Evaluating Virtual Reality 360 Video to Inform Interface Design for Driverless Taxis

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ABSTRACT

Autonomous, self-driving taxis are a commonly cited solution for future mobility but inevitably raise myriad human-centred design and usability challenges. However, conducting usability and user experience studies in imagined, future vehicles is troublesome, given the absence of safe, road-worthy exemplars (and indeed, recent COVID-19 restrictions). Applying a novel virtual reality (VR) Wizard-of Oz methodology, fifty-two participants were presented with immersive 360° videos (VR360-videos), which captured interactions with a range of potential human-machine interface (HMI) solutions, aiming to address vehicle identification and on-boarding tasks. Interactions and experiences were acted out by members of the research team, with potential HMIs and constituent tasks informed by a participatory design study, literature review and user requirements elicitation exercise also conducted by the authors. To evaluate the methodological approach, the VR360-videos were presented using either a VR-headset or laptop web-browser, with respondents offered the opportunity to participate in the laboratory or from their home, thus affording a 2×2 between-subjects study design with fixed factors of Method and Location. An overview of the user experience results indicated that all HMIs were generally received positively, with subjective ratings unaffected by Method or Location. Qualitative data suggested potential for greater immersion/presence using a VR-headset, although there were indications of higher "simulator sickness" using this approach. The study provides a novel methodology to deliver immersive user experiences for evaluation. Results will be used to inform HMI design and future evaluations associated with remaining journey stages (in-transit, arrival, payment etc.).

KEYWORDS

Autonomous taxi, virtual reality, 360 video, HMI design, usability

Introduction

Autonomous mobility services have the potential to make travelling in our cities safer, less congested, and more efficient, for example, by facilitating and improving traffic flow; removing the need for parking spaces in cities; and complementing mass public transport by providing first/last mile solutions (Merat et al., 2017; Krueger et al., 2016). Such services also address the need for a more sustainable transport and travel ethic, inviting users to move from conventional, single occupancy cars to shared, electric vehicles (Fagnant and Kockelman, 2014). However, this idealistic view of future mobility is predicated on the provision and successful integration of fully autonomous ("driverless") vehicles, such as "robotaxis". While significant effort and attention has been focussed on developing and harnessing the underlying technology to enable these vehicles to operate autonomously (i.e., without human intervention), there is limited established knowledge on how to make the experience feel safe, intuitive, and useful for users of the service. Exploring and understanding the appropriate form and function of the required human machine interfaces (HMIs) to enable this – and the nature of the experience they offer – is therefore paramount.

Needless to say, conducting “future technology” usability and user experience research is troublesome, not least in an automotive context where safety must prevail. Moreover, the recent COVID-19 pandemic has given short shrift to traditional, face-to-face usability testing. Thus, researchers have been encouraged to search further afield and to explore new and novel ways of conducting human-centred research activities. To this end, virtual reality (VR) provides a valuable tool to envisage and distil new and noteworthy experiences. VR affords a multitude of approaches, ranging from *technology-rich* experiences, aiming to immerse users within a persuasive virtual world, to *people-oriented* activities, in which factors to encourage presence (i.e., “being there”) are most important (Jerald, 2015). In usability and user experience contexts, it is arguably most important to consider VR in human-centred terms (see: Radianti, 2020 for a relevant discussion in the context of higher education). In other words, the aim of any applied VR methodology should be to encourage participants to believe that they are experiencing an interaction as a user might, not necessarily attempting to convince them that they are the actual user. To achieve this, it is important that the technical delivery of the experience is sufficiently immersive to encourage an appropriate level of presence, but it is participants’ perception of the experience that is most critical (see: Large et al., 2022; Burnett et al., 2021). The current study is predicated on this notion and was undertaken as part of ServCity project (https://www.servcity.co.uk/). The aim was to conduct informative usability and user experience research without the need to invest in high-end technology, or indeed intricate and time-consuming technical development, whilst maintaining real-world relevance and minimising the physical and COVID-19 specific risks to participants.

