPad), and be prepared to take over control in an emergency (see above). The participant was first briefed on the safety procedures and made aware of the proposed route while the engine was switched off. Specifically, they were told: 'Whilst driving, you are required to apply due care and attention to the driving task…Please remember to always drive in a way that is comfortable to you and your most important task is to drive safely. Remember that you may only perform the secondary task when it is safe to do so. You do not have to perform the touch screen task if you do not wish to'.

The participant was also provided with the opportunity to practise the secondary, button-selection tasks. Participants were then instructed to start the car's engine and directed by the experimenter to the start of the experimental route (which took approximately 10 min to reach). The experimental part of the drive took place on a 12-mile stretch of the UK M1 motorway, for which the posted speed limit is 70 mph. Participants were reminded of the speed limit, but no specific instructions were given regarding whether they should aim to achieve a target speed during the study. The drive from the University to the experimental part of the route, as well as the first mile or so on the motorway, were used as familiarisation to ensure that the participant was comfortable with the car's control and handling, and the road environment; participants self-declared their competence and willingness to continue. After completing the first half of the experimental route (northbound on the M1 motorway), the accompanying experimenter changed the iPad position (High to Low, or vice versa), according to a counterbalancing table. They directed the participant off the motorway at the next exit, and asked them to re-join the motorway in the opposite direction (southbound), whereby the second part of the study was undertaken. The total experimental part of the drive took around 10 to 20 min to complete in clear traffic. All journeys were scheduled to take place outside rush hour traffic (i.e. between approximately 10 am and 3 pm) to ensure that conditions were as comparable as practicable. If the route became congested, or other external factors (such as inclement weather) affected the successful completion of tasks or safe control of the vehicle, the study was terminated, and the participant was directed back to the University by the most appropriate and safest route.

2.5.2 | Driving simulator study ('Simulator')

For the Simulator study, the procedure was equivalent. The researcher joined participants in the front, passenger seat of the driving simulator. The same safety briefing was provided, advising participants: 'Whilst driving, you are required to apply due care and attention to the driving task…Please remember to always drive in a way that is comfortable to you and your most important task is to drive safely. Remember that you may only perform the secondary task when it is safe to do so. You do not have to perform the touch screen task if you do not wish to'. An additional statement relating to the potential risk of simulator sickness was added, with those susceptible to motion sickness, travel sickness, sea sickness, blurred vision, dizziness, migraines or epilepsy, or pregnant, advised not to take part.

Participants were provided with the opportunity to practise the secondary, button-selection tasks, while seated in the driving simulator, and were given a practice drive to ensure that they were comfortable with the controls and handling of the simulator, and could negotiate the virtual motorway environment; participants self-declared their competence and willingness to continue. Participants began on the motorway slip-road and all tasks were administered on a single 'outbound' leg of their journey, which lasted approximately 10 to 20 min. The posted speed limit was 70 mph, in accordance with the real-world motorway environment. Participants were reminded of the speed limit (as before), but no specific instructions were given regarding a target speed during the study. After completing all tasks, participants were asked to manoeuvre the vehicle to the side of the road and park safely.

2.6 | Measures

All visual behaviours and touchscreen interactions were captured using cameras. Videos were subsequently analysed using frame-by-frame video coding with Behavioural Observation Research Interactive Software, BORIS [25]. To quantify visual behaviours, the start and end of each fixation was coded to one of three areas of interest (AOIs): touchscreen ('HMI'), mirrors ('mirrors'), and roadway ('on-road')—the latter included all other driving-related fixations, such as the speedometer. Data were exported from BORIS and subsequently analysed using MATLAB (https://uk.mathworks.com/products/matlab.html).

For the purpose of assessing the visual distraction associated with the secondary task (i.e. interacting with the touchscreen), and making subsequent comparisons between Road and Simulator, off-road glances were calculated from the moment that the driver's eyes left the roadway (i.e. began moving from the 'on-road' or 'mirrors' AOI) to the time that their attention was redirected to the road, in line with convention. In other words, each off-road glance included the movement (or saccade) to the HMI, the fixation associated with the HMI, and the saccade back to the road. Visual distraction was thus defined for each task (i.e. each individual button press) by the mean number of off-road glances per button press (NG), the mean off-road glance duration (MGD), the maximum off-road glance duration (MxGD), and the total off-road glance time (TGT) for each task (i.e. button-press), in line with international standards [17].

