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Catherine Harvey, Neville A. Stanton, Carl A. Pickering, Mike McDonald & Pengjun Zheng

Transportation Research Group, Faculty of Engineering and Environment, University of Southampton, UK

Jaguar and Land Rover Technical Research, Jaguar Cars, Engineering Centre, Whitley, Coventry, UK

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To twist or poke? A method for identifying usability issues with the rotary controller and touch screen for control of in-vehicle information systems

Catherine Harvey*, Neville A. Stanton, Carl A. Pickering, Mike McDonald and Pengjun Zheng

Transportation Research Group, Faculty of Engineering and Environment, University of Southampton, UK; Jaguar and Land Rover Technical Research, Jaguar Cars, Engineering Centre, Whitley, Coventry, UK

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In-vehicle information systems (IVIS) can be controlled by the user via direct or indirect input devices. In order to develop the next generation of usable IVIS, designers need to be able to evaluate and understand the usability issues associated with these two input types. The aim of this study was to investigate the effectiveness of a set of empirical usability evaluation methods for identifying important usability issues and distinguishing between the IVIS input devices. A number of usability issues were identified and their causal factors have been explored. These were related to the input type, the structure of the menu/tasks and hardware issues. In particular, the translation between inputs and on-screen actions and a lack of visual feedback for menu navigation resulted in lower levels of usability for the indirect device. This information will be useful in informing the design of new IVIS, with improved usability.

Statement of Relevance: This paper examines the use of empirical methods for distinguishing between direct and indirect IVIS input devices and identifying usability issues. Results have shown that the characteristics of indirect input devices produce more serious usability issues, compared with direct devices and can have a negative effect on the driver–vehicle interaction.

Keywords: evaluation; interaction; in-vehicle information systems; usability

Introduction

In-vehicle information systems (IVIS) are menu-based devices that integrate many secondary functions into a single system, presented via a screen-based, graphical user interface (GUI) (Harvey et al. 2011b). The usability of an IVIS is affected by its human–machine interface, which determines how well a driver can input information, receive and understand outputs and monitor the state of the system (Daimon and Kawashima 1996, Cellario 2001, Stanton and Salmon 2009). IVIS GUIs can be controlled via a touch screen, a centrally located controller (usually in the form of a dial that can be rotated and pushed in different directions) or buttons surrounding the display screen (Kern and Schmidt 2009). Based on a survey of vehicles from 35 automotive manufacturers, Kern and Schmidt (2009) found that around half of the cars reviewed used a touch screen IVIS. Many British, American and Japanese manufacturers, including Jaguar, Ford and Toyota, tend to use a touch screen, whilst most German manufacturers, including BMW, Audi and Mercedes-Benz, prefer controller-based IVIS input (Kern and Schmidt 2009). Many of these systems have additional hard buttons, located around the display screen and/or central controller, to aid menu navigation. IVIS inputs can be categorised into two types: direct and indirect (Rogers et al. 2005). The main aim of this study was to assess how well empirical evaluation methods can identify usability issues, which are specific to these two input types. There is a need for a framework of methods that can successfully identify usability issues so that this information can be used to inform the design of new IVIS with enhanced usability (Harvey et al. 2011d). In this study, a touch screen was used to represent a direct input device and a rotary controller to represent an indirect input device. Both systems were connected to the same GUI and were tested using the same set of tasks, so that any differences observed would be a feature of the input type, rather than of the GUI design or task structure.

Touch screen: a direct input device

A touch screen enables direct inputs onto a display screen (Taveira and Choi 2009), which is located within reach of the driver. An advantage of this type of interaction is that there is a direct relationship between what the eyes see and what the hands do (Dul and

*Corresponding author. Email: c.harvey@soton.ac.uk
Weerdmeester 2001), which has been shown to increase user satisfaction and initial acceptance (Rogers et al. 2005). The use of a natural pointing gesture (Greenstein 1997) is also more intuitive and therefore easier for novice users to learn (Rydstöm et al. 2005, Taveira and Choi 2009). One of the main disadvantages of the touch screen is the position of the LCD, which must be within reach of the driver (Greenstein 1997, Dul and Weerdmeester 2001). This results in the screen being located significantly below the driver’s line of sight and also means that it is susceptible to glare from sunlight, because provision of shrouding around the screen must be traded off against accessibility (Commission of the European Communities 2006). The location of the touch screen also means that the driver’s arm needs to be held outstretched whilst performing tasks and this can sometimes result in muscle fatigue and may lead to low precision (Greenstein 1997, Taveira and Choi 2009). The touch screen also suffers from a lack of tactile feedback, which means that drivers are not provided with information to confirm their inputs (Stevens et al. 2002).

Rotary controller: an indirect input device

The rotary controller IVIS consists of a display screen, located at the driver’s eye level, and a hard rotary dial located on the centre console, within comfortable reach of the driver. The rotary controller is an indirect device as it involves translation between manual input and visual output. This type of input can be difficult to learn and use in high workload situations (Stevens et al. 2002) and is likely to result in lower levels of user satisfaction, particularly on initial use, although there is evidence that satisfaction increases with practice (Rogers et al. 2005). Indirect devices are often favoured by older and more experienced users, once the translation between inputs and outputs has been learned (Rogers et al. 2005). This translation is likely to increase task interaction times, compared with direct input devices, as the user is required to scroll through a number of menu items before arriving at the correct option. The rotary controller, however, is more suited to repetitive tasks and those that require a high level of precision (Rogers et al. 2005). Indirect devices also offer the advantage of having a better positioned visual display, which can be located further from the driver, in their line of sight (Dul and Weerdmeester 2001, Commission of the European Communities 2006). The screen can also be shrouded to reduce glare because the screen itself does not need to be accessed by the driver (Commission of the European Communities 2006). Another advantage of the rotary controller is the provision of tactile feedback, which is useful in giving the driver information about the interaction (Badescu et al. 2002).

Evaluating in-vehicle information system usability

There is clearly a need for a more usable IVIS that overcomes the problems associated with current input devices, whilst preserving the benefits offered to drivers by secondary in-vehicle functions. In order to develop the next generation of more usable IVIS, designers need to understand the issues associated with existing systems. One of the main motivations of this work was to help designers to identify usability issues and understand the importance of early identification and its significance for improved design. Harvey et al. (2011d) developed a framework for the evaluation of IVIS, which comprised a number of steps, linked to form an iterative cycle of evaluation and redesign. The first step was to define a need, which in this case was for a more usable IVIS. To specify this need in more detail, a set of usability criteria were developed for IVIS (see Harvey et al. 2011a). In order to evaluate a system against these usability criteria, appropriate evaluation methods were selected (Harvey et al. 2011d). In this study, a set of empirical methods, which form part of this framework, were applied in an evaluation to assess the potential for identifying usability issues and distinguishing between different IVIS input types. The two input devices evaluated in this study are shown in Figures 1 and 2.