HMI Design

One of the most popular, proposed means of interacting with an autonomous taxi – given the current ubiquity of mobile phones – is via a smartphone application (or “app”). In this context, a user would be expected to install a (likely proprietary, but also potentially cross-operator) app to their phone and create a profile, including their payment details and various preferences, similar to existing ride-hailing services such as Uber (https://www.uber.com/gb/en/ride/). However, He and Csiszár (2020) highlight that the specific functionalities that will be required from a smartphone app for an autonomous mobility service are still missing from existing literature and proposed concepts. Existing ride-hailing services also tend to provide users with a text message or app notification to help them identify their vehicle. It seems reasonable to expect that such information will be even more critical for passengers of an autonomous taxi, where there is no driver present with whom to corroborate details, although the best method of delivery remains to be explored.

A visual interface (such as a digital display or touchscreen) is also expected to feature in an autonomous taxi, as the vehicle will likely need to visually communicate certain information to passengers, even if they control most of the journey experience through a smartphone app. A visual interface is also crucial for people who do not use or possess a smartphone, or do not wish to/are unable to use their phone (for instance, if the battery is out of charge). An autonomous taxi will therefore need to offer alternative means of communication, over and above an app. It is expected that an external visual interface will be important in confirming passenger and journey details, and an internal visual interface could capture and communicate journey-based information to passengers, whilst also providing entertainment and other customer service information.

There is a further, pervasive view that passengers will be able to interact with autonomous vehicles using a voice-based interface (Pettersson and Karlsson, 2015). Indeed, a voice/speech interface was preferred by the majority of older participants in the Flourish project trials (Shergold et al., 2019), with a display screen ranked second. Similarly, Huff et al. (2019) found that older participants expected voice-based interactions and indicated a preference for this type of interaction. A particular benefit of voice-based interactions is that they may be accessible to users with limited or no vision. Indeed, 71% of the thirty-eight vision-impaired participants who took part in the focus group study conducted by Brinkley et al. (2020) indicated that they expected an autonomous vehicle would be equipped with speech interaction capability, although some cautioned about the potential for errors based on existing, less than satisfactory, experiences with current voice-based exemplars.

Regardless, the nature of the task will also likely influence the most appropriate HMI. For example, a key consideration during vehicle identification and on-boarding tasks (explored during this study) is matching the correct taxi to the correct user. From a user's perspective, it is important that they can confirm that they have approached the correct taxi, but equally, the taxi must only allow access to the correct user. During a walk-through study by Kim et al. (2019), passengers waiting for an autonomous taxi gave this "confirmation" stage one of the lowest scores across usability measures since the autonomous vehicle looked similar to regular taxis and was thus difficult to identify. There is also a clear distinction between pre-booked and ad hoc taxi usage (for example, by hailing a passing vehicle). Notwithstanding the need to gain the attention of a passing autonomous taxi in situations where no driver exists with whom to make eye contact, the user may also need to provide further information, such as their desired destination and payment details. To support this, it is envisaged that a contactless smartcard, akin to existing travelcards or payment cards, could identify the passenger and relay payment details prior to securing the service and providing access.

Taking these factors into account, and informed by an participatory design study and user requirement elicitation exercise (see: Large et al., 2022; Hallewell et al., 2022), the following four methods were selected to enable vehicle identification and on-boarding tasks: mobile phone (via an app), a natural language voice interface, and an external touchscreen enabling the user to identify themselves using a unique code (assuming the service was pre-booked) or with a smartcard (assuming they were engaging the taxi on an ad hoc basis).

Method

Participants

Fifty-two participants took part, comprising 28 male and 24 female in the following age ranges: 18-24 (8), 25-34 (18), 35-44 (18), 45-54 (5), 55-64 (3). Potential participants were able to choose to take part at home or in the laboratory, and could use their laptop or a VR-headset to view the four interaction methods, although the location and method was agreed beforehand with the facilitator and remained consistent for each participant (e.g. if they choose home and laptop, all interactions were experienced in this manner). Only participants who were permitted to be on campus (as stipulated by current University COVID-19 regulations), were able to take part in the laboratory, and thus this cohort primarily comprised University employees and students. Recruitment continued until an approximately equal number of participants were obtained for each of the four conditions (i.e. VR/lab=12, VR/home=15, laptop/lab=11, laptop/home=14).