2.7 | Analysis

The analysis approach aimed to explore the impact of button Size, Number, and iPad location ('Height') on visual distraction and to subsequently compare these behaviours between the driving simulator ('Simulator') and the on-road study ('Road'), in order to make an informed judgement about the validity of the driving simulator in the context of distraction testing. To achieve this, mixed ANOVAs were conducted with IBM SPSS Statistics 25 (https://www.ibm.com/analytics/spss-statistics-software) in situations where the assumptions for parametric testing were fulfilled. In non-parametric cases, the related-samples Wilcoxon signed rank test was used for the within-subjects factors (Size, Number, and Height) and the Mann–Whitney U test for the between-subjects factor, Study

(Road vs. Simulator). Statistical significance was accepted at $p < 0.05$. In line with other simulator validation studies, we also present an overview of driving performance data (as mean speed, MnSp), although the primary focus of the study is on off-road glance behaviour.

3 | RESULTS

The study has two main aims

1. To validate the use of a fixed-based, medium fidelity driving simulator in the context of HMI visual distraction testing
2. To contribute to the literature regarding the visual demand characteristics of HMI design elements (button size, layout, and number)

Results are presented to show the overall effects of the independent variables: Number, Size, and Height on visual behaviour (i.e. off-road glances, defined as the combined fixation to the HMI/iPad and associated saccades, in line with convention) in line with the second aim. Comparisons are subsequently made between findings obtained from the Simulator and those obtained on the Road, with main effects reported, including an additional metric on driving performance (notably, mean speed) to address the first aim. Illustrative figures are included, where appropriate, to summarise findings.

3.1 | Number of buttons (one, four)

The Number of buttons affected the NG (Z = 3.646, $p < .001$, r = 0.591), with an average of 1.56 glances (SD = 0.61), when one button was present, increasing to 1.87 glances (SD = 0.81) in the case of four buttons.

The MGD was also affected by the number of buttons (F(1, 36) = 27.042, $p < .001$, $\eta^2 = .429$), with a MGD of 0.84 s (SD = 0.19) for one-button and 0.98 s (SD = 0.23) when four buttons were displayed.

A significant effect was found for the MxGD (F(1, 36) = 83.047, $p < .001$, $\eta^2 = .698$), with maximum values of 0.94 s (SD = 0.19) for one button and 1.14 s (SD = 0.19) with four buttons.

The Number of buttons also made a significant difference to TGT (Z = 5.376, $p < .001$, r = 0.872), with 1.14 s (SD = 0.29) in the case of a single button and 1.53 s (SD = 0.33) when four buttons were presented.

Mean speed was not significantly affected by the number of buttons ($p = .833$). It was 58.64 mph (SD = 4.15) for one button and 58.85 mph for four buttons (SD = 4.49).

3.2 | Size of buttons (Small, Large)

The number of off-road glances was not affected by button size ($p = .356$). In the case of smaller buttons, the number of glances was 1.69 (SD = 0.66) and when larger buttons were displayed, it was 1.74 (SD = 0.72).

Button Size had a significant effect on MGD (F(1, 36) = 8.528, $p = .006$, $\eta^2 = .192$). Smaller buttons invited longer mean off-road glances (M = 0.93 s, SD = 0.20 s) than larger buttons (M = 0.89 s, SD = 0.20 s).

Similarly, MxGD was longer for smaller buttons than larger buttons, notably 1.06 s (SD = 0.17) and 1.02 s (SD = 0.19), respectively (F(1, 36) = 11.465, $p = .002$, $\eta^2 = .242$).

Button Size also had a significant effect on TGT (Z = 2.333, $p = .020$, r = 0.378). Small buttons resulted in longer TGT, notably 1.36 s (SD = 0.30), compared to 1.30 s (SD = 0.28) for large buttons.

Finally, MnSp was higher with small buttons (M = 59.04, SD = 4.32) compared to large buttons (M = 58.44, SD = 3.98), with a significant effect for Size (F(1, 36) = 9.241, $p = .004$, $\eta^2 = .204$).

3.3 | Height of HMI (High, Low)

The number of glances was not significantly affected by Height ($p = .241$), as drivers looked away from the road 1.76 times on average, when the HMI was in the High position (SD = 1.76) and 1.68 times when the HMI was in the Low position (SD = 0.73).

There was no significant effect of Height on MGD ($p = .080$). Glances off the road were on average 0.899 s long when the HMI was positioned High (SD = 0.209), and 0.926 s when it was Low (SD = 0.205). A Number*Study interaction effect (F(1, 36) = 18.364, $p < .001$, $\eta^2 = .338$) revealed that, in the case of one button, the Low HMI position invited longer MGD.

