Abstract

Both laboratory and field experiments are flawed in their appropriateness for Human-Centered Design (HCD) user testing. Simulated Task Environments (STEs) offer a viable alternative, enabling researchers to recreate realistic conditions and immersive environments whilst controlling variables under laboratory conditions. This paper details the design process and technicalities used by a multi-disciplinary HCD research team to develop a reproducible low-cost immersive STE called the *Perceptual Experience Laboratory* (PEL). The research and development of the PEL in its three distinct stages is outlined to share the lessons learnt for the benefit of researchers and practitioners. In its current form, cylindrical media is surface-mapped on a bespoke 2m-high, 200° video wall to deliver seamless 12K enhanced field-of-view content around the user to visually recreate environments not normally accessible to researchers. The staging area can be configured with props and multisensory cues, simulating an in-context approach for HCD product testing. Additionally, immersive and realistic soundscapes are created via a 20.4 audio system equipped with spatial panners which provide directional sound. A growing number of commercial and academic research projects have been delivered using the PEL with research validating the user testing environment and its ongoing success attracting research and enterprise capital investments to advance immersive capabilities.

Keywords – Usability Testing; Human-Centered Design; Simulated Task Environment; Immersive Virtual Reality; Behavioral Insights.

1. Introduction

Early usability testing is imperative to ensure that designers understand consumer behavior and consequent innovation reflects this (Rubin & Chisnell, 2008). Laboratory testing is beneficial as it allows the recreation of situations and controlled testing repeatability. Despite this, laboratory settings are known for their limited generalizability and lack of ecological validity (Dahl~~, Alsos &~~ et al. ~~Syanæs,~~ 2010). Ecological validity is the extent to which a re-created environment induces behavior found in the field environment and relates to 'presence' (Deniaud~~, Honnet, Jeanne & Mestre~~ et al., 2015). Excluding extraneous factors means that concepts tested in a laboratory will lack applicability to a real-world context and findings are harder to extrapolate (Viglia & Dolnicar, 2020; Gadiraju et al., 2015).

On the other hand, field research exposes users to real-world contextual factors which may impact usability (Woolley, 2008). Context provides familiarity and allows individuals to ground themselves in what they are doing; whereas scenarios devoid of context can become abstract and produce artificial results (Riihiaho, 2017). Field research can be problematic because researchers are unable to rigorously control extraneous variables, resulting in distorted causations and correlations. Moreover, conducting tests in genuine clinical environments remains unethical because testing could negatively impact ongoing work concerning critical patients, plus patient confidentiality prevents any video and audio recording (Dahl~~, Alsos & Syanæs~~ et al., 2010; Hays & Singer, 2012).

Neither field nor laboratory usability testing scenarios are superior. Instead, Woolley asserts that both approaches should be applied at distinct stages of the design process. Although in-context testing has value early on, prototypes of computer-embedded products such as cameras, phones, kitchen appliances etcetera tend to be overly delicate and require too much laboratory support to be practically tested in the field (Woolley, 2008).

Virtual Reality (VR) has been used in its current format since the mid-1980s. VR Head-Mounted Displays (HMDs) fasten to the user's head, offering a wide field of vision, presenting imagery in both the central vision and the peripheral vision (Virtual Reality Society, n.d.). HMDs have successfully been used to provide psychological therapy for various disorders: schizophrenia, anxiety, substance-related disorders, eating disorders and a fear of heights (Freeman et al., 2017; Freeman et al., 2018). However, an issue with VR is that ~~they~~ it may cause 'cybersickness' or motion sickness issues such as eye fatigue, nausea and disorientation. Repeated exposure to the same VR environment can reduce feelings of sickness but this also poses an issue if the younger generation grows up with VR, as the surprise element and feelings of being present are lessened (Chang~~,~~ et al.~~Kim & Yoo~~, 2020; Slater & Sanchez-Vives, 2016). Despite this, HMDs provide an extremely cost-efficient solution for researchers (Ronchi~~, Mayorga, Lovreglio, Wahlqvist & Nilsson~~ et al., 2019). A fundamental issue with VR HMDs is that they isolate the wearer from their immediate environment and any physical devices being tested, preventing effective usability testing (Wang~~, Escobar, Da Mota & Velasco~~ et al., 2021).

More recently, VR has advanced into Simulated Task Environments (STEs) and Cave Automatic Virtual Environments (CAVEs). These testing environments present users with room-sized graphics to create an immersive experience that impacts senses wholly because the user's consciousness and entire body are involved (Greenguard, 2019). STEs and CAVEs allow researchers to maintain controlled laboratory conditions during testing of physical devices in a realistic context (Manjrekar et al.~~, Sandilya, Bhosale, Kanchi, Pitkar & Gondhalekar~~, 2014; Kjeldskov & Skov, 2007). Furthermore, generating video and Computer-Aided Design (CAD) environments is straightforward, with situations easily 'paused' whilst participant feedback is collected. Additionally, STEs are a valuable tool when field research places participants in an unethical situation. For instance, measuring drivers' drowsiness following no sleep by doing a 50-minute simulated driving task (Eoh et al.~~, Chung~~

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~~& Sim~~, 2005). Simulation sickness is negated in these larger room-scale set ups as any conflict between the visual and vestibular systems is avoided (Pan & Hamilton, 2018).

Berg and Vance (2017) collected data about the use of VR such as CAVE systems in industrial research from 20 companies and found that it had numerous uses, including evaluating the reachability of an exterior door handle, interior vehicle design and cockpit arrangements. Uses of CAVE systems vary widely from assisting individuals driving wheelchairs (Genova et al., 2022) to collaborative learning of neuroanatomy (de Back~~, Tinga, Nguyen & Louwerse~~ et al.~~,~~ 2020). Additionally, STEs have allowed researchers to study consumer behavior and reactions to different holidaying or tourism experiences (Martins~~, Gonçalves, Branco, Barbosa, Melo & Bessa~~ et al., 2017; Tussyadiah~~, Wang, Jung & tom Dieck~~ et al., 2018). Overall, research conducted using STEs is vast: driving research, elderly pedestrian road crossing, as well as operator training in medical, rail, aviation and maritime roles (Eoh~~, Chung & Sim~~ et al., 2005; Gallagher et al., 2005; Maillot, Dommes~~, Dang &~~ et al.~~ Vienne,~~ 2017; Rosen, 2018). Some studies have compared the field environment with CAVE systems to determine whether user responses were similar. For example, reading a map (Brade et al.~~, Lorenz, Busch, Hammer, Tscheligi & Klimant~~, 2017) and fear of heights (Gromer et al., 2018) both elicited the same responses in the field and within the CAVE.

When using STEs for training or usability testing, it is vital to replicate psychological fidelity to such an extent that users perform the same behaviors as they would in the field environment (Dahl et al.~~, Alsos & Syanæs~~, 2010). Elevated levels of fidelity often involve interactive elements which are more expensive and time-consuming to produce (Rudd et al.~~, Stern & Isensee~~, 1996). Fidelity is measured in two ways: (i) objective fidelity whereby the number of elements that are identical between the simulation and the field environment are mathematically calculated; and (ii) measurement of user's performance in the simulated set up compared to their field performance. Overall, a balance must be sought between levels of fidelity and obtaining the maximum transference of training or findings (Liu et al.~~, Macchiarella, & Vincenzi~~, 2008).

