COMPUTER GAMES AS DISTRACTION FROM PAIN: EFFECTS OF HARDWARE AND DIFFICULTY ON PAIN TOLERANCE AND SUBJECTIVE IMMERSION

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ABSTRACT

Technology, such as computer games and virtual reality (VR), can be used to distract attention from pain. This type of non-pharmacological intervention is cost-effective, efficient and avoids complications arising from medication. However, the capacity of technology to capture attention and effectively distract from painful stimulation is determined by different factors related to the experience of immersion, such as: sensory immersion, i.e. the audio-visual presentation of the digital world, and challenge-based immersion, i.e. effortful engagement with goals in the digital world. Four studies were performed to explore the influence of both sensory and challenge-based immersion on pain tolerance using computer games in combination with the cold pressor test. Study One (N=30) explored sensory immersion by contrasting pain tolerance during gameplay using VR display, 2D head-mounted micro-display and flatscreen TV, but no significant effect of display type on pain tolerance was observed. Study Two (N=70) manipulated challenge-based immersion and reported a significant increase of pain tolerance when participants played a highly-demanding game compared to a game with low demand. Study Three (N=60) simultaneously manipulated sensory immersion via screen display size (40" vs 9") and challenge-based immersion (game demand); pain tolerance increased in a linear fashion with demand but no significant effect of display size was reported. The fourth study (N=40) also manipulated both forms of immersion via systematic manipulation of game music/sound volume (11.6 vs. 57.8dB) and game demand, no effect for audio volume was observed but pain tolerance increased when the game was highly demanding. All studies included measures of cardiovascular psychophysiology and a subjective index of immersion. Analyses of the relationship between measures revealed that greater autonomic activation exerted a direct, positive effect on pain tolerance, i.e. higher activation = greater pain tolerance. It is concluded that challenge-based immersion is the primary means by which technology can distracts attention from pain.

KEYWORDS: Pain; Attention; Games; Distraction; Immersion; Psychophysiology

INTRODUCTION

Distraction is a common technique used to increase pain tolerance and reduce emotional distress during clinical procedures, particularly in paediatric medicine (Koller & Goldman, 2012). It has been argued that technology, particularly games and Virtual Reality (VR) experiences, can distract from pain by drawing attention from painful stimuli (Law et al., 2011; Wohlheiter & Dahlquist, 2013). The utility of VR as a form of distraction therapy has been extensively reviewed (Malloy & Milling, 2010; Turner & Casey, 2014), particularly for painful procedures related to the treatment of burns (Morris, Louw, & Grimmer-Somers, 2009).

The neurocognitive perspective on attentional processes and pain (Eccleston & Crombez, 1999; Legrain et al., 2009) provides an explanation of how technology can distract attention from pain. Attentional engagement with the game is characterised as a top-down process, wherein task-specific stimuli are prioritised for action preparation (Allport, 1987). The presence of pain exerts an interruptive influence on this process (Eccleston & Crombez, 1999) leading to competition between top-down attention to task-relevant stimuli and bottom-up orientation to a painful sensation (Legrain et al., 2012). The resulting antagonism has been extensively explored in pain research; for recent summary, see (Torta, Legrain, Mouraux, & Valentini, 2017).

According to this neurocognitive perspective, any analgesic effect of technology is achieved by activating top-down attentional engagement as an integral part of the human-computer interaction. With respect to VR, engagement with the virtual world is achieved by creating a convincing illusion of spatial presence (Slater, 1999), which captures top-down attention and completely dominates the visual and auditory senses of the user. In the case of conventional computer games, top-down attention is engaged in a graded fashion by the degree of challenge presented to the player, which has been characterized as immersion (Jennett et al., 2008). Immersion was described as three stages of attentional focus on game-related stimuli, which are: (a) engagement (minimal effort investment to play), (b) engrossment (significant investment of attention and emotional involvement) and (c) total immersion (a state of complete involvement where players feels as though they are 'in the game') (Brown & Cairns, 2004); see Cairns, Cox, & Nordin (2014) for review of immersion and game play experience.

The potential of technology to create a sense of total immersion, when distraction from pain is maximised, is influenced by the technical characteristics of the hardware used to render the digital world and the level of immersion with the digital task (McMahan, 2003). In their analysis of gameplay experience, Ermi & Mayra (2005) made a distinction between: (a) sensory immersion (i.e. the audio-visual rendering of the digital world), (b) challenge-based immersion (i.e. level of cognitive and motor skill required to play the game) and imaginative immersion (i.e. emotional responses to story-telling, characterisation). Given the multifaceted nature of immersion as gameplay experience, which aspect is most important for a game to function effectively as a distractor from pain?

Sensory immersion describes the technical fidelity of hardware to accurately render the game world. For example, creation of the place illusion in VR is totally dependent on the technical quality of the display hardware, e.g. field of view, update rate, tracking movement (Cummings & Bailenson, 2016). With respect to conventional visual displays, a greater degree of immersion is associated with increased screen size (Hou, Nam, Peng, & Min Lee, 2012; Van Den Hoogen, IJsselsteijn, & De Kort, 2009; Wu & Lin, 2011). A number of related studies have found that head-mounted displays (HMD) are experienced as more immersive than flatscreen displays, as the HMD completely occupies the visual field (Bowman & McMahan, 2007; Schnall, Hedge, & Weaver, 2012; Tyndiuk, Lespinet-Najib, Thomas, & Schlick, 2004). The study conducted by Zeroth Julia, Lynnda, & Foxen-Craft Emily (2018) is particularly relevant to the current work, these authors utilised the cold pressor test, i.e. participants are required to immerse a limb in cold water until the resulting pain is unbearable, to study the effect of HMD vs. standard television displays on pain tolerance; they reported a reduction of pain for participants in the HMD condition. However, a number of experimental pain studies failed to replicate this advantage for HMD (Armstrong, Law, Sil, & Dahlquist, 2010; Gordon, Merchant, Zanbaka, Hodges, & Goolkasian, 2011; Sil et al., 2014). The graphical fidelity of the HMD is another dimension of sensory immersion that can also influence the effectiveness of VR to distract from pain with several studies reporting reduced pain relief when a low-fidelity HMD was used (Hoffman et al., 2004; Mosso Vázquez et al., 2018).

The auditory characteristics of the digital world is an important influence on the level of sensory immersion experienced by a player. Previous research has demonstrated increased immersion during gameplay with the addition of sound and music (Gallacher, 2013; Gormanley, 2013; Zhang, Jiulin & Fu, Xiaoquing, 2015). The introduction of music also increases emotional responses to events within a computer game (Abia & Caroux, 2019; Klimmt et al., 2019). With respect to research on the relationship between audio and pain, animal research has argued for a dose-dependent relationship between noise intensity and analgesia (Helmstetter & Bellgowan, 1994). In addition, exposure to music during painful experience has been found to reduce subjective pain (MacDonald, Kreutz, & Mitchell, L., 2012) and there is neurophysiological evidence for modulation of the pain response when the experience is paired with music (Dobek, Beynon, Bosma, & Stroman, 2014). Music and noise both distract the experience of pain (Boyle, El-Deredy, Montes, Bentley, & Jones, 2008; Finlay, 2014) and increase pain tolerance during the cold pressor test (Choi, Park, & Lee, 2018). There is also evidence that characteristics of the musical piece can influence observed effects of pain; for example, Kenntner-Mabiala, Gorges, Alpers, Lehmann, & Pauli (2007) reported that fast tempo music increased autonomic activation and enhanced subjective ratings of pain, but this effect was only observed in female participants.