There have been many empirical studies of driver distraction and its effect on various aspects of driving performance and workload. Many of these studies have used unnatural or ‘surrogate’ in-vehicle tasks to represent secondary task demand (e.g. Lansdown et al. 2004, Anttila and Luoma 2005, Carsten et al. 2005, Jamson and Merat 2005, Harbluk et al. 2007). Those that have used natural IVIS tasks have tended to focus only on a single task, such as making a phone call (e.g. Reed and Green 1999, Kass et al. 2007, Drews et al. 2008) or entering a navigation destination (e.g. Nowakowski et al. 2000, Baumann et al. 2004, Chiang et al. 2004, Tsimonhi et al. 2004, Ma and Kaber 2007, Oliver and Burnett 2008, Wang et al. 2010). There have been few empirical usability evaluations of IVIS input devices using a large and diverse set of natural secondary tasks. Rydstöm et al. (2005) compared one touch screen and two central controller-based IVIS using a set of 10 natural secondary tasks. Their study used the manufacturer-supplied GUIs associated with each of the IVIS. Whilst this would have resulted in high ecological validity, it did not allow direct comparisons to be made between the different input devices because the structure of tasks was different for each system and this, rather than the nature of the
input, may have been the cause of any performance differences. In the current study, the same set of tasks and GUI was used for both input devices, which ensured that usability issues could be attributed to the input device, rather than the task structure. In this study, ecological validity was less important because the main aim was to assess whether or not the empirical methods used were capable of highlighting important usability issues, rather than to produce an absolute assessment of IVIS performance.

**Selection of tasks**

Altogether, 20 tasks were selected to represent the four main IVIS function categories: infotainment; comfort; communication; navigation. Five tasks were selected in each of the first three functional groups. Only two tasks were selected to represent the navigation group, due to the increased time taken to carry out navigation tasks and the limited functionality available in the prototype GUI used in this study. In selecting IVIS tasks to study, Nowakowski and Green (2001) considered whether the task would be desired whilst driving, whether the task was already available in current systems, the frequency of task interaction and if the task could be accomplished within the 15-s rule boundaries (see Green 1999). The functions available in existing IVIS were analysed as part of a pilot study and only those that would be used during the driving task were selected. Many functions are provided by IVIS; however, some would not normally be needed whilst driving, e.g. IVIS, LCD and general vehicle settings. Furthermore, some IVIS guidelines advise that certain high-demand tasks, such as navigation entry, are turned off whilst driving because they present a high risk to safety (Green et al. 1995, Commission of the European Communities 2006). This is, however, a matter of some controversy among end-users, who might demand that interaction with tasks should be at their discretion. Consequently, many automotive manufacturers do allow access to functions such as destination entry whilst driving (Llaneras and Singer 2002), although it is recommended that these functions are accompanied by a warning to drivers regarding the potential distraction risks (Commission of the European Communities 2006). In this study, navigation tasks were included in the task set; however, there were no tasks that required users to monitor dynamic information on the screen, for example, watching TV. Frequency of interaction with tasks was
estimated based on a heuristic analysis conducted as part of a pilot study. Interaction frequencies for the tasks selected in this study ranged from low (e.g. adjust balance, enter navigation address) to moderate (e.g. select radio station, adjust fan speed). Higher frequency functions, such as adjust audio volume, tend to be provided via hard, dashboard-mounted controls, rather than as part of a menu-based IVIS (Llaneras and Singer 2002). These dashboard controls were not investigated in the current study. Each task selected for the study was also modelled using multimodal critical path analysis, in order to predict task times: none of the 20 selected tasks was predicted to exceed 15 s in total.

**Types of operation**

Tasks were also classified according to the types of operations they involved. Three main IVIS operation types were defined for this study: discrete selection; alphanumeric entry; level adjustment. Discrete selection operations involve the user selecting a standard menu item in order to open another menu or to select a function. Performance of this operation is affected by the number of alternative menu items displayed at one time (Hick’s law), the size of the target (Fitts’s law) (Card et al. 1983), the visibility of information displayed on the target (Stevens et al. 2002) and its position relative to the previous menu item in the sequence (Fitts’s law) (Card et al. 1983). Alphanumeric entry operations are a type of discrete operation, but specifically involve entering letters or digits. These are usually part of long letter/number sequences, for example, in an address or phone number. Layout of alphanumeric targets is particularly important because there is usually a relatively large number to choose from and selection time needs to be minimised. Because of their large number, alphanumeric targets are usually also relatively small, which increases the precision required for successful operation. Level adjustment operations involve the user increasing or decreasing a value, e.g. volume or temperature. This can be achieved by continuous movements of a dial or slider or by repeatedly pressing a single target to produce a certain amount of level change.

IVIS have a menu-based structure; therefore, the majority of tasks will involve making one or more discrete selections to navigate through this structure. Three of the tasks used in this study were selected because, in addition to discrete selections, they also involved alphanumeric entry and four other tasks were selected because they required some form of level adjustment. In this study, the level adjustment tasks involved repeat presses of a single increase/decrease button, rather than continuous movement of a slider or dial. Task selection was limited by the functionality of the prototype GUI used in this study. However, effort was made to select a broad range of tasks, representing all four IVIS functionality groupings and the three operation types of interest. Rotary controller input devices have been found to be better for precision tasks (Rogers et al. 2005) so it was expected that error rate and task time, particularly for tasks involving alphanumeric entry, which requires increased precision, would be lower with the rotary controller. Indirect devices are also suitable for repetitive tasks (Rogers et al. 2005) and it was expected that the rotary controller would also produce a lower error rate and shorter interaction times for tasks involving level adjustment. Rogers et al. (2005) found that direct devices, such as the touch screen, are better for discrete, pointing tasks. It was therefore predicted that the touch screen would yield shorter task times and lower error rates for those tasks that predominantly involved discrete menu selection tasks.