Although STEs yield more ecologically valid results in comparison to a plain laboratory setting, at low fidelity the STE risks creating discordance for participants (Gordon, 2007). Presence is defined as "the subjective experience of being in one place or environment, even when one is physically situated in another" (Witmer & Singer, 1998: p.225). STEs should be validated for the tasks they are intended to be used for as every experiment has its own requirements (Deniaud~~, Honnet, Jeanne~~ et al. ~~& Mestre~~, 2015). Yet, there is a gap in the knowledge surrounding optimal levels of ecological validation to induce presence together with a lack of quantifiable research on achieving participant 'presence' in a re-created environment.

Human-Centered Design (HCD) is based on understanding the needs, experiences, and desires of users to develop products, services and systems which are intuitive to use (Giacomin, 2015). An HCD-R (HCD-Research) group of multi-disciplinary individuals was established in 2002 to develop applied tools and approaches to assist HCD and effectively implement the processes used in product prototype usability testing within academic and commercial practice. As mentioned, neither field nor laboratory usability testing ~~are~~ is exclusively appropriate, so the HCD-R group identified the opportunity of using an STE to further explore the context of use in early product development (Woolley, 2008; HCD Research Group, n.d.). Subsequently, a prototype STE called the *Perceptual Experience Laboratory* (PEL) was developed by the HCD-R group to fill the void between traditional laboratory and field usability testing research. The culmination of academic and commercial research projects provided an informed research methodology to shape iterative versions of the PEL, which was primarily developed as a reproducible, low-cost facility to conduct applied user-testing in an immersive environment.

2. Research Methodology – The Development of PEL

Early STEs developed by the HCD-R group were low-fidelity and non-permanent fixtures (Gordon, 2007). The desire to achieve a sense of presence for participants and explore the context of use in early product development drove the HCD-R group to develop the PEL. Three iterations were developed from 2016 to 2021, described in this paper.

PEL-1 – Front Projection

The first PEL set up was manufactured on-site at a university and installed between four concrete support pillars. A custom plywood frame was cut using computer-numerically controlled machinery, backed with sound-deadening foam and branded on outwardly facing panels (Figure 1). A blackout canopy was installed to provide a dark projection space.

Figure 1. PEL-1 – External modular wall and inside set up.

Human binocular visual fields extend 180° horizontally, thus this was deemed the minimal lateral coverage to experience simulations in peripheral vision and augment presence (Strasburger et al.~~;~~

Rentschler, Ingo & Jüttner, 2011). Therefore, projection material was installed across the front and side walls, covering the sound deadening material, creating a seamless 180° lateral projection surface. The corners of the screen were curved to reduce the segmentation of the viewed media (Figure 2). Four 1080p (*In-Focus* 3200lumens) home cinema projectors were utilized in landscape mode, with two positioned on the floor projecting onto the side walls (blue grid, Figure 3) and two ceilings mounted at the rear of the room projecting across the front wall (green and red grids, Figure 3). *MadMapper* Video Jockey (VJ) projection mapping software was used to correct spatial distortions of projected media and blend overlapping edges so that media aptly matched the display surface. Problematically, users became blinded by the direct light from projectors and shadow silhouettes led to disorientation, reducing presence (Figure 2).

Figure 2. Projection method in use.

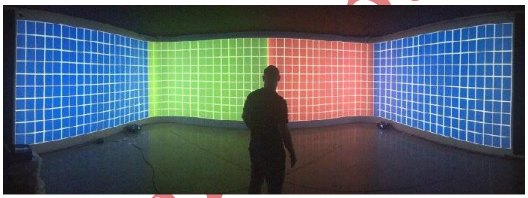

Figure 3. MadMapper VJ surface mapped projectors.

To overcome the aforementioned issues and maximize usable floor space, first-surface mirror assisted projection was introduced. Initially, acrylic half dome first-surface mirrors were purchased. These allowed close-range projection, with media reflected backwards over the projectors onto the display surface without obstructing the user's floor area. Unfortunately, these half dome mirrors had a high price-point and poor reflective quality. Image degradation and imperfections became substantial issues. The first-surface mirrors did not meet the requisite 180° lateral coverage and the surface mapping of media onto the projection surface increased in complexity due to the convexity of reflected media.

To expand the lateral coverage of media, the projection layout was reconfigured, and two first-surface mirrors were installed (Figure 4).

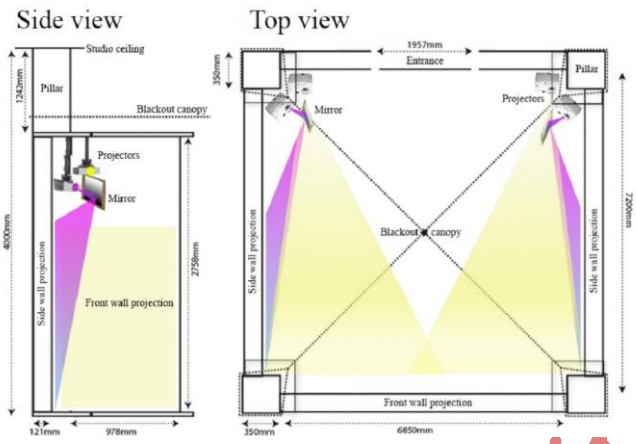

Figure 4. Projection paths using ceiling mounted first-surface mirrors and projectors.

This next iteration concerned installing projectors and flat first-surface mirrors at ceiling height in the back corners of the PEL-1. The midpoint overlapping projections were edge blended into seamless media on the front wall and extended coverage on both sides was created by positioning an angled mirror in front of both near-side projectors reflecting media inwards.

The new projector and mirror arrangement yielded the required 180° lateral coverage, enhanced the image quality, and compared to the half dome mirrors, surface mapping was simpler. Unfortunately, this projection method still caused media on the front display surface to be obscured with shadows, negatively impacting user presence. A potential solution was to heighten the elevation of the projectors, but the on-site location lacked sufficient ceiling space. Budgetary constraints at this time prevented the purchase of short-throw projectors to create a large picture from short distances.

PEL-2 – Back Projection Prototype

PEL-2 was driven by the desire to maximize user presence. The HCD-R group aimed to achieve consistent media quality across 180° of lateral coverage and users needed to be able to walk freely in the space without casting shadows across the projected media. Constraints included the need to utilize the already purchased projection technology and the room proportions.

Accordingly, design efforts switched to a rear projection set up and the first working iteration of a cylindrical projection environment was developed and prototyped. The cylindrical screen solved several interconnected obstacles, producing a unique projection experience that comprised:

- A freestanding cylindrical frame with 180° lateral screen coverage around the user.
- A screen that could be projected onto from the rear without casting silhouette shadows.
- Screen material attached under tension to create a crease-free projection surface.

- Specifications of the screen material were rigorously tested to remove the effects of hot spotting (caused when the line-of-sight projection is noticeably brighter than the surrounding area).
- Optimized screen performance using grey tinting to provide needed contrast to projected media within ambient light settings.

Projectors were rotated from landscape (PEL-1) to a portrait orientation to supply sufficient vertical coverage for standing users in PEL-2. The vertical extent of the human visual field is around 130°, with variance caused by an individual's facial features and expressions (Lachenmayr & Vivell, 1992). Thus, maximizing vertical coverage became paramount and two additional projectors were purchased, resulting in a six-projector video wall. Two corners of the room hosted three projectors which projected separate segments to fill 90° of the projection surfaces, either side of the mid-point. Each projection was surface mapped using *MadMapper* VJ and edge blended to produce unified media which suitably contoured to the 180° projection surface (Figure 5).