Stimuli Creation and Setup

Storyboards were created to define each of the four experiences (Figure 1). Experimental interfaces were subsequently created to demonstrate each experience/interaction method using a "Wizard-of-Oz" approach whereby participants were led to believe that the underlying technology is fully functional. A touchscreen was affixed on the front, side window of the vehicle, which remained stationary at the side of the road, as if waiting for its passenger. PowerPoint presentations were created to emulate the interactions and presented on the touchscreen. For the mobile phone, this involved scanning a *QR-code* displayed on the screen, which prompted a confirmatory message on the phone. For the *Keypad*, a 4-digit code was presented on the user's mobile phone (as if received from the taxi provider) and this was entered into a standard 10-digit keypad presented on the touchscreen. For the *Travelcard*, a dummy payment/travel card was created, and this was held in close proximity to the touchscreen akin to holding a contactless debit/credit card to a payment terminal. Finally, *Voice* interactions were created using an online text-to-speech generator (https://voicegenerator.io) and were accompanied by a sound wave visualisation and written text; these were saved as MP4 video files and incorporated into a PowerPoint presentation. To capture the experiences, a GoPro-Max 360 camera was mounted on the head of a researcher, who enacted each interaction (as described above). The resulting videos (Figure 2) were exported as 360° video files ("VR360 videos") using GoPro Player, then uploaded to YouTube. During the study, the VR360 videos were played directly from YouTube, either via a web-browser (for the laptop) or a dedicated app (for the VR-headset). Each video lasted approximately 60-seconds.

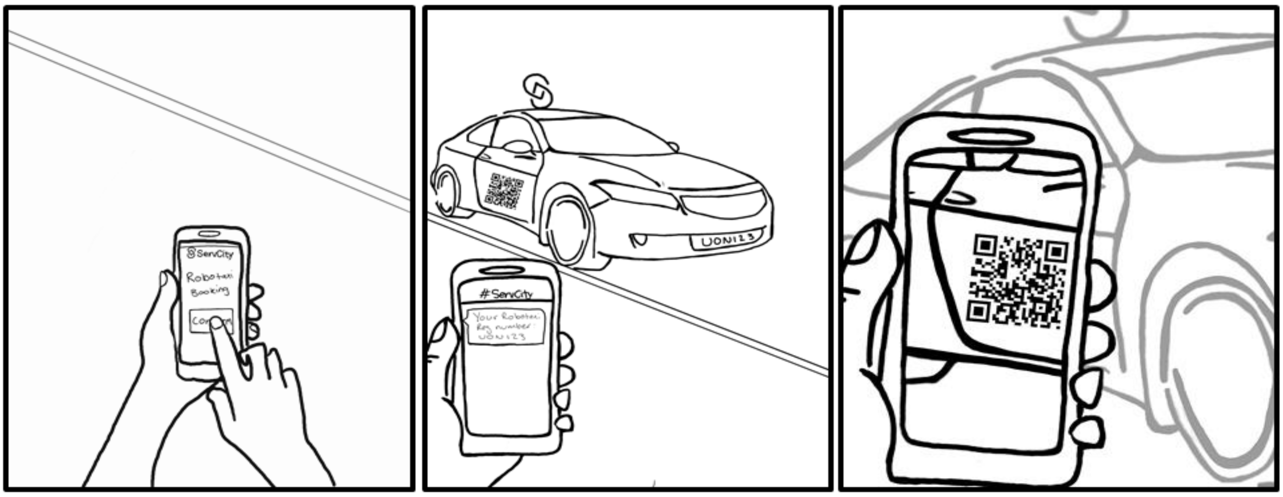

Figure 1: Storyboard depiction of mobile phone scanning a QR code to identify the taxi.