**Method**

**Participants**

In total, 20 participants (10 female, 10 male) aged between 21 and 33 (mean = 25, SD = 2.8) years took part in the study. All participants held a valid driving licence and had at least 1 year’s driving experience on UK roads (mean = 5, SD = 3.3). Mode annual mileage for the sample was 0–5001 miles. Participants were all right handed. Participants were recruited via email advertisements, from a sampling frame of Civil Engineering students and staff at the University of Southampton. They were each paid £20 for participating in the study. The study was granted ethical approval by the University of Southampton.

**Equipment**

**The University of Southampton’s driving simulator**

The study was conducted in the University of Southampton’s driving simulator. The simulator is a fixed-based system, consisting of a full Jaguar XJ6 right-hand drive vehicle. The vehicle controls are connected to four computers running STISIM Drive™ (System Technology Inc., Hawthorne, CA, USA) software. The road scene was projected onto three 240 cm × 180 cm screens in front of the vehicle, offering a 160° field of view. The rear-view mirror image was projected onto a screen behind the vehicle. The driving scenario used in the study simulated a combination of town, city and countryside driving environments, consisting of dual-carriageway road, with a combination of curved and straight sections, and with-flow and opposite-flow traffic. The distance
from start to finish was 21.9 km and participants had to drive the full length of the scenario in each condition. The simulator provided auditory feedback to signal when the vehicle strayed over the road edge and to give an indication of vehicle speed via increases/decreases in engine noise. Drivers were also encouraged to maintain suitable driving speeds by having an almost-constant stream of with-flow traffic in the left-hand lane of the dual-carriageway, forcing the driver to maintain an accurate path in the right-hand lane. There was also oncoming traffic in the opposing lanes to discourage the driver from crossing the centreline. If the vehicle was driven too far over the road edge, a crash would be simulated. This feedback encouraged the participants to drive in a natural way. In simulator studies, participants will be aware that poor performance, such as straying out of lane or speeding, poses little real risk to their safety. It was therefore important to provide feedback to demonstrate to drivers that there were negative consequences of poor driving behaviour (Green 2005).

**In-vehicle information systems**

The GUI used in this study was displayed on a 7 inch LCD screen, mounted on the dashboard to the left of the driver (towards the centre of the vehicle). The LCD screen was connected to a laptop in the rear of the vehicle, from which the experimenter could also control the GUI. The LCD enabled touch input. In the rotary controller condition, a rotary input device was mounted just in front of the gear lever in the car’s centre console. The controller moved clockwise and anticlockwise to scroll through the on-screen options. It could also be pressed down to select options; however, it did not move forwards/backwards/right/left, and therefore lacked the full functionality of most existing rotary systems, such as the BMW iDrive, Mercedes Command and Audi MMI. Both IVIS used the same GUI: screen shots of the main menu and climate menu screens are presented in Figure 3. Auditory feedback was not provided for either system.

**Eye tracking**

The simulator was equipped with an eye-tracking system (FaceLab™, version 4.6; Seeing Machines, Canberra, Australia), which is capable of measuring participants’ visual behaviour, including time spent looking at the road scene and the LCD display. This system consisted of two cameras and an infrared reflector pod, mounted on the dashboard in front of the driver.

**User questionnaires**

Each participant was provided with paper copies of a participant information sheet, a participant questionnaire, a consent form and the system usability scale (SUS) (Brooke 1996, Bangor *et al.* 2008). SUS consists of a 5-point scale, against which participants rated their agreement with 10 statements relating to the usability of a system. An overall score for system usability between 0 and 100 was calculated for each IVIS.

**Procedure**

Pilot studies were conducted in order to refine aspects of the study design, including the length and complexity of the driving scenario, number of tasks and method of task presentation. In the main study, participants were first briefed about the experiment and then asked to complete a questionnaire, to gather demographic and driving experience information, and a consent form. Participants were allowed to adjust the seat and mirror position before the test started. Each participant was then given a 10 min practice drive in the simulator, during which various vehicle controls and features of the road scenario were explained. Next,
participants drove through a simulated driving scenario, lasting approximately 25 min. In this control condition, they did not perform any secondary tasks via an IVIS. In the next phase of the experiment, participants completed the two IVIS conditions. Before each condition, participants were given 5 min to practise with the IVIS. In each experimental condition, participants drove through the same driving scenario as in the control condition, whilst performing a set of secondary tasks via each IVIS. A repeated measures design was used and the order of presentation of IVIS conditions was counterbalanced across participants to eliminate learning and practice effects. After each IVIS condition, participants completed the SUS questionnaire.

Secondary in-vehicle information system tasks

In each experimental condition, participants were instructed to complete 20 tasks whilst driving. This set of tasks was the same for the touch screen and rotary controller conditions and is shown in Table 1.

Instructions to complete each task were read out to participants by the experimenter, who was seated in the rear of the vehicle. Each task was read out approximately 20 s after the participant had completed the previous task. The order of task presentation was randomised for each participant to minimise practice effects. In each condition, three events were triggered by the experimenter to coincide with certain tasks (marked with an asterisk in Table 1). These tasks were representative of low (increase fan speed), medium (call from contact list) and high (enter destination address) levels of relative complexity. Levels of complexity were assigned based on analysis carried out previously via hierarchical task analysis and multimodal critical path analysis, which were used to explore the number of menu levels, number of operations and operation types. The three events were always presented in the same sequence, as follows:

1. Man walks out into the roadway in front of the driver’s vehicle, crossing from right to left.
2. Woman walks out into the roadway in front of the driver’s vehicle, crossing from right to left.
3. Dog walks out into the roadway in front of the driver’s vehicle, crossing from left to right.

Participants were not informed about the pedestrian events before any of the trials, or that these events would always coincide with particular secondary tasks. The pedestrian events were triggered by the experimenter. The triggering of events could not be seen by participants; this ensured that they would not be able to anticipate a collision and change their behaviour in response.

Data collection and analysis

The study employed a repeated measures design. IVIS condition was a within-subjects factor, consisting of three levels: control (no IVIS); touch screen; rotary controller. Primary driving performance data were recorded by the simulation software. This included mean speed and number of centreline crossings. A key logger was used to record secondary task interactions for the touch screen and rotary controller and task times were calculated from the data. Visual behaviour data were recorded by the eye tracking equipment. This logged the target (i.e. front projector screen, LCD screen) for visual attention at approximately 30 ms intervals. Performance of the eye-tracking equipment was affected by certain facial features and was less accurate for certain participants, particularly glasses or contact-lens wearers. In four cases, the results indicated low eye-tracking accuracy and the visual behaviour data for these four participants were removed prior to statistical analysis. Subjective ratings of system usability were recorded using the SUS questionnaire.