There was a small, but nevertheless significant effect on MxGD for Height (F(1, 36) = 4.602, $p = .039$, $\eta^2 = .113$), with longer maximum off-road glances associated with the High position (M = 1.041, SD = 0.17) compared to the Low position (M = 1.038, SD = 0.20).

There was no significant effect of Height on TGT off the road ($p = .334$). The total glance duration was 1.34 s (SD = 0.29), when the HMI was in the High position and 1.33 s (SD = 0.31), when the HMI was Low.

There was no significant effect of Height on MnSP (p = .233), with the mean speed, 58.58 mph in the upper (SD = 4.43) and 58.85 mph in the lower condition (SD = 4.19).

3.4 | Study condition (Road, Simulator)

3.4.1 | Number of glances (NG)

Comparing data between the Road and Simulator, it was evident that there were more off-road glances made on the Road (M = 1.83, SD = 0.45) than in the Simulator (M = 1.76, SD = 1.17), supported by a significant main effect (U = 96.500, $p = .013$, r = 0.398) (Figure 5).

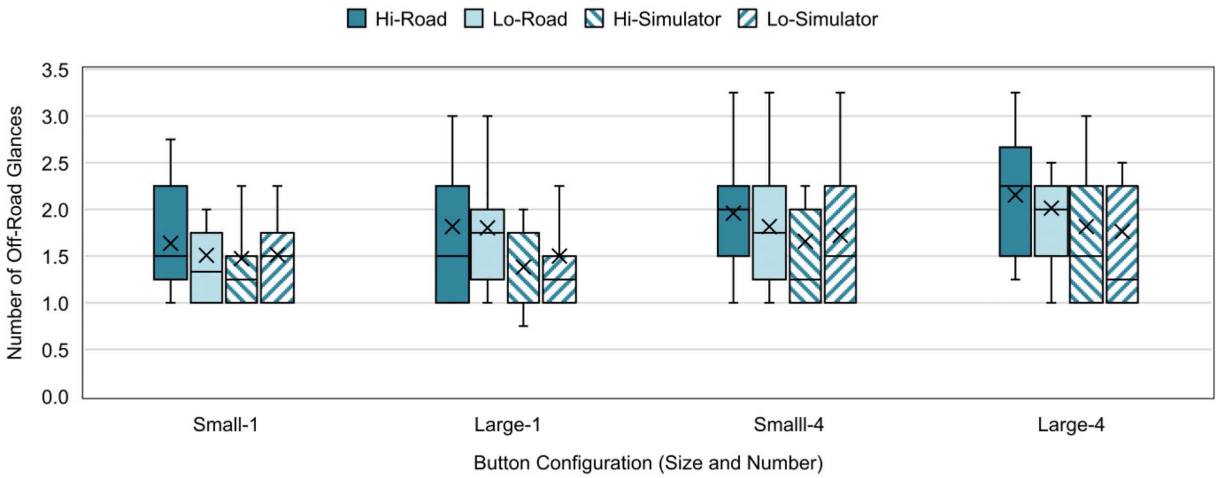

FIGURE 5 Boxplot showing Number of Off-Road Glances by button Size (Small, Large), Number (1, 4) and Height (Hi = High position and Lo = Low position) for Road and Simulator (Study). Plots show interquartile range with median (line) and mean (cross); bars extend to minimum and maximum values. Significant differences were found for Number and Study.