Figure 5. PEL-2 – Projector surface mapping.

Minimal rear vertical supports provided adequate structural integrity and maintained the tension of the projection material whilst avoiding obstruction of media projections. Approximately 70° was the maximum vertical coverage of viewable media for a standing user 175cm tall. The rear-projected media was sharp and could be viewed at close range without projection paths being obscured, improving immersive capabilities and positively impacting user presence.

Room proportions constrained the diameter of the semicircle projection surface plus the expanse of the floor space and user testing environment for staging props. Extant research has found that multi-sensory cues and props increase presence levels in STEs (Martins et al.~~, Gonçalves, Branco, Barbosa, Melo & Bessa,~~, 2017). Testing variables such as image resolution, sound, olfactory, temperature, air movement and accompanying props were undertaken.

A seaside tourism simulation was set up by the HCD-R group to test hedonic wellbeing. Relevant props were incorporated to provide a compelling contextual and immersive environment; a simulated beach environment was created using props such as beach sand, stones, a deck chair, and printed beach skirting (Figure 6). Electric fans generated a sea breeze, seaweed provided realistic olfaction and speakers played the sounds of seagulls and waves to further enhance presence in this tourism study (Baldwin et al., Haven-Tang, Gill, Morgan & Pritchard, 2021).

Figure 6. PEL-2 – Video media, allied props and multisensory cues created a seaside simulation.

Heartrate monitoring logged stress levels and participants completed the *Incredibly Short Profile of Mood States* (ISPOMS) questionnaire. Both the physiological responses and subjective questionnaire answers were triangulated, confirming that the PEL-2 set up was a robust method of measuring stress and mood as signifiers of hedonic wellbeing. However, feedback concerning presence highlighted that participants negatively reviewed their ability to view beyond the lateral and vertical coverage of projected media. Moreover, the audio quality was deemed too basic, and the room considered overly dark (necessary due to the low ambient light projectors) (Baldwin et al., Haven-Tang, Gill, Morgan & Pritchard, 2021).

Next, an outside simulation at optimal fidelity (staged with sound, olfactory, temperature, air movement and accompanying props) was observed alongside a matched real environment to establish the capability of the PEL-2 to convince users of environmental realism (Figure 7 & Figure 8). This Ecological validity study was developed by the UCD-R group to establish the 'relative validity' (the extent to which a virtual environment induces a parallel experience to that found in the field) of the PEL-2. If participants responded and behaved in PEL-2 as they did in the field, then the PEL-2 would have induced 'absolute validity' of presence, or 'being there.' Consequently, this would indicate that the set up has a prominent level of ecological validity (Gordon, 2021).

Figure 7. (Gordon, 2021): PEL-2 condition.

Figure 8. (Gordon, 2021): Field condition.

Gordon's (2021) study applied the non-invasive process of heart rate monitoring to provide a physiological indicator of presence (Meehan, 2001) and help substantiate relative validity (Deniaud~~, Honnet, Jeanne & Mestre~~ et al., 2015). However, heart rate monitoring cannot measure the quality of the involvement (Duffy, 1962). To address this limitation, the Face validity response (Kassab et al. 2011) and the *Positive and Negative Affect Schedule* (PANAS) questionnaires (Watson~~, Clark & Tellegan~~ et al., 1988) were used to supplement physiological data to discover the quality of participant involvement, and hence measure the level of presence (Guger et al., 2005; Dillon~~, Keogh, Freeman & Davidoff~~ et al., 2000). Face validity questions are recognized as a means of measuring 'presence' and allow interpretation of validity in a simulated environment, regardless of the medium used (Witmer & Singer, 1998; Kassab, 2011). PANAS is used to capture participant's 'emotional state' triggered by the different environmental conditions.

The study's heartrate data suggested that relative validity had been achieved for PEL-2. However, concerning recreating context, the Face validity data differed significantly as the PEL-2 environment did not absolutely replicate, nor induce the exact sense of presence as the field environment. It was identified that this result was because participants compared the PEL-2 as an identical replication of the real world. Nonetheless, participant responses to the PANAS questions demonstrated an improvement, with the PEL-2 achieving relative validity because the environment replicated enough likeness to the field environment to elicit certain emotions that were similar in both testing scenarios. Positively, participants commented that they felt 'surrounded' and immersed in the PEL-2 environment (Gordon, 2021). This study ecologically validated the PEL-2 in preparation for conducting usability studies.

Afterwards, a follow-up study was conducted to establish the optimum testing context for discovering product design flaws early in the design process. The PEL-2 was used to test a prototyped aircraft fuselage cleaning device in four varying fidelity levels of a simulated hangar. As expected, more usability issues were identified in the ~~higher~~ higher-fidelity test environments compared to the low-fidelity environments. Despite the low-fidelity STE being easier to set up, participants took longer to complete tasks, lacked meaningful product engagement and thus results were rendered less useful

(Gordon, 2021). The simulated context significantly affected the type of usability issues identified, with face validity and presence remaining strongest in the higher fidelity environments.

A further study with PEL-2 aimed to obtain an understanding of consumer presence within a supermarket context. Five immersive configurations of the same supermarket cereal aisle were simulated to determine the optimum level of presence (Lawrence, 2020). As well as altering the image fidelity, changes were made to sensory cues such as audio, bread scent spray and participants holding a shopping basket prop. Participants were given a task to simulate a shopping experience before completing a post-study questionnaire informed by the *Cross-Media Presence: ITC-Sense of Presence Inventory* (ITC-SOPI) (Lessiter~~, Freeman, Keogh & Davidoff~~ et al., 2001). It was found that the photograph of shelving with digitally overlaid packaging (hybrid photographic media) was well perceived by participants, and they did not notice the manipulated areas (Figure 9).

Figure 9. Cylindrical hybrid photographic media appears visually correct on the PEL-2 screen.

Hence, Lawrence (2020) provided media viability towards digitally modifying field environments to better suit a particular task or ameliorate product staging without seeking further permissions for on-site content creation.

In summary, high-fidelity configurations in both the above studies evoked the highest level of presence amongst participants (Gordon, 2021; ~~and~~ Lawrence, 2020). Research activities conducted within the PEL-2 have provided insight into user presence and sensitivity towards improving immersive capabilities with interactive elements such as sound, haptic and olfactory. A major limitation of the PEL-2 was that the locale was impacted by external noises, which negatively affected user experience and presence. This feedback helped validate the design and development of PEL-3.

PEL-3 – Current Commercial Prototype

Following the successful completion of several academic research projects, the PEL-2 was refined, upscaled, and a deliberate move was made towards increasing the off-the-shelf components to allow the PEL-3 to be more easily reproducible at a low-~~-~~ cost. To better meet academic and commercial activities, the PEL-3 was positioned in a new, dedicated space to improve the commercial identity, allow for better environmental control, and provide a higher level of security (and confidentiality for New Product Development (NPD)).

Ongoing developmental and user feedback from the PEL-2 highlighted the need to remove any out-of-context peripheral views of the room and the feeling that the simulated environment was being experienced through a window frame. The new location had a larger footprint, allowing the PEL screen to be increased vertically and extended beyond the former 180° lateral screen coverage. A priority target of 200° lateral coverage was set.