Primary driving performance and visual behaviour metrics were compared across the conditions using a Friedman’s ANOVA, for multiple related samples. The data for all measures were tested for normality and found to be non-normally distributed; therefore, non-parametric statistical tests were applied. Post hoc tests

<table>
<thead>
<tr>
<th>Task category</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td>Play radio station</td>
</tr>
<tr>
<td></td>
<td>Select CD</td>
</tr>
<tr>
<td></td>
<td>Select portable audio</td>
</tr>
<tr>
<td></td>
<td>Increase bass</td>
</tr>
<tr>
<td></td>
<td>Adjust balance</td>
</tr>
<tr>
<td>Comfort</td>
<td>Increase fan speed</td>
</tr>
<tr>
<td></td>
<td>Increase fan speed*</td>
</tr>
<tr>
<td></td>
<td>Set air direction</td>
</tr>
<tr>
<td></td>
<td>Reduce seat heat</td>
</tr>
<tr>
<td></td>
<td>Activate auto climate</td>
</tr>
<tr>
<td></td>
<td>Turn off climate</td>
</tr>
<tr>
<td>Navigation</td>
<td>Enter destination address</td>
</tr>
<tr>
<td></td>
<td>Enter destination address*</td>
</tr>
<tr>
<td></td>
<td>Enter destination postcode</td>
</tr>
<tr>
<td>Communication</td>
<td>Digit dial</td>
</tr>
<tr>
<td></td>
<td>Call from contact list</td>
</tr>
<tr>
<td></td>
<td>Call from contact list*</td>
</tr>
<tr>
<td></td>
<td>Call from last 10 calls made</td>
</tr>
<tr>
<td></td>
<td>Call from last 10 calls received</td>
</tr>
<tr>
<td></td>
<td>Call from last 10 calls missed</td>
</tr>
</tbody>
</table>

*Repeated task to coincide with a roadway event.
(Wilcoxon tests for two related samples) were also applied, with a Bonferroni adjustment for multiple comparisons. Effect sizes (r) are also reported in accordance with American Psychological Association guidelines (Wilkinson 1999). Outliers are shown as a point for values plus/minus 1.5 times the interquartile range (IQR) from the top/bottom whiskers and as an asterisk for values plus/minus three times the IQR from the top/bottom whiskers.

The age of participants in this study ranged from 21 to 33 years. There is some evidence to suggest that drivers aged 25 and under exhibit different driving performance, visual behaviour and crash risk, under dual task conditions, compared with drivers over 25 (Ryan et al. 1998, Liu 2000, Reimer et al. 2011). To examine whether or not this was a factor in the current study, each set of results was split by age into two groups: 21–25 year olds (n = 13, mean age = 23, SD age = 1.2, mean experience = 4 years, SD experience = 2.1, mode mileage = 0–5000 miles); 25–33 year olds (n = 7, mean age = 28, SD age = 2.4, mean experience = 8 years, SD experience = 3.9, mode mileage = 5001–10000). The two groups were then compared using Mann Whitney tests for two independent samples. No significant differences were found between the age groups on any of the usability measures reported here. Although it is widely accepted that there are age-related differences in driving performance and distraction caused by interaction with IVIS tasks, these differences may only be significant at the more extreme ends of the scale. For example, Shinar (2008) observed a decline in driving performance with a concurrent mobile phone task only with older adults aged 60–71 years. They found little difference in the performance of two younger age groups, aged 18–22 and 30–33 years. Horberry et al. (2006) also found few age-related performance differences in dual task conditions, particularly for drivers under 60. These findings support the results of the age comparisons in this study and results are therefore reported across the entire age range, 21–33 years.

Results and discussion

Primary driving performance

Previous studies have shown that, when drivers interact with secondary in-vehicle tasks, their workload increases and this can often lead to distraction (Lansdown et al. 2004, Jamson and Merat 2005, Dingus et al. 2006, Lees and Lee 2007, Wang et al. 2010). In this study, driving performance whilst interacting with secondary tasks was compared with a control condition of driving without task interaction. As expected, both IVIS produced significantly worse levels of driving performance, compared with the control condition. This was reflected in measures of mean speed, speed variance and number of centreline crossings.

Longitudinal control

The driver has immediate control over their speed and, consequently, this is one of the most significant factors in measuring driver distraction (Bullinger and Dangelmaier 2003, Fuller 2005, Collet et al. 2010). Speed was expected to be lower in the IVIS conditions, with the most distracting/demanding interface causing the largest reduction in speed. Reduction in speed as a result of increased workload has been observed in previous studies of driver distraction (e.g. Green et al. 1993, Young et al. 2003, Johansson et al. 2004, Lansdown et al. 2004, Tsimonhi et al. 2004, Jamson and Merat 2005). It is thought that most drivers employ this strategy to reduce primary task workload in order to cope with the demand from the interaction with secondary tasks. Drivers were told to drive at 40 mph consistently throughout each run and there were 40 mph speed limit signs displayed at regular intervals in the driving scenario. Drivers recorded the highest mean speed in the control condition and the lowest in the rotary controller condition. A box plot comparing speeds across the three conditions is shown in Figure 4.

There was a significant effect of condition on mean speed ($\chi^2(2) = 14.70, p < 0.001$). The mean speed in the rotary controller condition was significantly lower than in the control condition ($z = -3.21, p < 0.001, r = -0.51$); however, there was no significant difference between the touch screen and control conditions ($z = -1.33, p = 0.96$). Comparisons between the two IVIS showed that mean speed in the rotary controller condition was significantly lower than
in the touch screen condition ($z = -2.50, p < 0.05$, $r = -0.40$). Standard error speed was highest in the rotary controller condition, indicating wide variation in speed between users in the sample when interacting with this device. Speed was more consistent between users with the touch screen.

Lateral control

Lateral control was measured as the mean number of centreline crossings during each condition. A centreline crossing was recorded every time the wheels of the driver’s vehicle made contact with the other side of the roadway. Maintaining trajectory is one of the main driving tasks (Fuller 2005) and demands high visual attention in particular. If this attention is diverted to secondary tasks then performance will consequently suffer (Collet et al. 2010). A box plot comparing the number of centreline crossings across the three conditions is shown in Figure 5.