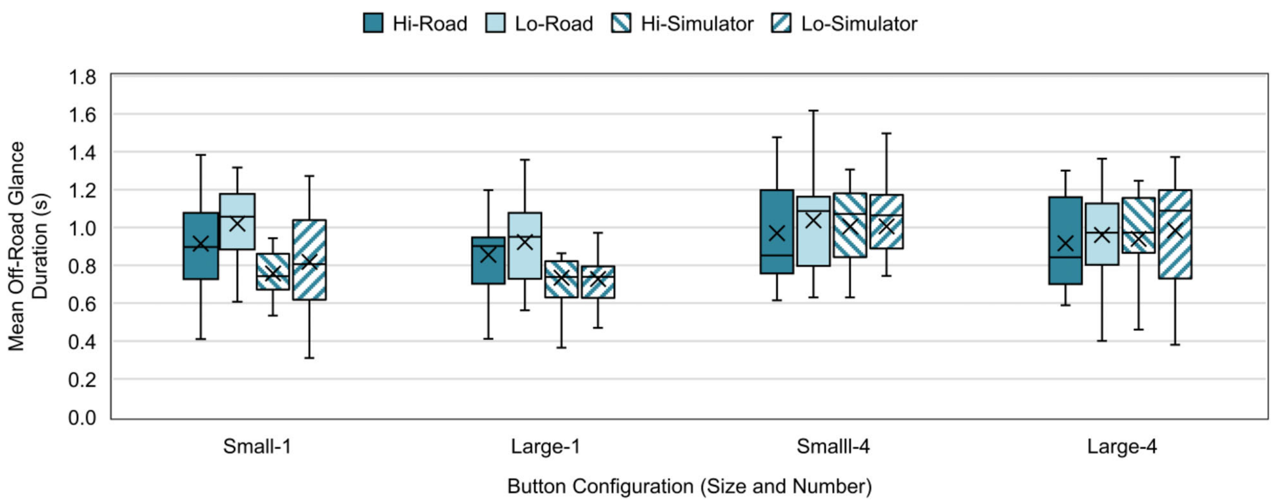

FIGURE 6 Boxplot showing Mean Off-Road Glance Duration by button Size (Small, Large), Number (1, 4) and Height (Hi = High position and Lo = Low position) for Road and Simulator (Study). Plots show interquartile range with median (line) and mean (cross); bars extend to minimum and maximum values. Significant differences were found for Number, Size and Study.

3.4.2 | Mean glance duration (MGD)

There were no significant main effects of Study (Road versus Simulator) on MGD (Figure 6). However, a Number*Study interaction effect ($F(1, 36) = 16.544$, $p < .001$, $\eta^2 = .315$) indicated that in the case of one button, MGD was longer on the Road, whereas for four buttons, MGD was longer in the Simulator.

3.4.3 | Maximum glance duration (MxGD)

MxGD was longer on Road (M = 1.11, SD = 0.19) than in the Simulator (M = 0.97, SD = 0.13), supported by a main effect for Study ($F(1, 36) = 6.754$, $p = .013$, $\eta^2 = .158$) (Figure 7).

3.4.4 | Total glance time (TGT)

A significant main effect for Study (U = 49.500, $p < .001$, r = 0.621) shows that TGT on Road was longer with a mean of 1.50 s (SD = 0.27), compared to a mean of 1.17 s (SD = 0.19) in the Simulator (Figure 8).

3.4.5 | Mean speed (MnSP)

MnSp was also affected by Study ($F(1, 36) = 161.803$, $p < .001$, $\eta^2 = .818$), with participants driving more slowly on Road (M = 55.06, SD = 2.35) than in the Simulator (M = 62.41, SD = 0.81) (Figure 9).

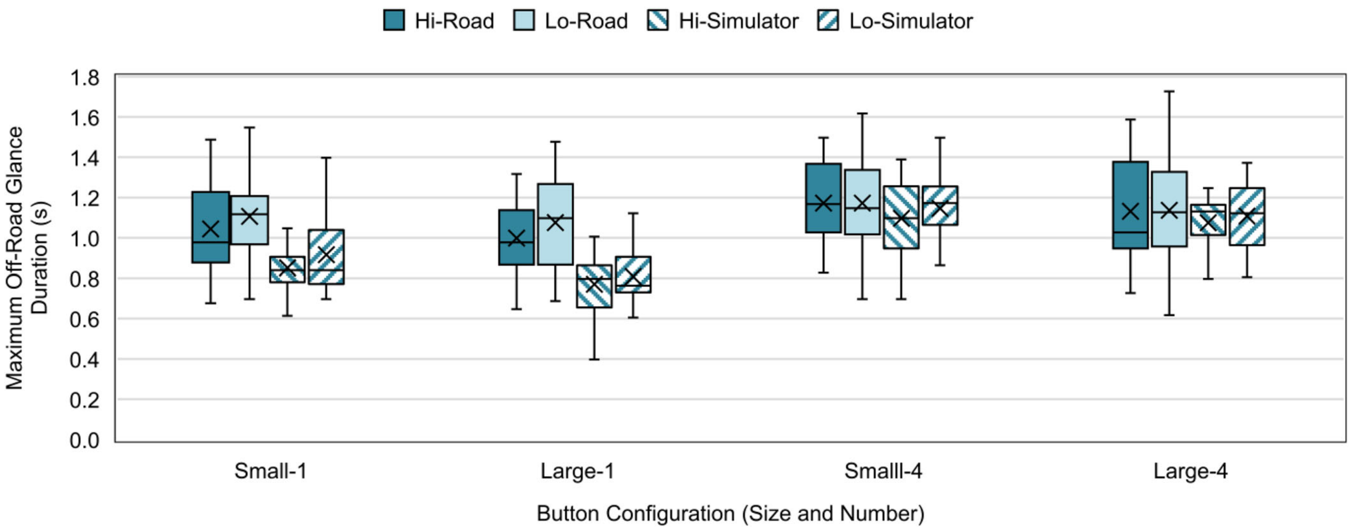

FIGURE 7 Boxplot showing Maximum Off-Road Glance Duration by button Size (Small, Large), Number (1, 4) and Height (Hi = High position and Lo = Low position) for Road and Simulator (Study). Plots show interquartile range with median (line) and mean (cross); bars extend to minimum and maximum values. Significant differences were found for Number, Size, Height and Study.