Moreover, the computer controlling the projectors was switched from the previous *iMac* system to a custom workstation which housed two high-end graphics cards, *Nvidia Geforce* (GTX) set up in a *Scalable Link Interface* (SLI). The SLI configuration improved matched display port connectivity across the six projectors and supplied additional display outputs to monitor and control the *MadMapper* VJ application plus other project applications.

Purchases included *Epson* projectors (EB-G7400U) with high lumen and resolution performance as well as dedicated short throw lens (ELPLU04). This new technology enabled studies to be conducted in higher ambient light conditions, allowing users to better interact with props. The short throw lens intensified projection resolution, enabling media to be extended further around the user, thus increasing media coverage in a standing user's visual field. The room dimensions and the location of six projectors (oriented in the landscape alongside the walls) were used in conjunction with short throw lens technical data to calculate video wall coverage inclusive of edge blending overlaps to produce 200° lateral coverage (Figure 10).

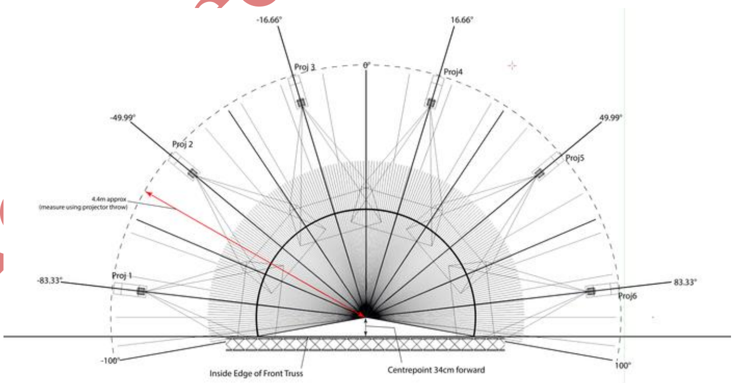

Figure 10. Throw calculations: projector locations and edge blending calculations.

To keep components off-the-shelf and replicable, commercial manufacturers ~~were~~ sought to supply the aluminum truss structure and fabricate the screen. The current cylindrical screen was developed from a freestanding light box and uses a 90mm deep aluminum profile. The top curved frame of the screen is secured to the ceiling truss structure and the bottom is secured to the floor, with two vertical profiles connecting these top and bottom profiles. Having a truss structure gives an illusion of a free-standing screen and was designed to allow uninterrupted rear projection paths. This was suitable for the installation of the improved projection material which was capable of utilizing maximum short throw coverage. Projection material was inserted under tension into the connection channel that runs throughout the frame system. The exhibition stage method of installation provides structural integrity to the frame components to withstand the tautness of the projection fabric. Floor-to-ceiling coverage was now a possibility in the PEL-3 and would reduce user's self-evident disconnect between the media boundary and staged props. This required refinement of the cylindrical frame profile whilst keeping the projection material under tension (Figure 11).

Figure 11. PEL-3 – Truss structure with custom cylindrical screen being rear projected.

Increasing the height of the STE was an endeavor to improve ecological validity and presence levels. The truss had a height of 2.5 meters, providing a 110° vertical extent of viewable media for a user 175cm tall standing centrally in the staging area. This was a marked improvement on the 70° provided by the PEL-2 design and significantly closer to the optimum 130° virtual field (Lachenmayr & Vivell, 1992).

The six projectors were mapped onto the rear surface of the cylindrical screen, aided by a mapping template image used to represent the width and length of the physical display. The mapping template was split into six equal segments, using a distinct color for each projector (Figure 12).

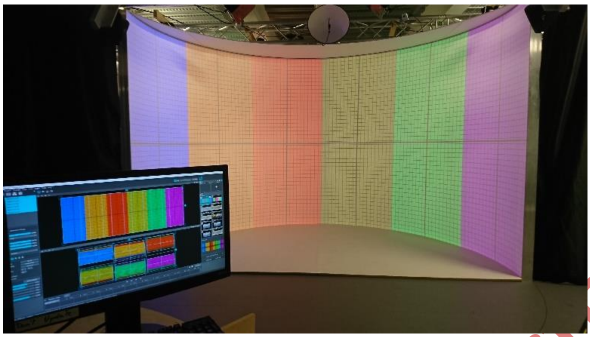

Figure 12. MadMapper VJ application showing surface template mapping.

A grid was applied across the mapping template, with each square being equal to 44 pixels (px), it demarks each color (projector) with 20 squares width by 45 squares height and a media template size of 1980px by 5280px. Additionally, the projectors were positioned with a 4-square overlay to produce a smooth edge blend across projections and aid in the seamless presentation of media. The mapping template grid was used to accurately surface map and edge blend each projector across the cylindrical screen, allowing environments to be presented as intended on the physical display using a matched media template (1980px by 5280px).

Bespoke media had to be created to fit the shape of the cylindrical screen. The most accurate method to do this necessitates a *Digital Single-Lens Reflex* (DSLR) camera and fisheye lens that captures a seamless, 180° wide-angle panoramic image. Using a fisheye lens avoids the need to stitch together multiple rectilinear camera lens photographs whilst also filling the projection screen more proportionately than typical panoramic media. Next, *Unity* game engine software is employed to directly convert fisheye media into a cylindrical projection format. This software delivers a real-time pathway to present and manipulate video and still media on the PEL screen (Figure 13). Integrally, the *Unity* platform allows the building of virtual environments and on-screen interactions using conventional gaming controllers.

Figure 13. PEL-3 – Cylindrical media rear projected onto the PEL screen to replicate real-life shopping aisle scenario for user testing.

Despite earlier PEL iterations hosting simplistic audio, the HCD-R group recognized the importance of incorporating more realistic environmental audio into the PEL-3. The focus was to increase user presence and augment ecological validity by creating a realistic soundscape through adding an Impulse Response (IR) pathway. An IR pathway would mean microphone input (user's speech) could be altered with the feedback of real acoustic spaces. To achieve this, an investment was made to deliver a bespoke *Ambisonics* soundscape. This Research and Development (R&D) project resulted in an immersive multi-speaker system that could integrate and synchronize with the media playback from existing linear and interactive video systems. Currently, twenty identical satellite speakers and four subwoofers (20.4 speaker array) are positioned around the PEL-3 screen to optimize sound distribution (Figure 14).

Figure 14. PEL-3 – Rear view photograph of the fixed position of speakers and projection technology.

Each subwoofer is associated with five satellite speakers. This compromises *Logitech Z-906 THX* certified 5.1 multimedia systems, chosen for their unparalleled price and performance. A controlling *iMac* sends audio to the speakers via a *MOTU LP32* audio interface and three 8-channel *Behringer ADA8200* analogue to digital and digital to analogue audio converters. This hardware configuration supports twenty-four discrete channels of audio input and output with the audio output channels used to feed the 20.4 speaker array (Figure 15).