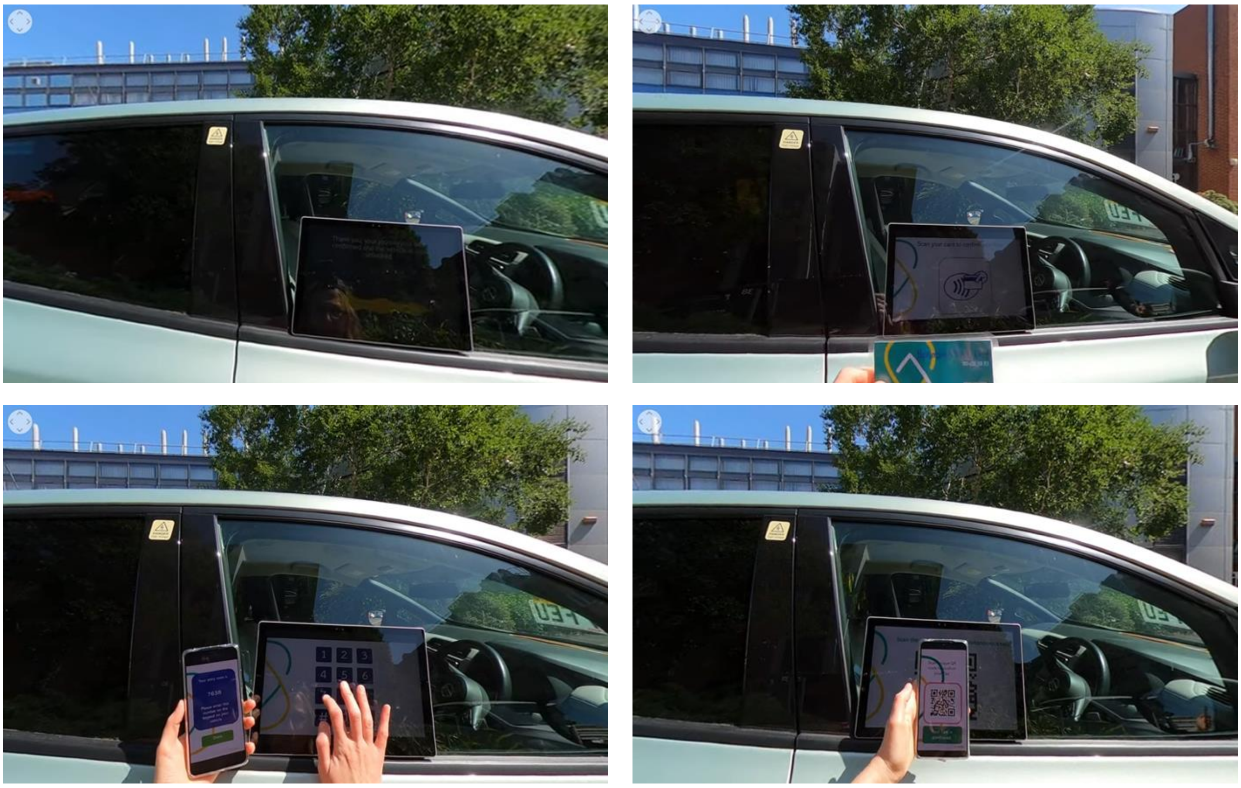

Figure 2: Screenshots from videos showing the four methods evaluated during the study: (clockwise from top, left) voice, travelcard, QR-code, keypad.

Study Design and Procedure

Participants who attended on campus ("in laboratory") were required to sign an online consent form prior to their attendance, which also confirmed their fitness to participate with regards to current COVID-19 regulations. A researcher accompanied and guided these participants throughout the study, ensuring that they met current social distancing regulations and guidance throughout. For those taking part remotely ("at home"), the researcher joined them on a Microsoft Teams call to provide support and guidance during the study. All participants viewed all four videos (with the order counterbalanced between participants) using their specified method (VR/laptop) and from their chosen location (home/lab). For "in lab" participants, an Oculus Quest 2 VR-headset or laptop was provided, as appropriate (with University approved cleaning procedures between participants); anybody taking part at home was required to use their own devices (i.e. laptop or VR-headset).