The highest rate of centreline crossings occurred in the rotary controller, followed by the touch screen and finally the control condition. The results showed a significant effect of condition on mean centreline crossings ($\chi^2(2) = 17.22, p < 0.001$). Compared with the control condition, there was a significantly higher mean number of centreline crossings by drivers in the touch screen condition ($z = -3.33, p < 0.001$, $r = -0.53$) and the rotary controller condition ($z = -3.44, p < 0.001$, $r = -0.54$). These results are consistent with findings from previous distraction studies (e.g. Lansdown et al. 2004, Jamson and Merat 2005). Of the two IVIS, the rotary controller condition produced the highest rate of centreline crossings ($z = -2.27, p < 0.05$, $r = -0.36$). As with other driving metrics, this degradation in lane-keeping performance is thought to be a consequence of reduced attention to the primary driving task. In contrast to the results of this study, Wang et al. (2010) did not detect any significant differences in longitudinal and lateral driving performance between the three IVIS that they tested. They attributed their result to the low level of demand induced by the secondary tasks in their study, which involved users entering a maximum of six characters for navigation entry. In the present study, the navigation and communication tasks consisted of the user entering longer alphanumeric combinations, resulting in a greater duration of secondary task demand. The frequency of task presentation in the current study is also likely to have increased workload, compared with the study by Wang et al. (2010). This study, as with other simulator-based experiments, was designed to compress the experience of secondary task interaction (Stanton et al. 1997), so that the magnitude of effect would be high, allowing usability issues to be identified more easily. In reality, drivers would never interact with such a high frequency of secondary tasks, in such a short period of time. This obviously will have affected the ecological validity of the current study; however, the researchers were interested in how effectively the methods could compare different systems and highlight usability issues and therefore the validity of the testing environment was not a particularly significant factor (de Winter et al. 2009).

Visual behaviour

The visual mode is the main mode of information presentation from system to human during primary driving (Wierwille 1993, Sivak 1996, International Organization for Standardization 2002, Brook-Carter et al. 2009, Victor et al. 2009). Drivers need to maintain a high level of visual attention to the forward road scene; however, they must time-share this attention with additional objects and events in the visual periphery, such as information displayed on an IVIS (Dukic et al. 2005, Pettitt et al. 2005, Pickering et al. 2007, Brook-Carter et al. 2009, Victor et al. 2009, Wang et al. 2010). The visual demand of secondary IVIS tasks will affect the level of interference with primary tasks and, consequently, the driver’s performance (Dukic et al. 2005, Wang et al. 2010). The visual behaviour of participants was monitored in each condition. For all participants, the majority of time during each trial was spent looking at either the forward road scene, which was defined as the left, right and front projector displays, or the LCD, situated within the vehicle, on which the GUI was displayed. For each condition, time spent looking at the road scene and LCD was measured and then calculated as a

Figure 5. Box plot of centreline crossings for the four conditions.
percentage of total trial time. The visual attention to the road scene for the three conditions is shown in the box plot in Figure 6. There were significant differences in visual attention to the road scene between the three conditions ($\chi^2(2) = 32.00, p < 0.001$). As expected, drivers spent a significantly higher proportion of time looking at the road scene in the control condition, compared with the two IVIS conditions (both IVIS-control comparisons: $z = -3.52, p < 0.001, r = -0.62$). The rotary controller condition also produced significantly less visual attention to the road scene than the touch screen ($z = -3.52, p < 0.001, r = -0.62$).

The LCD data showed that visual attention to the LCD was highest in the rotary controller IVIS condition. Visual attention to the LCD across the three conditions is shown in the box plot in Figure 7. There was a significant effect of condition on visual attention to the LCD ($\chi^2(3) = 30.13, p < 0.001$). Visual attention to the LCD in the two IVIS conditions was significantly higher than in the control condition (both IVIS-control comparisons: $z = -3.52, p < 0.001, r = -0.62$). In the rotary controller condition, visual attention to the LCD was significantly higher than in the touch screen condition ($z = -3.46, p < 0.001, r = -0.61$). The rotary controller IVIS produced the worst performance in terms of visual distraction, with highest attention to the LCD and lowest to the roadway. Wang et al. (2010) also identified their scroll-wheel input device as having the worst level of performance according to visual behaviour measures applied in their study. They identified the largest difference in visual behaviour between simulator and real driving environments for the touch screen IVIS. This result was attributed to the effects of glare in the real road driving condition, which increased visual demand to the IVIS. Glare would be likely to affect both interfaces used in the current study, under real road driving conditions, as they used the same LCD screen. In reality, the design of visual IVIS components can reduce the effects of glare, although this will be most difficult for the touch screen, because its LCD cannot be set back and shrouded from sunlight.

**Secondary task performance**

Secondary task performance measures reflect the effectiveness and efficiency of the interaction with an IVIS (Sonderegger and Sauer 2009, Harvey et al. 2011a). These measures were taken during the driving task to evaluate how well the input devices supported the driver–IVIS interaction when drivers were operating in a dual task environment.

**Secondary task times**

Secondary task times give an indication of the time that a driver spends without their full attention on the road scene. The more time a driver spends interacting with an IVIS, the higher the risk to safe driving (Green 1999, Wang et al. 2010). High task times also indicate low levels of IVIS effectiveness and efficiency. In each task, performance time was measured from when the driver selected the first IVIS option to when they selected the last option to complete the task. The task times reported in this study represent error-free tasks that were performed simultaneously with the primary driving task. When users made incorrect operations as part of a task, i.e. errors, the total task time was...
increased because of the additional time taken to make the initial error and then for the operations required to correct the error. As the errors made were not consistent across users, tasks that contained errors could not be used in the mean calculations and were therefore removed from the dataset. Tasks were being performed whilst driving and were therefore often interrupted, so drivers could attend to the primary task. Although the driving scenario was designed to be as consistent as possible, it was impossible to control for the amount of disruption across different tasks and different users. These task times should therefore be interpreted with some caution. The individual times are likely to be significantly longer than static task times and consistency between tasks, in terms of interruptions, is likely to be low; however, the magnitude of difference between mean task times and across the two IVIS is likely to be accurately represented by these results. For example, for both the touch screen and rotary controller, the results show that relatively simple tasks, such as increase bass and select CD, took considerably less time than more complex tasks, such as enter destination address and digit dial. Table 2 shows the mean and standard deviation task times for the 20 tasks performed using the touch screen and rotary controller IVIS. The removal of tasks that contained errors resulted in some task samples of less than 12, which were considered too small for meaningful statistical analysis (Nielsen 1993, Stevens et al. 2002). Only tasks with samples of 12 or more were analysed (using Wilcoxon tests for two related samples) and these results are also reported in Table 2.