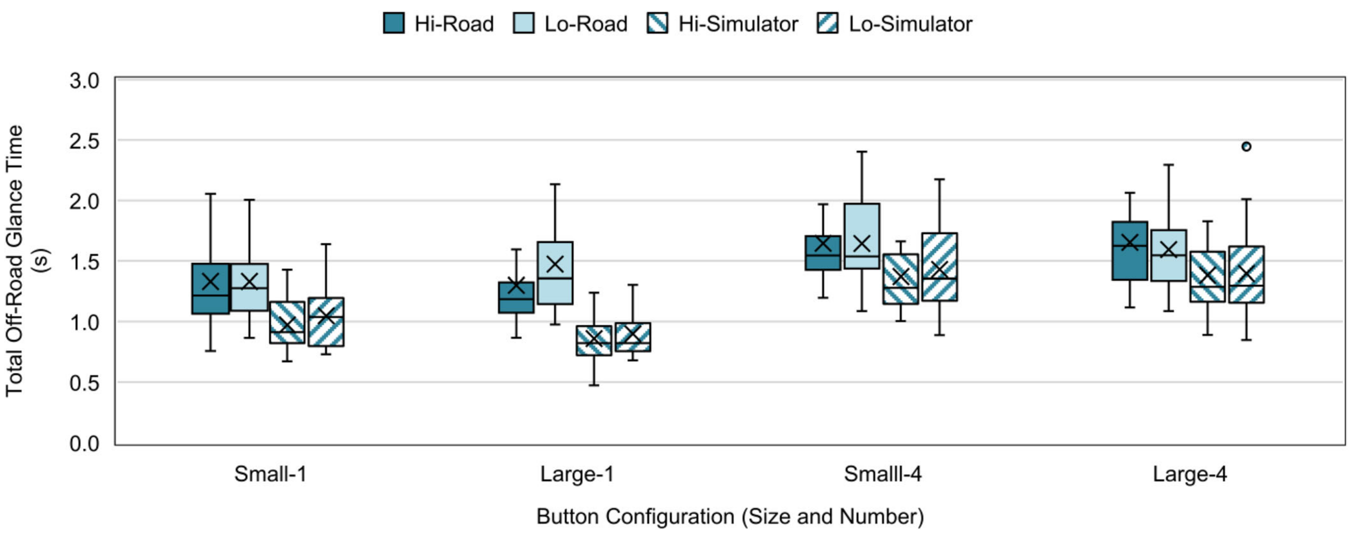

FIGURE 8 Boxplot showing Total Off-Road Glance Time by button Size (Small, Large), Number (1, 4) and Height (Hi = High position and Lo = Low position) for Road and Simulator (Study). Plots show interquartile range with median (line) and mean (cross); bars extend to minimum and maximum values. Significant differences were found for Number, Size and Study.

4 | DISCUSSION

The first aim of the study was to compare results obtained in a driving simulator (Simulator) with those collected on-road (Road) and use these data to evaluate the validity of a medium-fidelity driving simulator in the context of HMI distraction testing. In addition, the second aim of the study was to evaluate the effect of button size (Small, Large) and number (One, Four), and the location of the HMI (High, Low), on recognised visual metrics (i.e. off-road glances) and driving performance (mean speed). The results are discussed firstly in the context of HMI Design (the study's second aim) and subsequently, in the context of Simulator Validity (the study's first aim).

4.1 | HMI design and placement

The study revealed a number of effects pertinent to HMI design. In summary, data show that visual demand (in terms of the number and duration of off-road glances) increased with increasing number of buttons, and button size influenced the duration of off-road glances, with smaller buttons attracting longer off-road