Measures and Analysis

Subjective ratings were captured using the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993), the User Experience Questionnaire (UEQ) (Laugwitz et al., 2008), the IBM Usability Satisfaction Questionnaire (USQ) (Lewis, 1995) and the Presence Questionnaire (PrQ) (Witmer and Singer, 199), as follows:

To rate the interface/interaction (i.e. voice, travelcard, QR-code or keypad),

1. Participants completed the UEQ and USQ after each 360° video experience.
2. After experiencing all four videos, participants ranked the interfaces/interactions in their order of preference from most preferred (1) to least preferred (4).

To evaluate the methodological approach (i.e., Method of Delivery and Location),

1. Participants completed the SSQ before and after each 360°-video.
2. After viewing all four videos, participants completed the UEQ and USQ. On this occasion, participants were instructed to evaluate the methodology and not the individual interfaces.
3. Finally, participants completed the PrQ, based on their overall experience.

The *UEQ* questionnaire contains 26 items presented on seven-stage semantic differential scales. Items are grouped to reveal 6 factors: Attractiveness, Perspicuity, Dependability, Efficiency, Novelty and Stimulation. Contributing items are summed (and reversed-scored where appropriate). Thus, higher values relate to a more positive user experience. For the *USQ*, only relevant items were selected (for example, *the interface of the system was pleasant, this system has all the functions and capabilities I expect it to have*). Items were presented as 7-point Likert scale ranging from Strongly agree to Strongly disagree. The mid-scale rating (4) was labelled Neither agree nor disagree. A mean rating was calculated taking all items into account. Scales were reverse-scored such that a higher rating indicated a more positive experience. For *Presence*, items are grouped to reveal 6 factors: Involvement/Control, Natural, Auditory, Haptics, Resolution and Interface Quality. In addition, a Total Presence metric is calculated by summing all items. For *Simulator Sickness*, a mean rating was calculated.

Results

To evaluate the interfaces, ratings were compared using one way, repeated-measures ANOVAs, with pairwise comparisons and Bonferroni corrections. To evaluate the methodological approach, ratings were compared using two-way ANOVAs with fixed factors of Method and Location. Presence ratings were compared with fixed factors of Method, Location, Age group and Gender. Simulator sickness ratings were analysed based on the Stage of the Study (recall, simulator sickness ratings were taken at the start and then after each of the four videos).

Comparing Interfaces/Interactions

For *User Experience*, no significant difference between *Interfaces* (voice, travelcard, keypad and QR-code) were revealed for Attractiveness, Efficiency and Stimulation factors. Significant effects were found for Perspicuity (F(3,49) = 3.427, $p = .024$, $\eta_p^2 = .024$), although when these were corrected for multiple comparisons, they were not significant. For Dependability, there was a significant main effect (F(3,49) = 3.625, $p = .019$, $\eta_p^2 = .182$), with pairwise comparisons showing that Voice was less dependable that Travelcard ($p = .038$) and KeyPad ($p = .033$). There was also a significant main effect for Novelty (F(3,49) = 8.944, $p < .001$, $\eta_p^2 = .354$), indicating that Voice was more novel than both Travelcard. ($p < .001$) and Keypad ($p < .001$). For *Usability Satisfaction*, there was no significant effect for Interface on mean usability rating. There were no significant effects for *Method and/or Location* on UEQ factors and mean USQ ratings associated with the interfaces. A pairwise rank analysis indicated that participants preferences were: 1st QR-code (rank order score: 86), 2nd Keypad (81), 3rd Travelcard (64), 4th Voice (53).

Comparing Methodological Approaches

There were no significant effects for Method and/or Location on any of the UEQ factors and no significant effects for Method and/or Location on mean USQ ratings.

For *Simulator Sickness*, there was a significant main effect for Method (F(1,243) = 6.552, $p = .011$, $\eta_p^2 = .026$), indicating that sickness ratings were higher when using a VR-headset (M = .10 / 4.0) compared to a Laptop (M = .06 / 4.0). There was also a significant effect for Age Group (F(4,238) = 2.816, $p = .026$, $\eta_p^2 = .045$), showing that participants in the age-range 35-44 years indicated higher ratings of simulator sickness than those in age range 18-24 ($p = .047$). In addition, there was a significant interaction between Age Group*Gender (F(3,238) = 6.194, $p < .001$, $\eta_p^2 = .072$) suggesting that female participants in the age range 45-54 experienced higher simulator sickness than those aged 25-34 ($p = .015$) and 55-64 ($p = .017$), and male participants in the age range 25-34 experienced higher simulator sickness than those aged 18-24 ($p = .02$) and 45-54 ($p = .041$). There were no significant difference based on Stage of Study. In other words, simulator sickness did not vary with increased exposure.