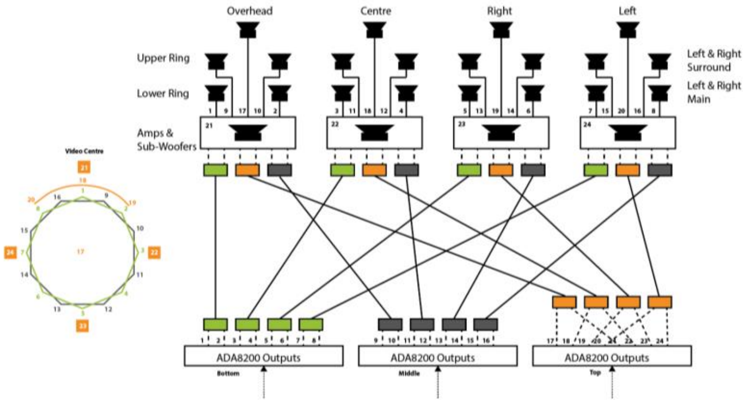

Figure 15. PEL-3 – Audio system schematic.

The audio system is driven by a custom software application called the *Array Processor.* It has been developed using *Max/MSP* from *Cycling74*; decoding *Third Order Ambisonics* (TOA) *B-Format* buss to derive the signals for the physical speakers in the array. Moreover, the *Array Processor* runs up to 16 channels of discrete audio inputs that are pre-set to virtualized speaker positions, supporting a range of standard multi-channel audio formats ranging from stereo through 5.1 and 7.1 surround formats, with the latest *3D Dolby Atmos* format.

The 'baked-in' movement of a sound from one side of a stereo image to the other, such as an insect, car or footsteps going past might not fit with the scene being presented. Usefully, the *Array Processor* can receive input from other audio applications running on the same computer via an internal audio routing application called *SoundFlower*. This enables a *Digital Audio* application to be used as a soundtrack development tool. When used in conjunction with linear video, the soundtrack and the TOA output (16 channel, Third *Order Ambisonics B-Format*) ~~is~~ are fed to the *Array Processor* internally via *SoundFlower*. For the soundtrack application to support TOA, the freely downloadable Facebook *FB360 Audio Workstation* suite of *Virtual Studio Technology* (VST) plugins is used. The *FB360 Spatializer* plugin is inserted on every track except for the master track and provides the individual controls (positioning and encoding) for sound effects to establish a location-based directional audio soundscape. The master track is used to define the dimensions and absorption characteristics of the overall acoustic space. For the decoder to work correctly, it is critical that the Azimuth, Elevation and Distance parameters (measured relative to the central listening position) are accurate as they define the mathematics of the decoding algorithm. Resultantly, operation of spatial panners enables interactive positioning of sound effects, increasing contextual relationships within the PEL.

All the above information relates to creating soundscapes for linear projects. Yet, soundscapes for interactive projects are created automatically within *Unity 3D* software. The audio output of *Unity 3D* is fed directly to the *Array Processor* for spatial decoding into the 20.4 speaker array.

Regarding the IR, in a supermarket simulation, this would involve the sonic measurement of sound in a food aisle in relation to a sound source. To enable the user to hear themselves in the acoustic space of the array, it was necessary to activate a microphone in the central listening position in the array whilst avoiding feedback from the speakers. Accordingly, a directional microphone with a parabolic reflector was used. The microphone is mounted above the central position of the screen, facing down at a predetermined head height of 175cm. The user's speech (microphone signal) is fed live into the soundtrack application (in a linear project) or into *Unity* (in an interactive project). Overall, where an IR is applied, this provides the user with the feedback of a real acoustic space. It is expected that being able to recall (or mimic) a field environment in this way will augment the ecological validity of simulations and enhance presence by allowing users to experience the way sounds alter in actual environments.

The greater fidelity of PEL-3 compared to PEL-2 needed to be tested to establish whether the ecological validity of a simulation and user presence had improved. The notion of revalidation is taken from previous research which references validating an environment for a specific use (Deniaud, Honnet, Jeanne & Mestre, 2015). As aforesaid, PEL-2 was compared with a matched field environment (Gordon, 2021). Therefore, it was important to test the PEL-3 with the same matched field environment in a repeat ecological validity study to ascertain the relative validity of the facility (Figure 16).

Figure 16. PEL-3 – Repeat ecological validity study set up.

A heightened sense of presence was attained in PEL-3 compared to the same set up in PEL-2. Positively, a superior ecological validity was achieved, with one participant stating that, 'PEL [-3] felt like I was in the outside environment' (Gordon, 2021). Further, the PANAS questionnaire and heart rate monitoring revealed no significant differences in the emotional responses of participants in either the PEL-3 or field environment conditions. This final iteration of the PEL achieved relative validity and exhibited improved levels of presence over the previous PEL-2 prototype.

Subsequently, with optimum fidelity authenticated through the above PEL-3 ecological validity study, another usability study was conducted. The purpose of this experiment was to confirm that critical product design flaws could be identified early in the HCD-R process. The *NextBike* (a bike rental service across the UK) was tested both in the field and the PEL-3 (Figure 17 & Figure 18).

Figure 17. NextBike usability testing: Eye-tracking glasses were used to study behavior in the field.

Figure 18. NextBike usability testing: Eye-tracking glasses were used to study behavior in the PEL-3.

Using a medium--fidelity prototype within the PEL-3 revealed a higher frequency of usability issues compared to the field environment, with no different issues found in the field. The results confirmed that the PEL-3 induced a 'good enough' presence and participants felt like they were in the real context of use. It was concluded that the PEL-3 can play a key role in facilitating context and identifying usability issues in the initial stages of the HCD process.

Following on from Lawrence's (2020) PEL-2 research into optimizing supermarket presence levels for the testing of packing designs, the PEL-3 was engaged in confirming a user testing methodology for commercial packaging design projects. The study considered the earlier limitations around field access – using supermarkets for field research – and explored the impact of hybrid CAD media (Lawrence et al., Loudon, Gill & Baldwin, 2019; Lawrence, 2020). This media was composed by generating CAD shelving and packaging on the original supermarket aisle photo (Figure 19).

Figure 19. Hybrid CAD media. (Lawrence, Loudon, Gill & Baldwin, 2019; Lawrence, 2020)

As before, participants were given a search task to simulate a shopping experience followed by a post-condition questionnaire informed by the ITC-SOPI alongside questions concerning enjoyment, likeability and believability (Lessiter~~, Freeman, Keogh & Davidoff~~ et al., 2001). Excluding 'believability,' no significant difference was perceived across the psychological variables. The study established that hybrid CAD media is a practical alternative to hybrid photographic media when creating STEs as it provides the researcher with greater control over content development without needing to seek permission for additional on-site visitation (Lawrence~~, Loudon, Gill & Baldwin~~ et al., 2019). However, the hybrid photographic media used in Lawrence's (2020) preparatory PEL-2 study was received as being more believable due to overlaid packaging not being detected; thus, it demonstrates a more robust media methodology to study packaging design iterations.

Another study was conducted to utilize the hybrid photographic media methodology, applying this to a commercial food packaging design project to provide key insights into consumer decision-making. A company's original and an alternative packaging design for a standard line of fresh produce were compared against competitors' packaging (Lawrence~~, Loudon, Gill & Baldwin~~ et al., 2019). This study investigated the commercial viability of using PEL-3 to conduct in-context supermarket packaging studies. Participants stood in the PEL-3 user testing area wearing eye-tracking glasses to record their attention throughout their shopping experience. Verbal responses to questions concerning their views on the graphical elements of the packaging designs were recorded. This PEL-3 study using hybrid photographic media methodology revealed key insights into consumer decision-making in response to alternative packaging designs. Robust design feedback was provided for the company and was used to inform further packaging development.