Challenge-based immersion is related to the level of effortful engagement with task-related goals (Fairclough, Gilleade, Ewing, & Roberts, 2013) and is tied to a motivational perspective on gameplay (Przybylski, Rigby, & Ryan, 2010). According to this perspective, top-down attentional engagement with goals is a necessary precondition for challenge-based immersion, for similar explanations, see: Chanel & Rebetez (2008), Ewing, Fairclough, & Gilleade (2016) and Nacke & Lindley (2008). A state of high attentional engagement with task-related goals characterizes a state of total immersion, which is associated with 'flow' (Csikszentmihalyi, 1990); see Michailidis, Balaguer-Ballester, & He (2018) for recent discussion of relationship between immersion and flow. However, it should also be noted that challenge-based immersion only occurs during the active investment of mental effort, and effort is only invested in response to increased demand if success is perceived to be achievable (Richter, Gendolla, & Wright, 2016). There is evidence that neurophysiological markers of effort are reduced when players faced with an impossible level of challenge during a computer game (Ewing et al., 2016). Hence, the potential of challenge-based immersion to distract from pain is dependent on the relationship between game demand and the skills of the player to meet those demands (Cowley, Charles, Black, & Hickey, 2008; Cox, Cairns, Shah, & Carroll, 2012), see also the "perceived-challenge-skill-balance" as described by Keller & Landhäußer (2012). The challenge-based dimension of immersion may incorporate additional psychological elements (Boyle, Connolly, Hainey, & Boyle, 2012), such as the demonstration of mastery, which enables players to persist in the face of repeated failure (Anderson, Campbell, & Steinkuehler, 2019) and strong emotional states (Mekler, Rank, Steinemann, Birk, & Iacovides, 2016). Emotional responses to game content and performance outcomes, particularly adverse states like anger or frustration, may be highly significant in this context, as negative emotions can exert a priming effect that enhances attention to painful sensations (Pourtois, Schettino, & Vuilleumier, 2013a).

The research literature on gaming demonstrates that higher levels of demand or challenge are associated with increased immersion (Burns & Fairclough, 2015; Cox et al., 2012; Qin, Rau, & Salvendy, 2010). With respect to the influence of challenge-based immersion on pain perception, few studies have systematically manipulated game demand to distract from painful sensations. The study conducted by Piskorz & Czub (2013) is one exception, these authors reported a reduction of subjective pain when participants performed VR tasks of high complexity vs. low complexity.

The current paper presents four experiments conducted to explore how sensory and challenge-based immersion influence the perception of experimental pain during a computer game. All studies utilised the Cold Pressor Test (CPT) (von Baeyer, Piira, Chambers, Trapanotto, & Zeltzer, 2005) as a protocol for experimental pain. This protocol was selected because it is possible to derive a behavioural measure of pain tolerance, i.e. the duration of time for which the participant can immerse the limb in very cold water. It was predicted that increased sensory and challenge-based immersion would enhance pain tolerance. The experiments were performed in a linear fashion in order to explore four hypotheses, which were:

1. Is pain tolerance increased when the game is presented via an HMD capable of rendering an immersive, three-dimensional presentation of the game world due to sensory immersion (Study 1)?
2. Does an increased level of game demand enhance the level of pain tolerance exhibited by participants due to challenge-based immersion (Study 2)?

3. When challenge-based and sensory immersion (visual display) are simultaneously manipulated, does increased game demand and screen size induce higher levels of pain tolerance (Study 3)?
4. When challenge-based and sensory immersion (game audio) are simultaneously manipulated, does increased game demand and louder levels of game music/sound effects lead to higher pain tolerance (Study 4)?

In addition to a behavioural measure of pain, all four experiments included a subjective measure of immersion and a cardiovascular measure to quantify the level of autonomic activation.

All experimental procedures reported in this paper were approved by our Institutional Research Ethics Committee prior to data collection. Due to the nature of the cold pressor test, exclusion criteria for participation in any of the four experiments included a history of: cardiovascular disease, fainting, seizures, chronic or current pain, Reynaud's disease or diabetes. Individuals who were pregnant or had fractures or open cuts or sores on the feet or calves were also excluded from participation.

STUDY 1

Study 1 was designed to explore the influence of display hardware on pain tolerance, subjective immersion and autonomic activation. It is hypothesised that playing a game in VR will increase pain tolerance, subjective immersion and heart rate compared to the flatscreen condition due to immersive properties of a 3D display (hypothesis 1).

Method

Design: The experiment was conducted as a between-participants design with three categories of hardware platform: flatscreen TV (FS), 2D micro-display (MD) and virtual reality (VR).

Participants: Thirty participants (13 males, 17 females) aged between 18-23 years (M=20.44, SD=1.45) were recruited via opportunity sampling. On average, the participant group spent 7.4 hours per week playing computer games.

Hardware platforms: Three types of display hardware were included in the experimental design. The Azibo 3D VR headset was combined with an Apple iPhone in order to create the VR condition. A Silicon Micro Display ST1080-10V1 acted as the MD; this HMD contained two LCD-based micro-displays that rendered a 2D representation of the game scene. A Samsung LE40B550 42" LCD TV was used in the flatscreen condition (FS); the TV was viewed from a distance of approximately 0.6m. Ear buds were used to deliver audio in all three conditions.

Game: A commercial game called InCell (Nival) was used for the study. InCell is an action/racing game where participants must avoid obstacles placed in their path. This game was chosen because it was portable across iOS (for VR presentation) and a PC version was downloaded from the Steam store for both FS and MD conditions. During the game, the player must control position by moving to the left and right in order to avoid obstacles. For the micro-display and flatscreen versions of the game, left/right controls were operated via two keys on a keyboard; for the VR version of the game, control was achieved by tilting the head to the left or the right. The relative simplicity of the controls provided a secondary reason for selecting this particular game.

Cold Pressor Test (CPT): Participants were required to submerge either the left or right foot into cold water (2ºC/35.6ºF) at a depth sufficient to cover the ankle. Water temperature was sustained using a bespoke device designed to deliver the CPT and water temperature was checked continuously against an electric thermometer. Participants placed a foot into the water at the beginning of the game and were under instruction to remove the limb when pain became intolerable.

Dependent Variables: The duration of time for which the limb was immersed in the water was recorded on a stopwatch as a behavioural measure of pain tolerance. Subjective immersion was recorded after each game using the 31-item version of the Immersive Experience Questionnaire (IEQ) (Jennett et al., 2008); the inter-item reliability (Cronbach's alpha) for the IEQ was 0.85. The level of autonomic activation associated with each game was assessed by measuring heart rate via the BioHarness (BioPac Inc.). This device recorded an electrocardiogram (ECG) at 250Hz from the chest, the resulting data were converted to a time-based index of heart rate (beats-per-minute) using AcKnowledge software (Biopac Inc.)