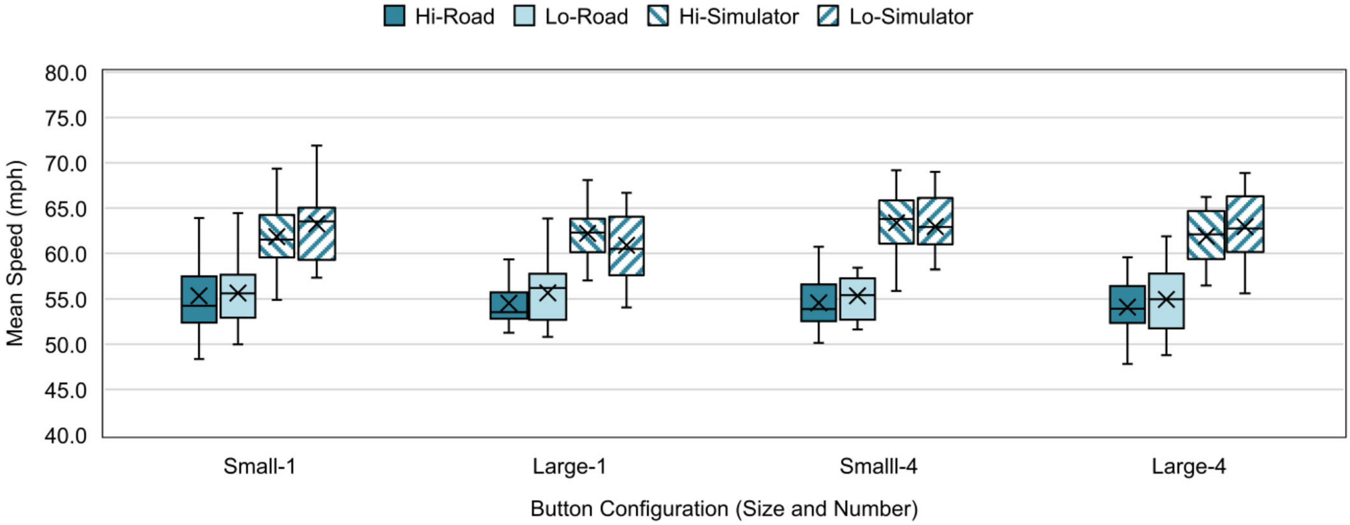

FIGURE 9 Boxplot showing Mean Speed by button Size (Small, Large), Number (1, 4) and Height (Hi = High position and Lo = Low position) for Road and Simulator (Study). Plots show interquartile range with median (line) and mean (cross); bars extend to minimum and maximum values. Significant differences were found for Size and Study.

glances. The findings therefore suggest that additional visual (and indeed, manual) demand is required when using smaller buttons (smaller target area) and larger arrays (increased complexity). These results are consistent with other, simulator-based research (see Feng et al. (2018) [26]). However, the current study notably demonstrates that such findings also apply on the road.

Results have a strong grounding in information theory [27], notably Fitts' Law and the Hick–Hyman Law [28–30], which concern the movement time necessary to acquire a visual target and the relationship between information load and choice-reaction time (i.e. the time taken to determine which target/item to acquire before moving towards it), respectively. Fitts' Law and the Hick–Hyman Law are predicated on the fact that human performance is limited primarily by the capacity of the human motor system, as determined by the visual and proprioceptive feedback that permits an individual to monitor their own movement and activity. Both laws have notably been applied successfully to the visual demand elicited by point-and-touch button selection tasks in the dual task context of driving (see [23, 24]), and the findings from the current study are also aligned with these fundamental principles and established wisdom, that is, smaller buttons or more complex arrays demand more visual attention.

In contrast, the position (height) of the HMI appears to have had very little impact on the visual metrics captured in the study, or indeed, driving performance, though it is noted that the difference in height between the two conditions (high/low) was relatively small (in consideration of the safety and wellbeing of study participants). Elsewhere, the placement of HMI displays has been shown to have a marked effect on visual behaviour, with relevant literature recommending that HMIs/displays which have high attentional demands, or that are frequently accessed by drivers, should be located as close as possible to the driver's normal line of sight (for example, on top of the dashboard or to the side of the steering wheel, equivalent to our 'high' position) (see [31, 32]). Such recommendations are predicated on minimising the gaze distance and subsequent movement or saccade time (in other words, the overall visual cost of redirecting visual attention from the roadway to the interface), but not necessarily the inherent visual demand of using it.

In this regard, numerous studies have introduced novel touchscreen interface designs specifically intended to minimise the inherent visual demand of touchscreen interactions, for example, by devising new interaction concepts [33], predicting a user's intended target by using a pointing gesture tracker [34], directly manipulating design elements (i.e. button size, location, and contrast) [20], or augmenting touchscreens with haptic information so that drivers can 'feel' the location of the on-screen targets [35] or be guided towards them [36]. While all approaches have reported successes, they remain fundamentally reliant on finger-touch input and as such, the driver's eyes are still required to see what their hand is doing. Thus, evaluating the visual distraction of in-vehicle interfaces remains an important component of driving-related research, and driving simulators, an important, enabling tool.