In two successive studies, these design insights were applied to the graphic elements of new packaging designs. The company provided a new packaging concept to test against their existing packaging and a retailer's own label in the fresh produce supermarket aisle (Figure 20).

Figure 20. The PEL-3 with hybrid photographic media of a supermarket fresh product aisle

Following the PEL-3 testing, participants discussed the rationale behind their responses. There was a consensus between the eye-tracking visualizations and participants stating that they preferred the new packaging design over the existing and supermarket own-label designs. This study validated that the current PEL could play a valuable role in the commercial packaging design process.

Discussion

The aim of developing the PEL was to build a new immersive research space that is easily replicable at a low cost for other research communities. Each of the three PELs increased in fidelity and led to higher levels of presence for the user. Compared to HMDs, the PEL avoids 'cybersickness' amongst participants and does not isolate individuals from the physical devices and context during testing (Pan & Hamilton, 2008). This paper demonstrates evidence in support of using STEs such as the PEL as a more appropriate and robust research method when field research is unavailable and laboratory research would be contrived (Patton, 2014).

Despite clear advantages of utilizing STEs, there is a lack of quantifiable research on achieving participant 'presence' in a re-created environment. This paper helps fill the pertinent gap in the literature. As evidenced, later iterations of PEL became more realistic which led to a greater sense of presence felt by participants (Patton, 2014). The HCD-R group utilized a widely used presence questionnaire to establish user's levels of presence in the PEL (Deniaurd, Honnet, Jeanne & Mestre et al., 2015; Krohn et al., 2020; Lessiter, et al.Freeman, Keogh & Davidoff, 2001; Slater et al., Lotto, Arnold & Sanchez-Vives, 2009). Ongoing assessments of presence during the various PEL iterations helped the HCD-R group identify areas of improvement, aiming to provide an immersive feeling of being in a real-world environment. Ongoing assessments of presence during the various PEL iterations helped the HCD-R group identify areas of improvement, aiming to provide an immersive feeling of being in a real-world environment.

Monitoring tourism in the field environment typically creates intrusion and inconveniences individuals (Viglia & Dolnicar, 2020). The PEL-2 successfully showed that a simulated tourism scene can connect people with a natural environment and can be used for measuring stress and mood as signifiers of hedonic wellbeing (Baldwin et al., Haven-Tang, Gill, Morgan & Pritchard, 2021). STEs have effectively been used to stir positive attitude change and increase visitation intention for destinations (Tussyadiah, Wang et al., Jung & tom Dieck, 2018). Additionally, the PEL-2 provided media viability towards digitally modifying supermarket packaging designs to better suit a particular task or ameliorate product staging without seeking further permissions for on-site content creation. This study also confirmed that higher fidelity contexts are associated with stronger measures of consumer presence (Lawrence, 2020).

Compared to the PEL-2, the PEL-3 exhibited advanced levels of presence and achieved relative validity with in a real-world context. The PEL-3 successfully induced presence to the extent that participants truly felt like they were in the context of use (Baldwin, Haven-Tang, Gill, Morgan & et al. Pritchard, 2021; Gordon, 2021; Lawrence, 2020). Moreover, the PEL-3 provided insight into using hybrid photographic media in an STE, validating the use of the PEL-3 in commercial food packaging design projects (Lawrence, 2020). PEL-3 was shown to be a robust academic research facility and a powerful marketing research tool for commercial companies. The capabilities of the PEL-3 continue to be explored by food safety researchers to gain insight into food safety practices, consumer behaviors and as a potential educational resource (Baldwin & Evans, 2020).

Initially, the PEL facility prioritized visual factors over audio, focusing attention and resources on designing and producing an immersive screen. Presence was then built upon by adding allied props and multisensory cues as previous research has found that real--world cues can improve presence (Lessiter, Freeman, Keogh & Davidoff et al., 2001; Martins, Gonçalves, Branco, Barbosa, Melo & Bessa et al., 2017). It transpired that the audio and haptic inclusion of holding a shopping basket containing cereal products in Lawrence's (2020) research revealed greater believability of the shopping context. Likewise, previous research concludes that an increased sense of immersion can be brought about by increasing sensory stimuli, reducing jarring for users (Dinh, Walker, Hodges, Song & Kobayshi et al., 1999; Murray, Ademoya, Chinea & Muntean et al., 2017). Sound effects can elicit emotional responses and sound augmentation has been found to enhance user engagement, particularly in an immersive context (Hillman & Pauletto, 2014).

Although olfactory was found to be the least prominent sensory cue, it was positively reported when noticed. Simulating environmental olfactory was identified as vital, because inclusion of scent improved presence levels within the PEL-3 (Lawrence, 2020). This finding is in support of the literature which found exposure of realistic olfactory stimuli increased the sense of presence in STEs

(Martins~~, Gonçalves, Branco, Barbosa, Melo & Bessa~~ et al., 2017; Munyann~~, Neer, Beidel & Jentsch~~ et al., 2016). Likewise, scent stimulates more psychologically influential memory recall than visual and verbal stimuli, so improving olfactory stimuli would be useful when the PEL is used for training (Chu & Downes, 2002; Herz, 1998).

The main advantage of conducting usability tests within the PEL in contrast to field testing is that extraneous variables can be more easily controlled, thus increasing the validity of the study. It is almost impossible to provide an equal level of realism when carrying out 'in vitro' laboratory studies. Nevertheless, 'in sitro' STE recreations that are as close as possible to the real-world context are advantageous because they allow researchers to maintain an elevated level of experimental control (Kjeldskov & Skov, 2007). Findings from the PEL studies provide valuable quality control details for a variety of applied STE research activities.

The authors are aware that some limitations remain with the PEL-3. Challengingly, the PEL-3 infrastructure and projection material of the cylindrical screen creates an acoustic barrier which impacts the audio performance of the *Ambisonics* speaker array. Ideally, any future iterations of the PEL facility will integrate the audio system within the R&D of the projection screen and supporting structure to curtail acoustic performance compromises to the immersive soundscape. Secondly, the user testing area remains rather small to stage props and for users to walk about because the projections point inwards. Overall, the HCD-R group ~~are~~ is willing to compromise on user testing space, instead of PEL concepts that undermine larger testing areas with shadow silhouetting, because they perceive the immersive payback of a shadow-free environment to be greater.

Conclusion

The PEL facility provides a robust user testing environment to conduct user testing, providing the benefits of laboratory settings whilst simulating real contexts of use. This technical account presents the development of a reproducible low-cost immersive environment. The PEL-3 is an unhindered space in which wearable eye-tracking and observation technology can be used to deliver an unbiased account of user behavior and product engagement. Presently, an academic tennis sports coaching experiment is being conducted to analyze the performance of opponent shots. The study benefits from the laboratory environment which ensures scenario repeatability, and the eye-tracking and observation technology enables assessment of decision-~~-~~making and movement efficacy. Several commercial food and drink NPD studies within the Welsh Food and Drink manufacturing community have utilized the PEL-3 set up to date.

Future anticipated work will include advancing the immersive capabilities and user presence. For example, olfactory improvements will be made by using the existing Unity platform to develop motion-–tracking capabilities that simulate scent dispensers. Further, the PEL facility could be upscaled to 300° to engage groups of users in a larger testing area – broadening the scope of PEL research. Lastly, underfloor projections would avoid unfavorable shadow silhouettes and provide a greater sense of immersion as well as reducing the time and cost involved in installing custom flooring.