Procedure: Participants arrived at the laboratory and read the Participant Information Sheet (PIS), which provided full details on the protocol and what they were expected to do. The PIS clearly indicated that participants could withdraw from the study at any time without the requirement to provide any explanation. After reading and indicating that they understood the information provided, participants provided written consent. After consent, participant received a 'familiarisation trial' with the cold pressor test where no data was recorded. The BioHarness was worn as a chest strap under the clothes, participants were directed to a private room in order to fit the chest strap and data were checked when they returned to the experimental room. The participant was randomly assigned to one of three groups (FS, MD, VR) and a baseline version of the CPT was administered, i.e. participants performed the CPT alone in the absence of any other activity. Participants washed their feet before submerging a foot into the cold water for a maximum period of 107sec, i.e. the maximum duration of the game. Following the baseline CPT, participants performed a short tutorial of the game. After this tutorial, participants in the VR condition completed the simulator sickness questionnaire (Kennedy, Lane, Berbaum, & Lilienthal, 1993). If any symptoms of sickness were observed, the study was discontinued for that participant (none of the participants reported any symptoms of sickness after the tutorial). Participants played a game of InCell (maximum duration: 107s) whilst simultaneously experiencing the CPT. Once the game was completed, the participant completed the IEQ. After the game had been completed, the BioHarness was removed, participants were thanked and debriefed but did not receive monetary compensation.

Results

Data were analysed via SPSS v24. A mixed 2 (baseline, game) x 3 (flatscreen, HMD, VR) ANOVA was performed on total CPT time. For within-participants contrast (baseline, game), sphericity was tested using Mauchly's Test; if the Mauchly's Test was significant, the Greenhouse-Geisser adjustment was used and degrees of freedom were adjusted. The ANOVA revealed a significant effect [$F(3,24) = 13.33$, $p<.01$, $eta^2 = 0.34$] and post-hoc Bonferroni tests indicated that CPT times were significantly higher in all gaming conditions compared to the baseline ($p<.01$), but there was no statistically significant difference in CPT times between the three hardware platforms.

Total scores on the IEQ scale were subjected to the same ANOVA model, which revealed a significant effect for hardware platform [$F(2,28) = 13.17$, $p<.01$, $eta^2 = 0.31$]. Post-hoc tests indicated that subjective immersion was highest for the VR condition compared to either MD and FS ($p<.01$); IEQ scores for MD were also significantly higher than FS ($p<.01$).

Heart rate data were quantified as beats-per-minute (bpm) and analysed via ANOVA across all three hardware platforms. A significant main effect was found [$F(2,28) = 3.95$, $p=.03$, $eta^2 = 0.22$] and post-hoc tests revealed that heart rates were significantly lower during the FS condition compared to either MD or VR ($p<.05$). All descriptive statistics are provided in Table 1.

Table 1. Mean and SD of cold pressor test times, IEQ and heart rate for all conditions (N=27).

	Baseline	Flatscreen	Micro Display	VR
Cold Pressor Times (secs)	30.51 [22.96]	44.51 [33.05]	48.99 [35.71]	51.95 [38.28]
IEQ scale	-	96.97 [16.13]	104.20 [14.05]	110.90 [13.76]
Heart Rate (beats per min)	-	88.61 [16.13]	96.33 [26.38]	94.18 [21.03]

Discussion

It was anticipated that the VR condition would deliver the highest levels of pain tolerance (i.e. longest duration in the CPT), heart rate and subjective immersion compared to the other two hardware platforms (hypothesis 1). This hypothesis was supported only by the analysis of subjective immersion scores. Heart rate was significantly higher during VR compared to FS condition, but was not significantly differentiated from the MD display. With respect to the CPT data, it was clear that playing the game increased pain tolerance, compared to the baseline (no game) condition, but no statistically significant differences were observed among the three display conditions.

Table 1 showed that the overall trend for CPT times followed the expected direction, being maximal in the VR condition, but it can also be observed that standard deviations were very high throughout; this high variability may have blunted the sensitivity of the CPT to distinguish between the hardware platforms in this particular sample of participants. In addition, a combination of the between-participants design and relatively low number of participants led to the study being under-powered from a statistical perspective, i.e. statistical power for a study of this type was only 0.58 to detect effect sizes in the modest range (i.e. .30). With the exception of subjective immersion, the absence of observed differences in HR or CPT between the MD and VR conditions suggests that: (1) wearing a head-mounted display increased psychophysiological activation during the game by visually occluding the physical environment, and (2) playing the game in a 3D environment failed to significantly enhance autonomic activation or increase pain tolerance in the context of this specific gaming experience. It is concluded that visually occluding the physical environment and completely filling the visual field with the gaming view intensified the level of psychophysiological activation associated with the game. With respect to the failure of the VR display to influence objective and subjective markers of immersion, it is possible that the configuration of this specific game, where the focus of visual attention remains exclusively on the forward view, may have suppressed the effectiveness of the VR display that offers a three-dimensional view of the game world. It should also be noted that the VR display was operated using a different control mechanic (head tilting) compared to the Micro Display and flatscreen TV, both of which utilised a conventional game controller; hence the comparison between those displays and VR may have been influenced by the form of input control in addition to the characteristics of display itself. For example, operating the game controller using the Micro Display may have introduced an additional level of difficulty compared to other conditions as the display occluded the visual field and participants were unable to view the controller.

In summary, the study failed to support the hypothesis that increased sensory immersion, in the form of a VR-based display, would increase pain tolerance. Subjective immersion was higher when the game was played using the VR HMD and psychophysiological activation was higher when any kind of HMD was used compared to a conventional screen.

STUDY 2

The purpose of study 2 was to explore the impact of changing game demand on pain tolerance, subjective immersion and autonomic activation. Participants played the racing game WipeOut HD (Sony) at two different difficulty settings on a large-screen TV. It was predicted that pain tolerance would be higher when game demand was hard due to increased levels of challenge-based immersion (hypothesis 2).

Method

Design: The experiment was conducted as a within-participants design with two levels of task difficulty: easy and hard. The statistical power for this within-participants design to detect a modest effect size (0.3) was 0.98.

Participants: Seventy volunteers (40 males, 30 females) aged between 18-26 years (M=20.70, SD=1.44) participated in the study. The average number of hours spent gaming per week for participants was 13.88. The exclusion criteria for participant recruitment were identical to study one.

Game: A commercial game called Wipeout HD was played on the Sony Playstation (PS3) attached to a 42" LCD TV viewed from a distance of approximately 0.8m. WipeOut HD is a futuristic racing game where the player competes against eight computer-generated opponents over three laps of a track. The game is controlled by using buttons or the left joystick on the PS3 gamepad to manoeuvre the vehicle from left to right and the 'X' button on the controller is pressed to sustain speed. Players can gain advantage over the competition by manoeuvring their vehicle over 'speed boosts' to gain short bursts of acceleration; they can also pick up weapons by passing over 'weapon pickups' that can be used offensively against their opponents. The game was played from a first-person perspective and participants completed three laps of the same track layout in each race using the same vehicle type; a full race was generally completed in a period between 95-110s. This game was selected because the game was intuitive to play and the control were easy to learn (left-joystick + 1 button), hence even participants with little gaming experience could familiarise themselves with the play mechanics in a short period of time.

Game demand: The difficulty of the game was manipulated by selecting 'Novice' versus 'Elite' settings, which adjust the Artificial Intelligence of computer-controlled opponents during the race. For example, when game difficulty is set to 'Novice' opponents rarely pick up speed boosts and weapons, whereas the opposite holds for the 'Elite' setting. These difficulty levels were used previously by (Burns & Fairclough, 2015) to effectively manipulate the demand of the game.

Cold Pressor Test (CPT): The same apparatus, water temperature and protocol were used as described in study 1.