The touch screen produced consistently shorter interaction times than the rotary controller. Contrary to the predictions made regarding the suitability of the different input devices to the different operation types, the rotary controller did not produce shorter interaction times for tasks that involved greater precision or repetitive operations. These results indicated that this method of input, i.e. turning the dial to highlight an option and pressing down on the dial to select the option, took more time than touching an option on the touch screen, irrespective of task type. In all but three tasks, the standard deviation task time was also larger for the rotary controller, indicating greater variability between users, compared with the touch screen. This is supported, in part, by the results of a study by Rogers et al. (2005), which compared task times across a touch screen and a rotary controller. This showed that with younger users task times were shorter for the touch screen for most task types that were assessed, including level adjustments and discrete selections. The picture was less clear for older users and for tasks that involved repetitive operations. As expected in this study, when a task coincided with an event in the road, task times were longer compared with the same task without the event. Reed-Jones et al. (2008) also reported an increase in secondary task times from a hazard-free driving

<table>
<thead>
<tr>
<th>Task Description</th>
<th>Touch Screen</th>
<th>Rotary Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Play radio station</td>
<td>30.70 (7.62)</td>
<td>12.42 (1.42)</td>
</tr>
<tr>
<td>Increase bass</td>
<td>10.34 (2.42)</td>
<td>26.18 (12.08)</td>
</tr>
<tr>
<td>Adjust balance</td>
<td>18.83 (17.3)</td>
<td>29.42 (13.92)</td>
</tr>
<tr>
<td>Select portable audio</td>
<td>9.91 (2.98)</td>
<td>29.81 (17.09)</td>
</tr>
<tr>
<td>Select CD</td>
<td>5.07 (1.05)</td>
<td>18.38 (9.19)</td>
</tr>
<tr>
<td>Increase fan speed</td>
<td>4.96 (2.39)</td>
<td>13.64 (6.79)</td>
</tr>
<tr>
<td>Increase fan speed*</td>
<td>12.60 (11.4)</td>
<td>26.91 (11.41)</td>
</tr>
<tr>
<td>Set air direction</td>
<td>14.29 (4.89)</td>
<td>45.16 (17.99)</td>
</tr>
<tr>
<td>Auto climate</td>
<td>4.52 (2.68)</td>
<td>8.43 (6.18)</td>
</tr>
<tr>
<td>Seat heat</td>
<td>8.46 (5.19)</td>
<td>22.63 (18.93)</td>
</tr>
<tr>
<td>Turn off climate</td>
<td>4.50 (2.51)</td>
<td>12.72 (4.18)</td>
</tr>
<tr>
<td>Enter destination address</td>
<td>27.34 (7.66)</td>
<td>71.37 (19.55)</td>
</tr>
<tr>
<td>Enter destination address*</td>
<td>46.09 (12.04)</td>
<td>107.63 (31.92)</td>
</tr>
<tr>
<td>Enter destination postcode</td>
<td>21.71 (2.83)</td>
<td>85.58 (40.42)</td>
</tr>
<tr>
<td>Digit dial</td>
<td>21.12 (1.15)</td>
<td>101.18 (86.54)</td>
</tr>
<tr>
<td>Call from contact list</td>
<td>11.43 (4.50)</td>
<td>31.93 (20.98)</td>
</tr>
<tr>
<td>Call from contact list*</td>
<td>29.28 (10.64)</td>
<td>32.21 (9.84)</td>
</tr>
<tr>
<td>Call from last 10 calls made</td>
<td>8.80 (2.67)</td>
<td>22.28 (8.68)</td>
</tr>
<tr>
<td>Call from last 10 calls received</td>
<td>10.54 (3.59)</td>
<td>25.95 (19.13)</td>
</tr>
<tr>
<td>Call from last 10 calls missed</td>
<td>9.19 (2.82)</td>
<td>23.69 (8.67)</td>
</tr>
</tbody>
</table>

*Repeated task to coincide with a roadway event.

Table 2. Mean and SD task times for error-free performance with touch screen and rotary controller in-vehicle information system.
scenario to a hazardous one, in which other road users entered the driver’s projected path. When a pedestrian was triggered to cross in front of the vehicle, participants either collided with the pedestrian or avoided it. Both outcomes had a negative effect on secondary task performance, which is reflected in the increased mean task times for the task/event combinations. For example, one participant performed the address entry task (without a concurrent event) in 27.5 s, which is close to the mean time for this task. In the address entry/pedestrian event combination task, the same participant collided with the pedestrian and was forced to interrupt the task to attend to the collision. This increased their task time to 63.3 s. Closer examination of the task revealed that there was an interruption of 31.2 s between two task steps: open destination entry menu; open address entry menu. At this point the participant was attending to the collision, rather than the task, and this contributed to a much longer task time. Another participant recorded times of 26.7 s and 36.8 s for the address entry task and task/event combination respectively. This participant managed to avoid colliding with the pedestrian; however, there was still an obvious interruption in the task (19.9 s), during which the participant was attending to the road in order to avoid the pedestrian. These examples support the conclusion that drivers were unable to successfully divide their attention between the primary and secondary tasks when primary demand was increased to a level above normal driving, i.e. by a roadway event. In tasks that did not coincide with an event, overall time was shorter and times between consecutive task steps were more consistent, indicating that the driver was able to divide their attention more effectively. In future work it will be useful to measure static task times, which can be compared to the dynamic times collected in this study, so that the effect of the dual task environment can be quantified.

Task errors

One of the requirements for an effective and efficient IVIS is a low error rate (Harvey et al. 2011a). Making an error means that the intended IVIS function will not operate correctly and will often require the user to identify the cause of the error and perform corrective operations (Card et al. 1983, Nielsen 1993). This increases the number of inputs into the system and the level of attentional demand required by the secondary task. Errors also frustrate users, leading to low levels of satisfaction (Jordan 1998). Error rates for each task are shown in Table 3. Errors are reported per task step: a task step was defined as each new selection of a different menu target. Longer tasks would be expected to produce more errors because there are more steps to successfully carry out; however, this would not reflect the actual difficulty of the task.