References

Baldwin, J., & Evans, E. (2020). Exploring Novel Technologies to Enhance Food Safety Training and Research Opportunities. *International Association for Food Protection*. *40*(6), 456–463. https://doi.org/10.4315/1541-9576-40.6.456

Baldwin, J., Haven-Tang, C., Gill, S., Morgan, N., & Pritchard, A. (2021). Using the Perceptual Experience Laboratory (PEL) to simulate tourism environments for hedonic wellbeing. *Information Technology Tourism*. *23*(1), p. 45–67. https://doi.org/10.1007/s40558-020-00179-x

Berg, L., & Vance, J. (2017). Industry use of virtual reality in product design and manufacturing: a survey. *Virtual Reality*, *21*(1), 1–17. https://doi.org/10.1007/s10055-016-0293-9

Brade, J., Lorenz, M., Busch, M., Hammer, N., Tscheligi, M., & Klimant, P. (2017). Being there again – Presence in real and virtual environments and its relation to usability and user experience using a mobile navigation task. *International Journal of Human Computer Studies*, *101*, 76–87. https://doi.org/10.1016/j.ijhcs.2017.01.004

Chang, E., Kim, H. T., & Yoo, B. (2020). Virtual Reality Sickness: A Review of Causes and Measurements. *International Journal of Human-Computer Interaction*, 1658–1682. https://doi.org/10.1080/10447318.2020.1778351

Chu, S., & Downes, J. (2002). Proust nose best: Odors are better cues of autobiographical memory. *Memory and Cognition*, *30*(4), 511–518. https://doi.org/10.3758/BF03194952

Dahl, Y., Alsos, O. A., & Svanæs, D. (2010). Fidelity considerations for simulation-based usability assessments of mobile ICT for hospitals. *International Journal of Human-Computer Interaction*, *26*(5), 445–476. https://doi.org/10.1080/10447311003719938

de Back, T. T., Tinga, A. M., Nguyen, P., & Louwerse, M. M. (2020). Benefits of immersive collaborative learning in CAVE-based virtual reality. *International Journal of Educational Technology in Higher Education*, *17*(1). https://doi.org/10.1186/s41239-020-00228-9

Deniaud, C., Honnet, V., Jeanne, B., & Mestre, D. (2015). The Concept of "Presence" as a measure of ecological validity in driving simulators. *Journal of International Science*, *3*(1), 1–13. https://doi.org/10.1186/s40166-015-0005-z

Dillon, C., Keogh, E., Freeman, J., & Davidoff, J. (2000). Aroused and Immersed: The Psychophysiology of Presence. *Goldsmiths College Independent Television Commission*.

Dinh, H., Walker, N., Hodges, L., Song, C., & Kobayshi, A. (1999). Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. *IEEE Annual International Symposium Virtual Reality*.

Eoh, H., Chung, M., & Kim, S. (2005). Electroencephalographic study of drowsiness in simulated driving with sleep deprivation. *International Journal of Industrial Ergonomics*, *35*(4), 307–330. https://doi.org/10.1016/j.ergon.2004.09.006

Freeman, D., Haselton, P., Freeman, J., Spanlang, B., Kishore, S., Albery, E., Denne, M., Brown, P., Slater, M., & Nickless, A. (2018). Automated psychological therapy using immersive virtual reality for treatment of fear of heights: a single-blind, parallel-group, randomised controlled trial. *The Lancet Psychiatry*, *5*(8), 625–632. https://doi.org/10.1016/S2215-0366(18)30226-8

Freeman, D., Reeve, S., Robinson, A., Ehlers, A., Clark, D., Spanlang, B., & Slater, M. (2017). Virtual reality in the assessment, understanding, and treatment of mental health disorders. In *Psychological Medicine* (Vol. 47, Issue 14, pp. 2393–2400). Cambridge University Press. https://doi.org/10.1017/S003329171700040X

Gadiraju, U., Möller, S., Nöllenburg, M., Saupe, D., Egger-Lampl, S., Archambault, D., & Fisher, B. (2015). Crowdsourcing Versus Laboratory: Towards Human-Centred Experiments Using the Crowd. *Lecture Notes in Computer Science*. https://dx.doi.org/10.1007/978-3-319-66435-4_2

Gallagher, A. G., Ritter, E. M., Champion, H., Higgins, G., Fried, M. P., Moses, G., Smith, C. D., & Satava, R. M. (2005). Virtual reality simulation for the operating room: Proficiency-based training as a paradigm shift in surgical skills training. *Annals of Surgery*, *241*(2), 364–372. https://doi.org/10.1097/01.sla.0000151982.85062.80

Genova, C., Biffi, E., Arlati, S., Redaelli, D. F., Prini, A., Malosio, M., Corbetta, C., Davalli, A., Sacco, M., & Reni, G. (2022). A simulator for both manual and powered wheelchairs in immersive virtual reality CAVE. *Virtual Reality*, *26*(1), 187–203. https://doi.org/10.1007/s10055-021-00547-w

Giacomin, J. (2014). What is Human Centred Design? *The Design Journal*, 14(4), pp. 606–623. https://doi.org/10.2752/175630614X14056185480186

Gordon, B. (2007). *Emulation of Real-life Environment via Augmented Virtual Environment.* [MSc thesis, Swansea Institute of Higher Education.]

Gordon, B. (2021). *Keeping it real: The potential for accessible mixed-reality usability testing environments.* [Doctoral thesis, Cardiff Metropolitan University.]

Greenguard, S. (2019). Virtual Reality (The MIT Press Essential Knowledge series). *MIT Press.* https://doi.org/10.7551/mitpress/11836.001.0001

Gromer, D., Madeira, O., Gast, P., Nehfischer, M., Jost, M., Müller, M., Mühlberger, A., & Pauli, P. (2018). Height simulation in a virtual reality cave system: Validity of fear responses and effects of an immersion manipulation. *Frontiers in Human Neuroscience*, *12*(372), p. 372. https://doi.org/10.3389/fnhum.2018.00372

Guger, C., Edlinger, G., Leeb, R., Pfurtscheller, G., Antley, A., Garau, M., Brogni, A., Friedman, D., & Slater, M. (2004). Heart-Rate Variability and Event-Related ECG in Virtual Environments. In *Proceedings of the 7th Annual International Workshop Presence 2004* (pp. 240–245).

Hays, R., & Singer, M. (2012). *Simulation Fidelity in Training System Design: Bridging the Gap Between Reality and Training.* Springer, Berlin Heidelberg.