Dependent Variables: The duration of time for which the limb was immersed in the water was recorded on a stopwatch as a behavioural measure of pain tolerance. Subjective immersion was recorded after each game using the 31-item version of the Immersive Experience Questionnaire (IEQ) (Jennett et al., 2008)**;** inter-item reliability for the IEQ was 0.90. The level of autonomic activation associated with each game was assessed by capturing systolic blood pressure (SBP) using a CARESCAPE Vital Signs Monitor (V100) (DINAMAP Inc.) that involved placement of an inflatable cuff on the upper left arm. Readings were obtained at a pre-game baseline and during the game, after 60s of game play.

Procedure: After reading the Participant Information Sheet (see study 1) and providing written consent, participants washed their feet and received a 'practice' exposure to the cold pressor test to familiarise themselves with the procedure. Participants also completed a WipeOut HD race on an easy setting as a training exercise; the game settings for the training exercise (vehicle, track, number of laps) was identical to the test session. The order of presentation of the easy and hard games was counterbalanced across participants. The first game was initiated with a baseline reading of blood pressure, participants subsequently started the game and placed a foot in the cold water. Blood pressure readings were taken after 60s of game play in both conditions. After the game, participants placed their foot on a warm towel (to facilitate recovery from the CPT) and completed the IEQ. Therefore, there was a 3-4min period between subsequent games. Participants alternated between left and right foot between the three administrations of the cold pressor test. After both games had been completed, the cuff was removed from participants, they were thanked and debriefed but did not receive any monetary compensation.

Results

Data were analysed via SPSS v24. For within-participants ANOVA, sphericity was tested using Mauchly's Test; if the Mauchly's Test was significant, the Greenhouse-Geisser adjustment was used and degrees of freedom were adjusted.

An ANOVA was performed on total time that the limb was immersed in the water during the CPT across: baseline, Novice demand and Elite demand. Two participants kept their foot in the water for the maximum duration across all three conditions and were omitted from the CPT analysis. The ANOVA revealed a significant main effect [$F(2,66) = 32.55$, $p<.01$, $eta^2 = 0.32$] and post-hoc Bonferroni tests indicated that CPT times during Elite demand were significantly higher than either Novice demand or the baseline condition; it was also found that CPT time was significantly higher for Novice demand versus baseline (p<.01). Descriptive statistics are provided in Table 2.

Systolic blood pressure (SBP) data were analysed via ANOVA at baseline and both levels of game demand. A significant main effect was found [F(2,66) = 11.1, p=.03, eta^2 = 0.16] and post-hoc tests revealed that SBP was significantly higher during Elite demand compared to baseline and Novice demand (p<.01). SBP was also higher during Novice demand compared to baseline (p=.03), see Table 2 for descriptive statistics.

Table 2. Mean and SD of cold pressor test times and systolic blood pressure for Baseline, Novice Demand and Elite Demand (N=68).

	Baseline	Novice Demand	Elite Demand
Cold Pressor Times (secs)	52.42 [53.58]	73.44 [65.00]	90.23 [75.85]
Systolic Blood Pressure (mmg/Hg)	102.87 [42.38]	112.60 [34.93]	120.77 [29.81]

Total scores on the IEQ questionnaire collected after each game were subjected to an ANOVA model. The mean IEQ score for Novice demand (M = 59.6, s.d. = 58.6) was lower than the score obtained during Elite demand (M = 62.4, s.d. = 61.8), but no statistically significant effect for game demand was found [F(1,67) = 1.75, p=.19].

Discussion

The purpose of the second study was to explore the influence of challenge-based immersion on pain tolerance, subjective immersion and autonomic activation. The analyses of data from the CPT indicated a significant increase of pain tolerance between Novice and Elite levels of demand (Table 2); also, **four participants kept the limb immersed in the cold water for the maximum period of time during Elite demand**. It was also apparent that pain tolerance significantly increased due to the simple act of playing the game, which was expected. The sensitivity of the cold pressor data to game demand was mirrored by SBP data (Table 2), which also significantly differentiated between all three conditions. The analyses of subjective immersion did not include a comparison with a no-game condition for obvious reasons, but the questionnaire data failed to significantly differentiate Novice from Elite demand.

Study 2 demonstrated that pain tolerance was modulated by the level of game demand, presumably due to challenge-based immersion. Hence, increased game demand enhanced the capacity of the game to engage top-down attentional processes and mitigate the bottom-up interruptive effect of pain. This effect achieved statistical significance despite high levels of variability in the cold pressor data (Table 2) within each "cell" of the design. The increase of systolic blood pressure observed from baseline to Elite demand can be interpreted as a linear increase of autonomic activation in response to increased game demand. Like the cold pressor test, only one blood pressure reading was collected per game, which is a low sampling rate for approximately 100s of data collection. SBP also tends to increase in the presence of pain (Saccò et al., 2013) and although this effect is controlled through the design of the study, it should be noted that the patterns of SBP reactivity presented in Table 2 reflect a combination of game demand and pain induction that cannot be disentangled within the current experimental design.

The absence of any significant differences with respect to subjective immersion between Novice and Elite levels of game demand was unexpected. The trend was in the expected direction, but the difference between scores was mathematically small and data were highly variable. This finding may point to a methodological complication wherein both the levels of skill and motivation of the participants interacted with game demand. Unfortunately, we did not measure previous gaming experience or current proportion of time spent playing games in this particular study, so this aspect could not be addressed. We may speculate that participants who were highly motivated and familiar with this type of game were more likely to experience Elite demand as highly challenging and engaging. Those participants who are less familiar and/or less motivated would be more likely to disengage from the game during the Elite demand condition. Hence, data on subjective immersion during Elite demand may encompass an interaction between player skill and objective game difficulty, which effectively reduced the sensitivity of the subjective scale.

To summarise, the second study demonstrated that increased challenge-based immersion in the form of higher game demand increased both pain tolerance and autonomic activation.

STUDY 3

The third study was designed to simultaneously manipulate challenge-based immersion (game demand) and sensory immersion (size of visual display). Participants played the racing game WipeOut HD (SCEE) at three levels of demand on either a large (40") or a small (9") screen. The study was conducted to explore **whether pain tolerance was enhanced when the screen was large (40") and game demand was high** (hypothesis 3).

Method

Design: The experiment was conducted as a mixed design. Game demand was manipulated as a within-participants factor with three levels (Novice, Skilled, Elite) and screen size (large, small) as a between-participants factor. The statistical power for this mixed design given the sample size combined with a modest effect size (0.3) was 0.99.

Participants: Sixty participants performed the study (30 female) with a mean age of 23.85 yrs (s.d. = 7.84). Each between-participant group (large vs. small screen) contained equal numbers of males and females. In addition, there were no significant differences with respect to age (M = 25.3 vs. M = 23.5 yrs.) or mean number of hours per week spent playing computer games (M = 12.8 vs. M =14.8 hrs.) between the large vs. small screen size groups. The exclusion criteria for participant recruitment were identical to the two previous studies in the paper.

Game: A commercial game called Wipeout HD was played on the Sony PlayStation (PS3) in both screen size conditions. A complete description of the game can be found in the Method section of Study 2. The same track layout and participant vehicle was used in both conditions.

Game demand: The level of game demand was manipulated by selecting 'Novice,' 'Skilled' and 'Elite' settings. As in Study 2, these settings adjust the AI of opponents during the race, increasing the 'intelligence' of the bots from Novice to Elite, i.e. more likely to pick up speed boosts and weapons.