4.2 | Simulator validity

The data show differences between the Simulator and the Road, both in terms of visual behaviour and driving performance. Notably, drivers made more and longer off-road glances when interacting with the touchscreen HMI on the Road, compared to occasions in which the same tasks were conducted in the Simulator, leading to longer TGT overall on the Road. On face value, this may appear to be inconsistent with other, related research. Indeed, several validation studies (e.g. [8])

have reported the opposite, that is, significantly longer fixations observed in the simulator compared to an on-road environment, especially in low-demand, simulated driving situations. Nevertheless, such studies have tended to focus on drivers' visual scanning behaviour associated with the primary driving task and have not considered the impact of a secondary, non-driving related task—such as interacting with a touchscreen HMI—and the associated off-road attention it demands. The results from the current study suggest that in this dual task or divided attention context, the duration and frequency of fixations associated with off-road glances is significantly higher on the Road compared to the Simulator. In other words, drivers find it more visually demanding interacting with a touchscreen while driving on the Road than in a Simulator. Presented as such, this finding conforms with common expectations, and suggests that it takes longer and demands more visual attention to extract salient information from a touchscreen HMI when drivers are already encumbered by the demands of real-world driving.

Indeed, with the exception of an interaction effect for MGD, all off-road visual metrics were higher on the Road than the Simulator, and these effects were consistent across all HMI design variables (i.e. the ordering of effects for number of glances, mean glance duration, maximum glance duration, and total glance time were the same on the Road and in the Simulator). For example, visual demand increased as the number of buttons increased.

In addition, mean speed was higher in the Simulator than on the Road. Several explanations are possible for this. For example, drivers may have underestimated their speed in the Simulator due to poor speed perception in the absence of motion cues. Alternatively, they may have been willing to drive faster in the driving simulator due to the low risk presented by the virtual environment, or the demands of the virtual environment were lower, even though the worlds were designed to be geo-equivalent and reflect 'off-peak' driving conditions; nevertheless, this may have encouraged higher speed selection. Such a finding is indeed consistent with other research [9, 10, 11], although it is opined that the relative validity of off-road visual behaviour suggests that drivers were still able to operationalise risk in their visual behaviour. Thus, it is suggested that differences are more likely due to poor speed perception than low risk perception in the virtual environment.

Overall, the data thus support good *relative validity* associated with a fixed-base, medium-fidelity driving simulator for HMI distraction testing. In other words, drivers' off-road glance behaviour and speed maintenance, and more specifically, the ordering of effects in response to changes to the interface design, were the same, relatively, in the Simulator to those observed on Road. For example, there were more, and longer, off-road glances associated with four compared to one button in both situations. Nevertheless, it remains notable that *absolute validity* (that is, identical behaviour and ordering of effects) was not achieved, though this is no cause for concern. Indeed, in the context of vehicular interface design, distraction testing typically aims to evaluate HMI designs either at a formative level, early in the design cycle, to determine factors such as design feasibility— for example, to identify which proposed design/s should be dismissed early in the design cycle. Or, at a summative level, driving simulator distraction studies aim to deliver highly controlled comparisons of several, more established HMI designs. In practice, both activities tend to be 'within-subjects' (i.e. all participants experience all possible HMI designs) and therefore, neither is contingent on absolute validity, provided relative validity is assured. Indeed, allowing valid *relative* judgements to be made (e.g. which interface is more distracting than others) is crucial in justifying the dismissal of a particularly obtuse HMI design, or to identify the least distracting solution from several under evaluation. In contrast, *absolute validity* becomes important in situations where the goal is to compare results to a benchmark or arbitrary pass/fail distraction criteria, and in this context, our results suggest that a fixed-base, medium-fidelity driving simulator may be less suitable, unless the said criteria are defined with a driving simulator study in mind (as is the case for NHTSA's driver distraction guidelines for in-vehicle electronic devices, which compare behaviour to a standardised reference task [17]).