For *Presence*, there were no significant differences for ratings of Involvement/Control, Natural, Auditory, Resolution, Interface Quality and Total Presence. A significant difference was revealed for Haptics associated with Location (F(1,48) = .333, $p = .045$, $\eta_p^2 = .081$), suggesting that participants were better able to move and manipulate objects in the lab than at home. There were no significant differences in Presence associate with Age and Gender.

Comments from Participants

Participants were also asked to comment on their experience of participating in the study itself (their “likes” and “dislikes”) relating to factors such as the context (at home or in the lab) and the technology used (VR headset versus laptop). Responses were coded using a thematic analysis approach, first identifying types of response (positive or negative), and then collecting them into themes. Where quantitative details are included in parentheses, the number refers to references made to the code rather than number of participants, as some participants discussed multiple issues within a single response. The following, interconnected themes were identified: *the overall concept, the experience of participating, the methodology, the materials used*.

Participants commented positively on the ***overall concept*** of the research (i.e. autonomous vehicles/taxis) as well as the different interface concepts. Several participants mentioned that they thought the concept of autonomous vehicles (and associated technologies) was futuristic and innovative (5): *“The idea feels very futuristic, and it was exciting to be able to have glimpse of what* *this could look like in the future"*. Some participants liked the interfaces, suggesting that (2): *"Simple interfaces in the clips would enable a positive customer experience and ease of transaction"*. The novelty of the research approach was also noted (4) *"helping on a very innovative research idea"*.

Many positive comments were made about their ***experience of participating*** in the study, for example, indicating that people found participating in the study interesting (13): *"Topic is extremely interesting"* and *"It was interesting to see the different scenarios"*. Responses suggest that the experience of participating was engaging (4) *"Very engaging way to do it"*; enjoyable (9) *"I found the study rather enjoyable and exciting"*; immersive (1) *"VR headset made it feel a more immersive experience so easier to gauge the process"*; informative (1) *"The videos were informative and easy to understand"*; and interactive (2) *"It was quite interactive"*. On the other hand, the majority of responses relating to what participants disliked about the experience included issues with the equipment and process, including the VR-headset (3) *"The headset was heavy and therefore distracting from the scenario"*; motion sickness (3) *"The slight motion sickness"*; poor quality of the videos (4) (which may have resulted from connectivity problems) *"Poor video quality made it difficult to understand some aspects quickly"*; and the lack of interactivity (3) *"Not being able to interact i.e., tapping the smartcard or typing in the number myself"*. Interestingly, one person who participated in the laboratory noted that the results could have been the same had they participated from home, and another participant commented that they disliked the fact that they had been requested to participate via a laptop rather than VR headset.

Participants also commented on various aspects of ***the methodology***. For example, participants liked the use of VR (7) *"being able to look around in the virtual environment"*; the simplicity or ease of use of the method (6) *"all aspects simple to use and easy to understand"*; the ability to participate remotely (4) *"it was also cool that I was able to do it from home, since the entire thing is virtual"*; and that it was well planned (3) *"well thought through"*. However, the need to "measure" the experience (for the purpose of comparing approaches, presented herein) resulted in a significant number of questionnaires – relating to both the interface as well as the methodology, and in some cases, the same questionnaires were used for both. Moreover, as it often the case with standardised questionnaires, some questions/items were difficult to answer/rate in the context of the experience presented (5) *"Some of the wording of the questions took a while for me to understand"* and the amount of questions/repetition of questions for each mode of interaction (6) *"too many repetitive questions"*.