Screen Size: Participants played the game using either a 'Large' display, which was a Samsung LE40B550 40" LCD TV viewed at a distance of 1.5m. In the 'Small' display condition, they played the game on a Lilliput 569GL 5" LCD camera monitor viewed from a distance of approx. 0.38m. Both displays were connected to the Playstation3's HDMI output, and displayed the game using their native 1080p mode.

Cold Pressor Test (CPT): A full description of the set-up for the cold pressor test can be found in the Method section of Study 1.

Dependent Variables: The duration of time for which the limb was immersed in the water was recorded on a stopwatch as a behavioural measure of pain tolerance. Subjective immersion was recorded following each game using the 31-item version of the Immersive Experience Questionnaire (IEQ) (Jennett et al., 2008)**;** inter-item reliability for the IEQ in this study was 0.86. The level of autonomic activation associated with each game was assessed by capturing systolic blood pressure (SBP) using the same apparatus and protocol as Study 2. However, due to a computer malfunction, subjective data and psychophysiological data were only collected for 40 of our 60 participants.

Procedure: The procedure for the study was identical to Study 2 for both large and small screen display groups in the current study.

Results

Data were analysed via SPSS v24. For within-participants ANOVA, sphericity was tested using Mauchly's Test; if the Mauchly's Test was significant, the Greenhouse-Geisser adjustment was used and degrees of freedom were adjusted.

A 2 (large/small screen) x 4 (baseline/Novice/Skilled/Elite) ANOVA was performed on the mean time spent with limb immersed during the CPT. Three participants were excluded from the analysis because they kept their foot immersed in the water for the maximum period in all four conditions, i.e. 1 in the Small screen group and 2 from the Large screen group. The ANOVA revealed a significant effect for game demand [$F(3,53) = 19.90$, $p<.01$, $eta^2 = 0.53$] but no significant effect for screen size [$F(1,55) = 0.25$, $p=.62$] and there was no significant interaction effect. Post-hoc tests for demand revealed that mean CPT time was shortest in the baseline condition compared to all game conditions ($p<.01$); it was also apparent that CPT times for Novice game demand were shorter than other game demand conditions ($p<.01$) but there was no significant difference in CPT times between Elite and Skilled levels of demand. Descriptive statistics are presented in Table 3.

Table 3. Descriptive statistics for CPT times (N=57), systolic blood pressure (N=40) and subjective immersion (N=40) for three levels of game demand.

	Baseline	Novice	Skilled	Elite
Cold Pressor Times (secs)	43.60 [34.18]	57.32 [35.38]	69.36 [42.29]	78.76 [59.74]
Systolic Blood Pressure (mmg/Hg)	113.53 [17.45]	117.75 [21.10]	122.88 [19.01]	124.90 [18.63]
Subjective Immersion (IEQ)		47.67 [46.22]	52.88 [50.96]	57.48 [54.88]

Data from the IEQ were analysed via a 2 x 3 ANOVA to assess subjective levels of immersion. There was a significant main effect for game demand [$F(2,37) = 9.75$, $p<.01$, $eta^2 = 0.34$] but the size of the screen did not significantly affect subjective immersion [$F(1,38) = 1.29$, $p=.26$]; there was no significant interaction effect. Post-hoc testing of game demand revealed significant differences between all levels of game demand (Table 3).

Mean systolic blood pressure data were analysed via a 2 x 4 ANOVA, which revealed a significant main effect for demand [$F(3,36) = 25.15$, $p<.01$, $eta^2 = 0.68$] but no significant effect of screen size [$F(1,38) = 0.44$, $p=0.51$] and there was no significant interaction effect. Post-hoc tests revealed that mean SBP was significantly lower during baseline compared to all gaming conditions ($p<.01$). It was also found that mean SBP was significantly lower during Novice demand compared to either Skilled or Elite ($p<.01$) (Table 3).

Discussion

This third study was designed to explore the relative impact of sensory immersion (screen size) and challenge-based immersion (game demand) on pain tolerance within the same study. Our results indicated that screen size failed to significantly influence pain tolerance or subjective immersion, nor did this independent variable increase autonomic reactivity during game play. However, the manipulation of game demand increased both subjective immersion and levels of systolic blood pressure. The analyses of CPT times indicated that: (1) playing the game per se increased pain tolerance relative to baseline (as expected), and (2) playing the game at higher levels of demand (Skilled or Elite) increased pain tolerance relative to the lowest level of game demand (Novice).

The primacy of challenge-based immersion over sensory immersion as an influence on pain tolerance and subjective immersion was perhaps a surprising result. The finding that game demand increased systolic blood pressure was perhaps self-evident by comparison because this variable has been associated with mental effort, which responds to the level of task demand (Richter et al., 2016). The failure of screen size to influence either subjective and behavioural measures of immersion begs a question about the design of the experiment. **In the first instance, the lack of sensitivity of the IEQ to screen size could reflect the fact that subjective data were not collected from 20 of the 60 participants. In addition, it** could be argued that our decision to use a between-participants manipulation to examine screen size and a within-participants comparison to explore game demand introduced greater variability into the former as participants did not act as their own controls. However, a comparison of both screen size groups during baseline CPT revealed CPT times were essentially equivalent across the two groups, e.g. Large screen (M = 40.58, s.d. = 30.31) vs. Small screen (M = 46.51, s.d. = 37.83). It should also be noted that gender, age and gaming experience were also essentially equivalent between the two screen size groups.

The results of this third study demonstrated that a manipulation of game demand (challenge-based immersion) had a significant effect on behavioural markers of pain tolerance (CPT times), subjective immersion and systolic blood pressure, whereas a manipulation of screen size (sensory immersion) did not.

STUDY 4

Like the previous study, the goal of the fourth study was to simultaneously manipulate challenge-based immersion and sensory immersion using the same game to explore the influence of both variables on pain tolerance. Rather than manipulating the visual display, this fourth study varied the audio characteristics (volume of game music and sound effects) in conjunction with game demand. Participants played a VR-based game called InCellVR at two levels of demand while hearing music and sound from the game at high or low levels of volume. As in study 3, the purpose of this study was to **test whether a**

combination of high sensory immersion (high volume of game sound/music) and high challenge-based immersion (high demand) produced the greatest increase of pain tolerance (hypothesis 4).

Method

Design: The experiment was conducted as a mixed design. Game demand was manipulated as a within-participants factor with two levels (easy, hard) and audio volume (quiet, loud) functioned as a between-participants factor. The statistical power for this mixed design to detect a modest effect size (0.3) was 0.96.

Participants: Forty participants performed the study (8 female) with a mean age of 20.90 yrs (s.d. = 2.97). Each between-participant group (quiet vs. loud) contained equal ratio of males to females (4 females in each group). In addition, there were no significant differences with respect to age (M = 20.6yrs vs. M = 21.2yrs) between quiet vs. loud groups. The exclusion criteria for participant recruitment were identical to the three previous studies in the paper.

Game: The commercial game 'InCellVR' (Nival) was used for the study (as used in study one). InCellVR is an action/racing game where participants must avoid obstacles placed in their path. An iOS version was downloaded to an iPhone 5S and used in combination with the J TOHLO 3D VR Virtual Reality Headset 3D Glasses VR for iPhone headset. Using this version of the game, the player must control the position of their avatar by tilting their head to the left or the right to avoid obstacles and to collect boosts. Each game lasted for a minimum of 90sec and a maximum of 120sec, depending on the number of boosts collected by each player.