Based on previous findings, which support the suitability of indirect devices for precision and

Table 3. Mean and SD errors per task step for the touch screen and rotary controller in-vehicle information system.

<table>
<thead>
<tr>
<th>Touch screen errors/</th>
<th>Rotary controller errors/task step</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Play radio station</td>
<td>0.19</td>
</tr>
<tr>
<td>Increase bass</td>
<td>0.05</td>
</tr>
<tr>
<td>Adjust balance</td>
<td>0.03</td>
</tr>
<tr>
<td>Portable audio</td>
<td>0.00</td>
</tr>
<tr>
<td>Play CD track</td>
<td>0.00</td>
</tr>
<tr>
<td>Increase fan speed</td>
<td>0.00</td>
</tr>
<tr>
<td>Increase fan speed*</td>
<td>0.10</td>
</tr>
<tr>
<td>Set air direction</td>
<td>0.03</td>
</tr>
<tr>
<td>Auto climate</td>
<td>0.03</td>
</tr>
<tr>
<td>Reduce seat heat</td>
<td>0.02</td>
</tr>
<tr>
<td>Turn off climate</td>
<td>0.10</td>
</tr>
<tr>
<td>Enter destination address</td>
<td>0.02</td>
</tr>
<tr>
<td>Enter destination address*</td>
<td>0.03</td>
</tr>
<tr>
<td>Enter destination postcode</td>
<td>0.02</td>
</tr>
<tr>
<td>Digit dial</td>
<td>0.09</td>
</tr>
<tr>
<td>Call from contact list</td>
<td>0.07</td>
</tr>
<tr>
<td>Call from contact list*</td>
<td>0.04</td>
</tr>
<tr>
<td>Call from last 10 calls made</td>
<td>0.01</td>
</tr>
<tr>
<td>Call from last 10 calls received</td>
<td>0.01</td>
</tr>
<tr>
<td>Call from last 10 calls missed</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*Repeated task to coincide with a roadway event.
repetitive operations (Rogers et al. 2005), it was predicted that the rotary controller would produce fewer errors than the touch screen for alphanumeric tasks, including enter navigation destination and digit dial, and level adjustment tasks, including balance, bass, seat heat and fan speed. The results of the current study showed that the rotary controller produced a lower per-task error rate for the ‘play radio station’, ‘increase fan speed’ (with event), ‘turn off climate’ and ‘digit dial’ tasks. The fan speed and digit dial tasks involved high precision and/or repetitive operations and this result supports the prediction. However, the other tasks that were predicted to yield better results with the rotary controller actually produced a higher or equal rate of errors with this device. Error rates were compared using Wilcoxon tests, which showed that there were no significant differences between the touch screen and rotary controller.

Subjective measures: system usability scale

The SUS consisted of 10 statements about different aspects of product usability, against which users rated their agreement (Brooke 1996, Bangor et al. 2008). A single usability score for each IVIS was calculated from these ratings. A box plot comparing the scores is shown in Figure 8.

The SUS score for the rotary controller was significantly lower than the score for the touch screen ($z = -3.31, p < 0.005, r = -0.52$) and there was the least variation in this value, indicating a consensus of poor opinion among participants. This result is commensurate with the primary and secondary task performance measures, which showed the touch screen to have better performance and usability than the rotary controller. This indicates that the participants were able to use the SUS to successfully predict the trend in the results of the objective usability measures, supporting the use of both types of measures as part of the evaluation framework (Sonderegger and Sauer 2009, Harvey et al. 2011d).

Usability issues

The main aim of this study was to investigate the usability issues associated with two IVIS input devices, touch screen and rotary controller, so that designers can better understand how to improve the usability of these systems. Usability issues associated with the rotary controller, touch screen and the design of the GUI in general, together with their causal factors, are presented in Tables 4, 5 and 6 respectively. Causal factors distinguish whether the usability issues are attributed to the input device type, GUI/menu structure or a problem of input/GUI optimisation.

Rotary controller usability issues

Increased task times indicated that it took longer for the rotary controller to scroll between different menu items in order to reach the desired target, compared with moving the hand directly to a target. This was a feature of the device because the translation between controller input and on-screen movement took longer than direct movements of the hand to the touch screen, and also of the menu structure and layout, which, for some tasks, meant that the user had to scroll through a large number of menu options before reaching the target. The latter issue was a problem of GUI/device optimisation because the menus were not designed specifically for navigation with a rotary controller. In a

Table 4. Rotary controller usability issues and causal factors.

<table>
<thead>
<tr>
<th>Rotary controller usability issues</th>
<th>Causal factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect input, increased time for menu scrolling</td>
<td>Input device type (indirect)</td>
</tr>
<tr>
<td>Too many options to scroll through before target</td>
<td>GUI/menu structure not optimised</td>
</tr>
<tr>
<td>User must check progression towards target</td>
<td>Input device type (indirect)</td>
</tr>
<tr>
<td>Visual feedback not strong enough</td>
<td>GUI design not optimised</td>
</tr>
<tr>
<td>Unpredictability of movement through alphanumeric sequences</td>
<td>GUI/menu structure not optimised</td>
</tr>
<tr>
<td>Lack of rotary controller sensitivity</td>
<td>Hardware issue</td>
</tr>
</tbody>
</table>

GUI = graphical user interface.
The main aim of this paper was to investigate the usability of different input devices and therefore the usability issues of most interest are those that can be attributed to input type. This study highlighted two usability issues with the rotary controller input device:

- Increased time to locate and activate different air direction options. This is likely to have increased task time. Users also took a relatively long time to locate the audio balance option, which was one of the factors that increased task times associated with the ‘adjust balance’ task, compared with other level adjustment tasks, such as ‘increase bass’.

- Unnecessary complexity of air direction task. Observations also showed that the layout of buttons made the ‘air direction’ task more complex than it needed to be. Users had to work out that buttons needed to be pushed in order to deactivate, as well as activate, different air direction options. This is likely to have increased task time. Users also took a relatively long time to locate the audio balance option, which was one of the factors that increased task times associated with the ‘adjust balance’ task, compared with other level adjustment tasks, such as ‘increase bass’.