While the findings relate to a fixed-base, medium-fidelity driving simulator, and are presented as such, it is recognised that succinctly defining 'fidelity' can be difficult and somewhat ambiguous [37]. By convention, driving simulator fidelity is normally described as low, medium, and high [38], though it is noted that higher fidelity facilities will not necessarily produce higher quality results [12]. In practise, there is limited guidance, and currently no set standards, regarding what these terms actually mean. As a rule of thumb, a 'low fidelity' facility might be expected to comprise a single, desktop display, out-of-the-box gaming wheel and pedals. 'Medium fidelity' will likely include a static, standalone car or buck with integrated controls and at least 180-degrees field of view, and a 'high fidelity' driving simulator would be expected to have a dedicated, fully integrated vehicle, motion base, and a 360-degree visual scene [39]. One might naturally therefore expect the fidelity of the driving simulator to have a significant impact on a driver's motivation, performance and behaviour— highlighting the ongoing need for validation studies, though the results from the current study clearly remain applicable to fixed-base, medium-fidelity simulators only, and further evaluations would be required to validate simulators with different or differing levels of fidelity.

4.3 | Limitations

It is noted that only two levels were explored for each independent, HMI-design variable (notionally, small/large, one/four and high/low) and the touchscreen interface arguably lacked ecological validity (i.e. interfaces were rudimentary and only presented buttons actively being used in the study). Evidently, one button barely constitutes an array, and a genuine interface would likely have other design elements competing for a driver's visual attention; moreover, primary driving task demand could vary considerably. Nevertheless, these experimental factors were chosen to minimise potential confounds and enable a controlled comparison, thereby ensuring internal validity. In addition, these measures were necessary precautions to ensure the safety and wellbeing of participants, and the overall study design aimed to minimise fatigue and motion/simulator sickness (although we did not specifically measure fatigue/workload to evaluate this). Caution should be applied when drawing conclusions or making recommendations on HMI design from the findings. The first aim of the study was to validate the use of a fixed-base, medium-fidelity driving simulator for visual distraction testing, although it is noted that such findings may differ if more complex or ecologically valid interface designs were used, or in more demanding driving conditions.

A further unavoidable limitation is that even with relatively restricted and rudimentary interfaces used during the study, elements of experimental control may have been compromised during the Road evaluation, making it difficult to provide a controlled evaluation of primary task demand. This is an inevitable limitation of real-world, naturalistic studies. Indeed, external and environment factors (e.g. the presence or absence of other road users, perturbations to road surface, ambient lighting, weather etc.) are tightly controlled and equivalent for each participant in a simulated world, whereas these factors may differ significantly between participants on the road. For example, changes in lighting or weather conditions (e.g. sun glare) on the road can affect the visibility of the HMI, making button selection difficult, or unexpected perturbations in the road surface can hinder or inhibit accurate motor control—though there was no direct evidence of this during the study. In addition, the unpredictable nature of the other traffic and road users in the vicinity of the ego vehicle may delay the time between tasks on the road, or affect road speed. In practice, these factors represent real-world issues associated with naturalistic, on-road studies, and, if anything, make an even stronger case for the use of driving simulators to study driver distraction—assuming its validity has been established.

5 | CONCLUSION

The study offers a unique validation of a fixed-based, medium-fidelity driving simulator for HMI visual distraction testing. Significant differences in visual behaviour were identified between the driving simulator and on-road. However, the order of effects in response to changes in HMI design elements was the same, suggesting good relative validity. For example, differences were noted in response to button size and number, with smaller buttons and larger arrays attracting higher visual attention in both situations. Results highlight a clear relationship between HMI design elements and the ensuing visual demand characteristics, and are in line with existing research and established wisdom. However, the study notably shows that such findings also apply on the road. It is noted that the interfaces under evaluation were limited in their design (e.g. only two levels of button size and number). Consequently, caution should be exercised if attempting to generalise HMI design guidance or principles from the results, or indeed, determine absolute levels of visual distraction. Nevertheless, the study adds to the corpus of in-vehicle HMI research and supports the use of a fixed-based, medium-fidelity driving simulator for HMI visual distraction testing, though one might caution that it is most suited for comparative 'within-subjects' evaluations, for example, to determine whether one touchscreen interface is more visually distracting than another. Future work should consider more representative HMI designs elements and explore different driving situations.

AUTHOR CONTRIBUTIONS

David Large: Formal analysis, Methodology, Visualization, Writing – original draft; Sanna Pampel: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing; Siobhan Merriman: Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing; Gary Burnett: Conceptualization, Methodology, Supervision, Writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

FUNDING INFORMATION

None.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CREDIT CONTRIBUTIONS

David R. Large: Methodology, Formal analysis, Writing—Original Draft, Visualization; Sanna M. Pampel: Investigation, Data Curation, Formal analysis, Writing—Original Draft, Writing—Review & Editing; Siobhan E. Merriman: Methodology, Investigation, Data Curation, Formal analysis, Writing—Review & Editing; Gary Burnett: Conceptualization, Methodology, Supervision, Writing—Review & Editing

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