Game demand: The level of game demand was manipulated by selecting different levels. At Level 1 (Easy Demand), the avatar travels at a moderate speed and it is relatively easy to avoid the obstacles placed in the path of the player. Level 2 (Hard Demand) represents a higher level of game demand wherein the speed of the avatar is significantly increased and a greater number of obstacles are encountered.

Game audio: The audio for the game consists of electronic music and sound effects activated when players pick up boosts and collide with obstacles. The audio for the game was delivered to all participants using QuietComfort 35 Wireless Bluetooth Noise Cancelling Headphones (Bose). In the quiet audio condition, the volume was played at 11.60dB, whereas participants in the loud audio condition had the volume set to 57.95dB.

Cold Pressor Test (CPT): A full description of the set-up for the cold pressor test can be found in the Method section of Study 1.

Dependent Variables: The duration of time for which the limb was immersed in the water was recorded on a stopwatch as a behavioural measure of pain tolerance. Subjective immersion was recorded after each game using the 31-item version of the Immersive Experience Questionnaire (IEQ) (Jennett et al., 2008); inter-item reliability for the IEQ in this study was 0.86. Participants also completed a 10-point numeric rating scale (NRS) for subjective pain where 0 = no pain, 5 = moderate pain and 10 = worst pain. The BioHarness device (see study 1) was used to record an ECG, which was subsequently converted to heart rate data.

Procedure: Participants read the Participant Information Sheet (see study 1) before providing written consent and being fitted with the BioHarness device. Participants played a tutorial level of InCellVR after which they completed the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) to assess for any symptoms of VR-induced nausea; participants who experienced one or more symptoms on the SSQ would be excluded from the study at this point, but no sickness was reported from any of the participants. Participants were randomly assigned to either the quiet or loud audio group and performed the first game (easy and hard demand were presented in counterbalanced order). Each game contained a countdown timer to initiate play and participants placed their left foot in the water during this countdown. When the game was completed, the post-test procedure was performed as participants completed IEQ scales and the NRS for pain. Participants subsequently completed a baseline cold pressor test (no game) by placing the right foot in the water until the pain was intolerable; after the baseline cold pressor test, they completed the NRS and the post-test procedure was performed. The protocol for the second game was identical to the one used for the first game. When the study has been completed, participants were thanked and debriefed but did not receive any monetary compensation.

<u>Results</u>

Data were analysed via SPSS v24. For within-participants ANOVA, sphericity was tested using Mauchly's Test; if the Mauchly's Test was significant, the Greenhouse-Geisser adjustment was used and degrees of freedom were adjusted.

A 2 (quiet/loud audio) x 3 (baseline, Easy demand, Hard demand) ANOVA was performed on CPT times. One participant from each of the quiet and loud audio groups was excluded because they kept their foot immersed in the water for the maximum period in both conditions. There was no significant effect for the effect of audio [$F(1,36) = 0.06$, $p=.81$] but the ANOVA revealed a significant effect for game demand [$F(2,35) = 161.52$, $p<.01$, $eta^2 = 0.82$]. No significant interaction was observed. The post-hoc tests for the demand effect revealed a significant increase of cold pressor times between baseline and both game demand conditions. Cold pressor times were also significantly higher during hard demand compared to easy demand (all $p<.01$). Descriptive statistics are presented in Table 4.

The same ANOVA model was applied to subjective ratings of pain obtained after each cold pressor test with the 10-pt numeric rating scale for pain intensity. As with the analysis of cold pressor test times, the effect of audio group was not significant [$F(1,36) = 1.28$, $p=.27$] but there was a significant main effect due to game demand [$F(2,35) = 18.95$, $p<.01$, $eta^2 = 0.44$]. The analyses of post-hoc tests revealed a significant reduction of pain intensity at hard demand compared to either baseline or easy demand conditions ($p<.01$) (Table 4). No significant interaction effect was observed in the ANOVA for subjective pain ratings.

Table 4. Descriptive statistics for CPT times (sec) for baseline and three levels of game demand (N=38).

	Baseline	Easy Demand	Hard Demand

Cold pressor times (sec)	28.05 [17.69]	50.18 [34.83]	107.52 [19.61]
Numeric Rating Scale (Pain)	5.95 [1.36]	5.71 [1.39]	4.95 [1.52]

Data from the IEQ were analysed via a 2 x 2 ANOVA to assess subjective levels of immersion due to audio and game demand. There was a significant main effect for game demand [$F(1,38) = 5.86$, $p<.05$, $eta^2 = 0.13$], no effect of audio volume [$F(1,38) = 1.58$, $p=.22$] and no significant interaction effect. Subjective immersion was significantly higher during hard demand (M = 108.2, s.d. = 19.40) compared to easy demand (M = 102.4, s.d. = 17.09).

Inspection of heart rate data revealed that baseline levels were different between the two audio groups, i.e. M = 89.84 bpm for quiet audio vs. M = 98.36 bpm for loud audio. Although this effect did not quite reach statistical significance when tested via univariate ANOVA [$F(1,38) = 2.91$, $p=.09$], it was decided to subject heart rate data to a baselining procedure, wherein baseline heart rate was subtracted from heart rates during easy and hard games to correct for this confound. The baselined heart rate data were subsequently subjected to a 2 x 2 ANOVA to assess physiological levels of activation. Four participants (two from each audio group) were excluded from this analysis because they were outliers (i.e. baselined values were +/- 3 standard deviations from the group). There was a significant effect for game demand [$F(1,34) = 10.39$, $p<.01$, $eta^2 = 0.23$] and a significant interaction effect [$F(1,34) = 5.13$, $p<.05$, $eta^2 = 0.13$], but the main effect of audio volume fell outside of statistical significance [$F(1,34) = 3.41$, $p = .08$]. The effect for game demand indicated that baselined heart rate was significantly lower during high demand (M = -3.89bpm, s.d. = 9.47) compared to easy demand (M = -0.68bpm, s.d. = 7.60). Post-hoc t-tests were conducted to decompose the interaction effect. It was found that the main effect of game demand on baselined heart rate was only observed for participants in the loud audio group [$t(17) = 3.13$, $p<.01$]. A second post-hoc t-test revealed that baselined heart rate was significantly higher for the loud audio group (M = 2.81bpm, s.d. = 7.27) compared to the quiet audio group (M = -4.19bpm, s.d. = 6.34) but only when game demand was easy [$t(34) = 3.08$, $p<.01$].

Discussion

This study was designed to explore the influence of game demand (challenge-based immersion) compared to sensory immersion (audio volume) on pain tolerance. The results supported the primacy of game demand over audio volume as an influence on behavioural and subjective measures of pain tolerance. When the game was highly demanding, cold pressor times increased and numeric ratings of pain intensity decreased. No similar effect was found when the volume of the game audio was increased. Similarly, the analysis of subjective immersion revealed an effect for game demand but no equivalent finding for audio volume.

It was anticipated that increasing the game audio would stimulate psychophysiological activation and increase heart rate. The analyses of heart rate data revealed a mixed picture wherein this finding was only observed when game demand was easy, presumably because the demand of the game failed to significantly impact on levels of autonomic activation in this condition. However, it was also found that heart rate only increased during high game demand when audio volume was high, which points to an additive effect wherein loud audio potentiated the influence of game demand on heart rate reactivity.

The influence of game demand in this study provides a clear example of how challenging levels of high demand distract from painful stimulation, leading to greater pain tolerance and a subjective reduction of pain intensity (Table 4). The results of this fourth study confirm that the level of cognitive demand placed on participants rather than display size was the primary factor driving the immersive experience as opposed to hardware characteristics.