Participants recognised the value of ***the materials used*** to demonstrate each concept (9) *"The video scenarios were good and much better than someone explaining the process or reading about it"* and the realism afforded by the videos (4) *"It was visually realistic"*. However, two participants indicated that they felt that the interaction was too short *"Would have liked longer videos!"* and *"I was expecting the scenario to continue to other activities"*, and one participant pointed out *"the use of video rather than cartoon/ just a description encouraged focus on the specifics rather than overall concept"*.

Discussion

The study aimed to evaluate different HMI solutions proposed for autonomous taxi identification and on-boarding tasks, and to evaluate the use of VR360 video for this purpose. The candidate interfaces and experiences were informed by other research activities (see: Large et al., 2022; Hallewell et al., 2022) and literature (e.g. He and Csiszár, 2020; Kim et al., 2019; Shergold et al., 2019), but it is noted that these are not exhaustive and other exemplars exist, for example, a gestural interface.

A key challenge when evaluating any future technologies is the creation of a plausible experience such that the usability of the prototype/experimental interface does not detract from the usability of the proffered solution. Using VR360 video naturally affords the delivery of controlled and curated experiences, and thus avoids the need to develop an operational prototype (or indeed, face-to-face, in-person data collection). However, when creating the videos, there is a need to manage the tension between users' expectations of future functionality and capability – *based on their experience of current and early manifestations of the technology* – and developers' anticipated, future solutions. This challenge is exemplified by speech-based interactions, where developers are undoubtably working towards resolving difficulties in speech comprehension etc., but where poor usability of existing talking technology is often expressed (e.g. Brinkley et al., 2020) and may subsequently influence participants' views and opinions of the concept more broadly. Conversely, users are more likely to be familiar and satisfied with current mobile smartphones "apps" and therefore perceive the task of "scanning a QR-code" to be robust and reliable. This may have influenced participants' preference ratings – QR-code (effectively, using a mobile- smartphone app) was selected as the most preferred option, and voice interface as the least preferred. Nevertheless, all usability and user experience ratings were generally high, suggesting that any of the solutions may be plausible and worth pursuing.

Importantly, there were no significant differences in subjective ratings of usability and user experience revealed by the different methods or locations, suggesting that all four methods of presenting the VR360 video produced similar user experience data. Nevertheless, participants' comments hint towards more positive benefits associated with the VR-headset. For example, it was described as, "*more immersive*". Moreover, it was common that participants using a web-browser on their laptop were initially unaware that the video could be "dragged' to reveal a wider field of view (until prompted to "have a look around you" by the researcher), whereas a VR-headset naturally afforded this behaviour. Benefits associated with the VR-headset were not necessarily forthcoming in the ratings of Presence, however, though it is possible that the video was too short and insufficiently "interactive" to reveal differences. The slight increase in symptoms of simulator sickness and mention of poor comfort associated with the VR-headset is a concern, though not entirely unexpected. Even though all ratings were low (either "none" or "slight"), it is an area for further investigation. It is also worth noting that several participants encountered technical problems or commented on the poor quality of the videos. This is suspected to be an artefact of internet connectivity, though again will need to be addressed in future applications of the methodology.

Overall, it appears that using VR360 video provided a promising method to engage with novel, future interactive technologies (particularly when viewed using a VR-headset), and even raised further questions about the experience of using an autonomous taxi, as one participant contemplated: *"Can you divert your route? Can you ask for music or air con? Can you activate services or stop en route to pick up a friend if it's not pre-booked?"* These questions (and others) will be explored in future investigations.

Conclusion

Results support the use of VR360 video to showcase experiences and interactions with technology. The approach offers a viable alternative to traditional, "in-person" usability testing, and avoids the need to develop functional, "real-world" prototypes. It is relevant in situations where there is apprehension and reticence towards face-to-face testing (which remains the case following COVID-19), but also in situations where formative evaluations of early-stage conceptual designs (e.g., future, yet-to-be-realised technologies, such as autonomous taxis) may be required. In future studies, we aim to refine the methodology to evaluate interfaces and user experiences associated with other journey stages. Further work should also seek to understand how virtually-delivered experiences compare to traditional, real-world usability testing.

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