Optimisation of graphical user interface and input device

These results show that there were a number of usability issues associated with the rotary controller, the touch screen and GUI (which was used for both input devices). Some of these issues can be attributed to the fact that the GUI, and associated menu structure, was not optimised for use with the rotary controller. Whilst these issues can give a good indication of potential problems with IVIS, it is not fair to conclude that these are issues with indirect input devices in general, because in reality a GUI should be optimised for the input device associated with it. The lack of sensitivity found in both the rotary controller and touch screen should be attributed to the specific hardware used in this experiment and is not necessarily a true reflection of the sensitivity of touch screen or rotary controller IVIS used in vehicles today. This is not to say, however, that these issues are not important and designers should always take account of how hardware and GUI/menu optimisation could impact on usability.

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Graphical user interface/menu structure usability issues

There were also a number of task-specific issues, relating to the way certain tasks were presented via the GUI. A higher error rate for the ‘play radio’ task, supported by observations, showed that it was not clear to users that the Radio 4 preset option was located in a sub-menu of the AM/FM menu. Observations also showed that the layout of buttons made the ‘air direction’ task more complex than it needed to be. Users had to work out that buttons needed to be pushed in order to deactivate, as well as activate, different air direction options. This is likely to have increased task time. Users also took a relatively long time to locate the audio balance option, which was one of the factors that increased task times associated with the ‘adjust balance’ task, compared with other level adjustment tasks, such as ‘increase bass’.

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that go some way in explaining why performance was worse with this device, compared to the touch screen:

(1) The time required to translate the movement of the control into movements on screen to reach the target item increases overall task time, compared with moving the hand directly to an option.
(2) The visual demand associated with tracking the movement of a highlight or cursor through different menu items is increased, compared with visually locating a target and moving the hand directly there.

These usability issues relate to the nature of input, i.e. whether it is direct or indirect. The direct relationship between inputs and outputs is one of the main advantages of the touch screen and evidence of the benefits of this to secondary task interaction times and primary driving performance has been found in the current study. Previous studies have shown that the direct nature of touch screen input increases learnability and initial satisfaction with the device, compared with the rotary controller (Rogers et al. 2005) and this is also supported by the results of the current study.

The results of this study have shown that it is not only the design of the input device that affects the usability of an IVIS, but the optimisation between the input device and the structure and layout of the GUI. In this study the GUI was not optimised for use with the rotary controller for some of the tasks. This was because there was a need to have the same content and structure of tasks for both conditions; however, it also means that the results may not be an accurate reflection of performance for some of the rotary controller tasks. These tasks were those that involved some form of level adjustment and those that required relatively long sequences of alphanumeric entry. The rotary controller is ideally suited for level adjustment because the dial can be turned to increase/decrease on a continuous scale; however, in this study the rotary controller could only be used to select a plus/minus button and push down to increase/decrease. It is likely that rotary controller performance would have been improved for these task types had the GUI been designed specifically for this type of operation. The picture is less clear for alphanumeric entry because the rotary controller must still scroll through a large number of menu items in order to select a letter or number and this is a relatively inefficient process. It is likely, however, that a different GUI layout could improve this task for rotary input. For example, in the BMW iDrive, which utilises a rotary dial, letters for address input are arranged in a circle, which represents the movement of the rotary dial more accurately than presenting letters in horizontal lines. Further tests would be required to show if GUI optimisation can improve the performance of the two IVIS.

Implications
The participants had no prior experience of the two devices tested in this study and the findings therefore represent the interaction of novice users with the two IVIS. Nowakowski et al. (2000) reported a 64% increase in IVIS task interaction times with novice users, compared to expert users. This means that it may not be suitable to extrapolate the findings of the current study to users with more experience of IVIS. With experienced users, the rotary controller may demonstrate higher usability according to the measures applied here (Rogers et al. 2005) and this is something that needs to be taken into account in future applications of the evaluation framework. Taveira and Choi (2009) also expressed doubts about the usability of touch screens for older users, particularly in terms of accuracy and comfort. Rogers et al. (2005) reported findings that supported the use of rotary controllers for older adults, as this produced less performance variability, compared with a touch screen. The participant sample used in this study, with a maximum age of 33 and a mean age of 25 years, was not representative of the older driver population. Previous studies (Tijerina et al. 1998, Nowakowski et al. 2000) have found that older drivers take, on average, approximately double the time of younger drivers to perform IVIS navigation tasks, demonstrating an effect of age on IVIS interaction. Tijerina et al. (1998) also found that older drivers produced more centreline crossings and recorded more eyes-off-road time when interacting with IVIS navigation tasks, compared to their younger counterparts. Again, further studies would be needed to evaluate the usability of these two systems with drivers of all ages.

One of the main motivations underlying this work was to help designers identify and understand usability issues. The results show that the empirical methods used in this study were capable of distinguishing between the two IVIS in terms of primary and secondary task performance, visual behaviour and subjective usability. It has also been possible to identify a number of serious usability issues based on these results. In order to highlight these usability issues, the driving and secondary task conditions were exaggerated, producing a higher level of demand than would be expected during real driving. It is therefore important that the results, particularly for driving performance and visual behaviour, are interpreted within this context. They provide a relative prediction of usability between the two systems investigated,
rather than an absolute measure of the effect of interacting with the two systems on driving performance. This type of empirical testing is therefore recommended for relatively early stages in the evaluation process, when major usability issues still need to be identified with a sample of users. Later in this process it will be more appropriate to use testing conditions that can replicate real on-road driving more accurately, in order to identify more subtle usability issues and to produce absolute measures of performance.

Conclusions
Evaluating the usability of IVIS can help designers to understand the limitations of current systems through the identification of important usability issues. Harvey et al. (2011d) developed a framework for usability evaluation, involving the application of analytic and empirical methods. In this study, empirical methods were applied in the evaluation of two of the most commonly used IVIS input devices currently used by automotive manufacturers: touch screen for direct input; rotary controller for indirect input. The methods used in this empirical study make up a detailed, user-centred approach for investigating how different input devices affect performance with particular tasks and GUIs. This has enabled the identification of usability issues that are specific to input device types and also those that are related to other aspects of IVIS design, including GUI/menu structure and hardware characteristics. The usability issues associated with the direct and indirect input device types will be useful to designers who want to select the most suitable device, given the particular task in question. This study has highlighted the difficulty in evaluating input devices independent of GUI layout and menu structure and illustrates the importance of considering the optimisation between input device and GUI/menu structure in design and evaluation. Different input devices are more suited to particular task types and this points towards a multimodal solution for IVIS. Different menus within a single multimodal system will then need to be structured and presented in a way that is optimised for the intended input device in each case.

References