RELATIONSHIP BETWEEN MEASURES AND MEDIATION ANALYSES

All four studies described in this paper included three categories of measurement: behavioural measures of pain tolerance (CPT times), autonomic activation (systolic blood pressure or heart rate) and a subjective measure of immersion (IEQ). In order to explore the relationship between these measures in greater detail, data were pooled across the different individual studies. Dataset 1 (N=65) represented a combination of data collected during studies 1 and 4, which all included CPT times, mean IEQ score and average heart rate (HR). Dataset 2 (N=108) combined data from studies 2 and 3 and included: CPT times, mean IEQ score and average systolic blood pressure (SBP).

In the first instance, a matrix of Pearson's correlation coefficients was created for all three variables obtained from Dataset 1 (Table 5a) and Dataset 2 (Table 5b).

Table 5. Correlation coefficients for CPT time, autonomic activation and subjective immersion (IEQ) for both (a) Dataset 1 (N=65) and (b) Dataset 2 (N=108); ** = significant at p<.01.

(a)

	Heart Rate	**IEQ**
CPT time	**0.23****	**0.01**
Heart Rate		**0.24****

(b)

	SBP	**IEQ**
CPT time	**0.30****	**0.02**
SBP		**-0.10**

The correlational analyses shown in Table 5 reveals that autonomic activation is positively associated with greater pain tolerance (higher CPT times). There is also a significant positive correlation between heart rate and IEQ in the case of Dataset 1 (Table 5a).

In order to explore the relationship between the three variables in greater detail, a mediation analyses (Hayes, 2017) was conducted. Given that heart rate is correlated with both CPT times and IEQ scores in Dataset 1, we wanted to quantify the direct effect of heart rate on CPT times using IEQ as a mediator. The purpose of this analyses was to establish whether subjective immersion had exerted an indirect influence on behavioural pain. The pattern of correlations observed in Dataset 2 (Table 5b) was less ambiguous in this respect, but a mediation model is included for the sake of completion.

Two sets of mediation analysis were conducted, one for Dataset 1 and another for Dataset 2. These analyses were conducted in SPSS v24 using PROCESS v3.4 (Hayes, 2019). The confidence intervals for these analyses were 95% and bootstrapping samples was set to 5000.

The results of the mediation analysis for Dataset 1 are illustrated in Figure 1a below. There was no evidence of any indirect effect of heart rate on cold pressor times via subjective immersion, *ab* = -0.03 BCa CI [-0.22 0.09]. However, heart rate exerted a significant total effect and direct effect on cold pressor times, i.e. higher heart rate = greater pain tolerance. There was no significant indirect effect in the mediation model created for Dataset 2, *ab* = -0.01 BCa CI [-0.15 0.11], but it should be noted that both total and direct effects of SBP on pain tolerance fell just outside levels of significance [p=.07].

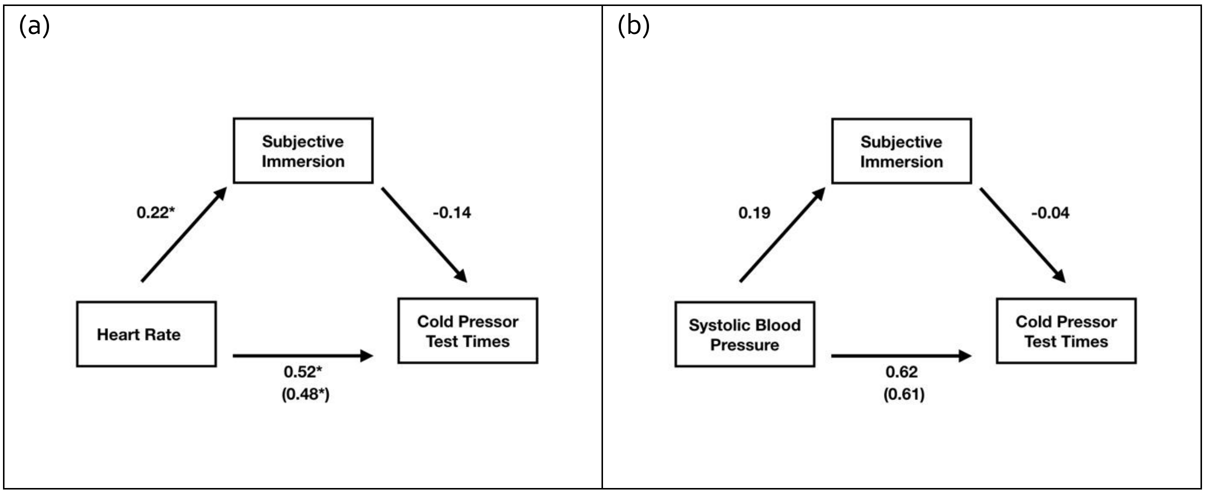

Figure 1. Results of the mediation analyses to explore the presence of direct and indirect effects between autonomic activation and cold pressor test times for Dataset 1 (a) and Dataset 2 (b); * = significant at p<.05, direct effect in brackets.

GENERAL DISCUSSION

The four studies conducted in the current paper were structured upon four hypotheses related to the influence of sensory immersion and challenge-based immersion on the capacity of computer games to effectively distract from pain. The first study found no significant increase of pain tolerance when participants played the game in VR compared to a TV or 2D presentation via a micro-display (hypothesis 1). This null pattern for the manipulation of hardware characteristics should be interpreted with caution, given the poor statistical power of the first study; however, this null effect was replicated in further studies where sensory immersion (e.g. display size and audio volume) was manipulated during testing of hypotheses 3 and 4. Nevertheless, the three studies that manipulated game demand supported an association between challenge-based immersion and pain tolerance, as tested in isolation in study two (hypothesis 2) and in combination with a manipulation of sensory immersion via studies three and four.

The effectiveness of game demand to promote distraction from pain supports findings from laboratory experiments that reported increased pain tolerance with high cognitive demand using standard tasks from experimental psychology; see Section 3.2 of (Torta et al., 2017) for review. Top-down attentional processes (Eccleston & Crombez, 1999; Legrain et al., 2012) that mitigate the influence of bottom-up stimulus selection are engaged by increased game difficulty in a manner that is consistent with the explanatory framework of load theory (Lavie, 2005). Because our participants were playing computer games, as opposed to performing cognitive tasks in the laboratory, it can be argued that the intrinsic level of motivation and self-determination (Rheinberg, 2008; Ryan, Rigby, & Przybylski, 2006) known to characterise gameplay also contributed to these observed effect. Players are motivated by challenge and a desire to win, which translates into an intense desire for goal achievement during the game activity (Przybylski et al., 2010), with concomitant strengthening of those cortical networks associated with top-down, task-related attentional processes (Corbetta, Patel, & Shulman, 2008). However, the precise contribution of motivation to distraction from pain remains difficult to quantify in the current work and further research is required wherein analgesic effects of cognitive tasks in the laboratory (e.g. working memory) are compared to a manipulation of game demand.

All four studies measured autonomic activation via heart rate and systolic blood pressure in combination with manipulations of sensory immersion and challenge-based immersion. Autonomic activation was positively associated with game demand in all three studies where demand was manipulated. There was some evidence that sensory immersion increased autonomic activation, i.e. heart rate was higher when participants used an HMD (study 1) and when audio was loud during easy game demand (study 4), but these effects were less consistent than the global influence of challenge-based immersion on autonomic activation. An investigation into the relationship between the dependent variables revealed a pattern of positive correlations between pain tolerance and autonomic activation (Table 5). A mediation analysis (Figure 1a) indicated that mean heart rate directly affected both subjective immersion and pain tolerance with no significant mediation via subjective immersion.