HCD Research Group. (n.d.). Retrieved July 12, 2023, from www.ucdresearch.com

Herz, R. S. (1998). Are odors the best cues to memory? A cross-modal comparison of associative memory stimuli. *Annals of the New York Academy of Sciences*, 670–674. https://doi.org/10.1111/j.1749-6632.1998.tb10643.x

Hillman, N., & Pauletto, S. (2014). The Craftsman: The use of sound design to elicit emotions. *The Soundtrack*, *7*(1), 5–23. https://doi.org/10.1386/st.7.1.5_1

Kassab, E., Tun, J., Arora, S., King, D., Ahmed, K., Miskovic, D., Cope, A., Vadwana, B., Bello, F., Sevdalis, N., & Kneebone, R. (2011). Blowing up the Barriers in surgical Training: Exploring and Validating the concept of Distributed Simulation. *Annals of Surgery*, *254*(6), 1059–1065. https://doi.org/10.1097/SLA.0b013e318228944a

Kjeldskov, J., & Skov, M. (2007). Studying Usability In Sitro: Simulating Real World Phenomena in Controlled Environments. *International Journal of Human-Computer Interaction*, *22*(1–2), 7–36. https://doi.org/10.1207/s15327590ijhc2201-02_2

Krohn, S., Tromp, J., Quinque, E. M., Belger, J., Klotzsche, F., Rekers, S., Chojecki, P., De Mooij, J., Akbal, M., McCall, C., Villringer, A., Gaebler, M., Finke, C., & Thöne-Otto, A. (2020). Multidimensional Evaluation of Virtual Reality Paradigms in Clinical Neuropsychology:

Application of the VR-Check Framework. *Journal of Medical Internet Research*, *22*(4). https://doi.org/10.2196/16724

Lachenmayr, B., & Vivell, P. (1992). *Perimetrie*. Stuttgart.

Lawrence, A. (2020). *Thought for Food: An evidence-led approach to improving Welsh food industry competitiveness*. [Doctoral thesis, Cardiff Metropolitan University.]

Lawrence, A., Loudon, G., Gill, S., & Baldwin, J. (2019). Simulated Environments for Food Packaging Design Assessment. *International Conference of Culinary Arts and Sciences*.

Lawrence, A., Loudon, G., Gill, S., Pepperell, R., & Baldwin, J. (2019). *Geometry vs Realism: an exploration of visual immersion in a synthetic reality space*. International Associations of Societies in Design Research Conference, Manchester, 2–5 September. Available at: https://iasdr2019.org/uploads/files/Proceedings/te-f-1248-Law-A.pdf

Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J. (2001). A Cross-Media Presence Questionnaire: The ITC-Sense of Presence Inventory. *Presence*, *10*(3), 282–297. https://doi.org/ 10.1162/105474601300343612

Liu, D., Macchiarella, N. D., & Vincenzi, D. A. (2008). Simulation fidelity. In *Human Factors in Simulation and Training* (Issue December 2008, pp. 61–74). https://doi.org/10.1201/9781420072846.ch4

Maillot, P., Dommes, A., Dang, N., & Vienne, F. (2017). Training the elderly in pedestrian safety: Transfer effect between two virtual reality simulation devices. *Accident Analysis and Prevention*, *99*, 161–170. https://doi.org/10.1016/j.aap.2016.11.017

Manjrekar, S., Sandilya, S., Bhosale, D., Kanchi, S., Pitkar, A., & Gondhalekar, M. (2014). CAVE: An emerging immersive technology -a review. *Proceedings - UKSim-AMSS 16th International Conference on Computer Modelling and Simulation, UKSim 2014*, 131–136. https://doi.org/10.1109/UKSim.2014.20

Martins, J., Gonçalves, R., Branco, F., Barbosa, L., Melo, M., & Bessa, M. (2017). A multisensory virtual experience model for thematic tourism: A Port wine tourism application proposal. *Journal of Destination Marketing & Management*, *6*(2), 103–109.

Munyann, I, Neer, S., Beidel, D., & Jentsch, F. (2016). Olfactory stimuli increase presence in virtual environments. *PLoS ONE*, *11*(6), 1–19. https://doi.org/10.1371/journal.pone.0157568

Murray, N., Ademoya, O., Chinea, G., & Muntean, G. (2017). A Tutorial for Olfaction-based Multisensorial Media Application Design and Evaluation. *ACM Computing Surveys*, *50*(5). https://doi.org/10.1145/3108243

Pan, X., & Hamilton, A. (2018). Why and how to use virtual reality to study human social interaction: The challenges of exploring a new research landscape. *British Journal of Psychology*, *109*(3), 395–417. https://doi.org/10.1111/bjop.12290

Patton, D. (2014). How real is good enough? Assessing realism of presence in simulations and its effects on decision making. In D. Schmorrow & C. Fidopiastis (Eds.), *Foundations of augmented cognition. Advancing human performance and decision-making through adaptive systems.* Springer, Greece.

Riihiaho, S. (2017). In Norman, K., & Kirakwski J. The Wiley Handbook of Human Computer Interaction. https://doi.org/10.1002/9781118976005.ch14

Ronchi, E., Mayorga, D., Lovreglio, R., Wahlqvist, J., & Nilsson, D. (2019). Mobile-powered head-mounted displays versus cave automatic virtual environment experiments for evacuation research. *Computer Animation and Virtual Worlds*, *30*(6). https://doi.org/10.1002/cav.1873

Rosen, K. (2018). The history of medical simulation. *Journal of Critical Care*, *23*(2), 157–166. https://doi.org/10.1016/j.jcrc.2007.12.004

Rubin, J., & Chisnell, D. (2008). *Handbook of Usability Testing. How to Plan, Design and Conduct Effective Tests. Second Edition.* Wiley Publishing, Indianapolis.

Rudd, J., Stern, K., & Isensee, S. (1996). Low vs. high-fidelity prototyping debate. *Interactions*, *3*(1), 76–85.

Slater, M., Lotto, B., Arnold, M. M., & Sanchez-Vives, M. V. (2009). How we experience immersive virtual environments: The concept of presence and its measurement. *Anuario de Psicologia*, *40*(2), 193–210.

Slater, M., & Sanchez-Vives, M. V. (2016). Enhancing our lives with immersive virtual reality. In *Frontiers Robotics AI* (Vol. 3, Issue DEC). Frontiers Media S.A. https://doi.org/10.3389/frobt.2016.00074

Strasburger, H., Rentschler, I., & Jüttner, M. (2011). Peripheral vision and pattern recognition: A review. *Journal of Vision*, *11*(3). https://doi.org/10.1167/11.5.13

Tussyadiah, I., Wang, D., Jung, T., & tom Dieck, M. (2018). Virtual reality, presence, and attitude change: Empirical evidence from tourism. *Tourism Management*, *66*, 140–154. https://doi.org/10.1016/j.tourman.2017.12.003

Viglia, G., & Dolnicar, S. (2020). *A review of experiments in tourism and hospitality*. Annals of Tourism Research. 80, pp. 1–15. https://doi.org/10.1016/j.annals.2020.102858

Virtual Reality Society. (n.d.). *Head-mounted Displays*. Retrieved December 5, 2020, from https://www.vrs.org.uk/virtual-reality-gear/head-mounted-displays/

Wang, Q. J., Escobar, F. B., Da Mota, P. A., & Velasco, C. (2021). Getting started with virtual reality for sensory and consumer science: Current practices and future perspectives. *Food Research Internationa*l, *145*(110410). https://doi.org/10.1016/j.foodres.2021.110410

Watson, D., Clark, L., & Tellegan, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scale. *Journal of Personality and Social Psychology*, 54(6), 1063–1070.

Witmer, B., & Singer, M. (1998). Measuring Presence in Virtual Environments: A Presence Questionnaire, Presence. *Teleoperators and Virtual Environments*, *7*(3), 225–240. https://doi.org/10.1162/105474698565686

Woolley, A. (2008). *Contextual testing of interactive prototypes at the early stages within the discipline of design* (Issue December 2008). University of Wales.

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