There is significant overlap between cortical centres associated with pain perception and control of the autonomic nervous system. There is also evidence that short-term elevation of sympathetic activation (i.e. increased heart rate or systolic blood pressure) in healthy participants is associated with suppressed pain perception (Schlereth & Birklein, 2008); but see Kenntner-Mabiala, Andreatta, Wieser, Muhlberger, & Pauli (2008) for exception. Given that numerous studies have reported an association between sympathetic activation and increased task demand (Fairclough, Venables, & Tattersall, 2005; van der Wel & van Steenbergen, 2018), it is very likely that activation of the autonomic system contributed to the analgesic effect of increased game demand observed in three of our four studies. A similar argument could be made with respect to increased secretion of endorphins, which can also have an analgesic effect during challenging tasks such as performance of a musical piece (Dunbar, Kaskatis, MacDonald, & Barra, 2012). A third possibility is that gameplay engaged top-down attentional processing by virtue of being experienced as a fun activity associated with positive affect even when performance is unsuccessful (Hoffman & Nadelson, 2010). If we accept the argument that negative emotions can prime attention to painful stimulation (Godinho, Magnin, Frot, Perchet, & Garcia-Larrea, 2006; Pourtois, Schettino, & Vuilleumier, 2013b; Wunsch, Philippot, & Plaghki, 2003), then it is at least possible for the opposite effect to occur when gameplay elicits positive emotional states; see Thong, Tan, & Jensen (2017) and Strand et al. (2006) for supporting evidence. Our results suggest that increased autonomic activation is responsible for the analgesic effects observed for challenge-based immersion.

Three of the four studies incorporated a manipulation of hardware properties in order to investigate sensory immersion. None of these manipulations (VR vs. TV, large vs. small display, loud vs. quiet audio) exerted any significant effect on pain tolerance using the CPT protocol. There was evidence for a significant increase of heart rate and subjective immersion in study one when participants played the game using an HMD compared to a flatscreen display, but no equivalent effects were observed for screen size or audio volume. Both study one and study four utilised a smartphone-based VR system as opposed to higher-quality HMD and the relatively low quality of the former may have contributed to the observed null effect (Hoffman et al., 2006).

There are several reasons for the superiority of challenge-based immersion over sensory immersion with respect to the mitigation of experimental pain observed in studies three and four: (i) once the game was underway, participants' attention was engaged by the challenge of the game and associated task goal (winning), which remains constant regardless of hardware, (ii) hardware characteristics are relegated to the role of a framing device for the challenge of the game and degree of challenge drove increased autonomic activation and pain tolerance, and (iii) due to (i) and (ii), the moment-by-moment demands of the gaming task tends to occlude the contribution of display type or sound volume to the experience of the player.

A number of limitations on our methodology should be noted. All four studies deployed racing games of one kind or another. This category of game was selected because racing games are easy to learn, even for novices, and engage the attention of the player via intensive perceptual-motor demands that are time-critical. With respect to repurposing commercial gaming software for the purposes of experimental manipulation, racing games also offer transparency between manipulation of game demand and corresponding events on the screen, i.e. higher speed combined with a greater number of obstacles (InCell). However, this focus on a single genre of game does beg questions about the generalisability of our findings. For example, a game with a leisurely pacing of activities and events may not distract attention from painful stimulation in the same way or to the same extent, particularly if sympathetic activation played a mediating role in the analgesic effects that we observed. Racing games also tend to direct visual attention to central area of the visual field and predicted path of the vehicle. This pattern of visual attention may diminish the general impact of a three-dimensional rendering of the game world (Study One), or a large screen compared to a small screen size (Study Three). Therefore, our null findings with respect to display hardware should be replicated with different types of game. It should also be noted that our manipulation of game demand as challenge-based immersion was limited in two senses. In the first instance, we did not explicitly explore specific emotional (excitement, frustration) or high-performance states (flow) but utilised game demand as a broad, non-specific manipulation of attentional engagement. In addition, we did not explore the potential of imaginative immersion (Ermi & Mayra, 2005) to act as a distraction from pain. The results from three of our four studies have indicated that game demand exerts a significant influence on pain tolerance, the specifics of this relationship, i.e. the role of emotions, the influence of narrative, are topics for further exploration.

In order to manipulate game difficulty, pilot studies and at least one published study (Burns & Fairclough, 2015) were conducted to identify different levels of game demand to be used in the studies reported here. However, we adopted a 'one-size-fits-all' approach to the setting of game demand that took no account of the playing experience or skills of the individual participants. Given that game difficulty represents an interaction between the skill of the individual and the objective characteristics of the task, a more rigorous approach would have required calibrating the level of game demand to the ability of each individual via extensive pre-testing; this practice of matching game demand to the skills of the individual is similar to the concept of player balancing (Cechanowicz, Gutwin, Bateman, Mandryk, & Stavness, 2014; Vicencio-Moreira, Mandryk, & Gutwin, 2015). It should also be noted that our methodology only permitted an evaluation of player experience via the IEQ when participants played the game and submitted themselves to the experimental pain protocol, hence the combined influence of pain experience and gameplay is confounded within that subjective index of immersion in the current paper.

The use of experimental pain in the form of the cold pressor test raises a similar issue as painful stimulation was generic and not personalised to the sensory sensitivity of the individual, hence enormous variability was observed in our behavioural pain data across all four studies. In addition, there was an element of social evaluation that was inherent to the protocol for the cold pressor test as the experimenter sat in the room as the participant underwent the test to record the duration of the test. It would be desirable to replicate the findings observed in the current paper using a different mode of pain induction, e.g. heat pain with personalised thresholding. The CPT protocol also includes a strong element of self-determination, i.e. participants are able to remove the limb from the cold water at any time; this internal locus of control over painful stimulation is atypical, particularly in the context of pain in the clinic. **With**

respect to autonomic measures, a decision was made to switch from unobtrusive monitoring of heart rate (via a chest strap) in Study 1 to explicit monitoring of physiology via blood pressure in the second and third studies, which was reversed for the final study. The change between Study 1 and Studies 2 and 3 was made on the basis that systolic blood pressure provides a more direct index of sympathetic activation compared to heart rate, which is influenced by both sympathetic and parasympathetic branches of the autonomic nervous system. However, this sensitivity was counteracted by the intrusive nature of blood pressure monitoring via a cuff attached to the non-dominant arm; participants indicated that blood pressure monitoring was distracting and hence psychophysiological monitoring reverted to the less obtrusive option of heart rate measurement during the fourth and final study.

The superiority of challenge-based immersion as an influence on pain tolerance strongly suggests that in future work: (1) game demand should be manipulated during clinical studies, (2) portable devices, such as tablets and smartphones, should be fully explored in the clinic alongside HMD/VR, e.g. Shahid, Benedict, Mishra, Mulye, & Guo (2015), and (3) manipulation of demand should be included when VR is used as a distraction from pain, especially in the clinic.

To summarise, the four studies reported in the current paper found that manipulation of game difficulty (challenge-based immersion) was the primary factor that influenced tolerance of painful stimulation. Manipulation of sensory immersion, such as display type, size and audio volume, failed to exert any significant effect on behavioural measures of pain tolerance.

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