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Manipulating and decoding subjective gaming experience during active gameplay: a multivariate, whole-brain analysis

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A B S T R A C T

A large number of perceptual and cognitive processes are instantiated during active gameplay, culminating in what is termed the overall "gaming experience", which encapsulates multiple, subjective dimensions of how one feels about the game. Although some research has been conducted into the neural mechanisms underlying the gaming experience, previous studies so far have relied on commercial games that provide little control over key aspects of gameplay and also have focused only on a few individual dimensions of the gaming experience. Here, we used a custom-made, immersive driving car game in four different gameplay versions (baseline, obstacle increase, goal decrease, speed increase) to assess and modulate the subjective gameplay experience while participants underwent a fMRI scan. A multivariate correlation analysis of whole-brain neural activity with behaviorally-identified subjective gaming experience uncovered brain networks associated with different experiences, including higher-level visual processing networks, the default network, and emotional areas. These regions were in addition able to decode the four different game conditions above chance. Our results for the first time describe the full range of cortical networks that become engaged to create the subjective experience during active gameplay.

1. Introduction

Since the advent of brain imaging technology, neuroscientists have tried to unravel the neural mechanisms from lower-level perceptual processes up to higher-level cognitive processes. Functional magnetic resonance imaging (fMRI) in particular has helped to shed light on how the brain recognizes objects (Clarke and Tyler, 2015), processes environmental sound (Wang, 2018), controls hand movements (Shenoy et al., 2013), and even how it evaluates the hedonic aspects of stimuli (Hu, 2016). Traditionally, these investigations have been done with simple, well-controllable stimuli and in non-interactive settings with so-called open-loop paradigms (Pennartz, 2018). In such paradigms, participants will typically be presented with a stimulus in each trial and then will be asked to respond to one of its qualities. Importantly, the response of the participant will have no direct feedback to the stimulus; hence the term "open-loop". In the real world, however, learning and processing of the brain all happen in highly interactive contexts, in which perception, cognition, and action are tightly coupled – any action will change the environment, hence changing the perceptual input in a closed, perception-action loop (Pennartz, 2018). Therefore, in order to understand the brain's processing in such real-life situations better, closed-loop experiments in which participants can interact with realistic environments become necessary.

Owing to the availability of more immersive display technology (such as stereo goggles (Gaebler et al., 2014)), the development of more advanced analysis methods (such as multivariate pattern analysis (MVPA) (Haxby et al., 2001; Norman et al., 2006; Haxby, 2012),), as well as the increased knowledge of the mechanisms of lower-level processing in the brain, recent research has started to move from passive, open-loop paradigms towards investigating the brain's responses in interactive, immersive, closed-loop situations. Several studies, for example, have started to investigate brain processes in the context of video games as these offer the potential for rich, interactive experiences in a controlled environment (Palaus et al., 2017). Accordingly, video games have been used to investigate visuospatial processing (Schmidt-Hieber and Häusser, 2013; Miller et al., 2015), decision-making (Zanon et al., 2014; Patil et al., 2017), reward expectations (Cole et al., 2012; Katsyri et al., 2013a, b), and skill acquisition (Lee et al., 2012; Voss et al., 2012). One higher-level aspect that has received comparatively little attention in this regard, however, is the *subjective* aspect of the gaming "experience" itself, that is, our feelings of "being in the game", of "liking the game play", of "feeling challenged". These aspects form a crucial part of the reason why people play games as they may become rewarded by overcoming a challenge, or may get frustrated since the game play is too dull and repetitive.

Supplementary video related to this article can be found at https://

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In order to provide a fuller picture of the subject gaming experience, recently the Gaming Experience Questionnaire (GEQ) was developed (IJsselsteijn et al., 2013). This questionnaire contains a set of measures aimed at assessing subjective experience (Norman, 2013) and its seven measurement dimensions span a wide range of evaluative aspects of gameplay. The dimensions encompass competence, immersion, flow, tension, challenge, positive affect, and negative affect and will be explained further in the methods part below.

Among the studies using video games in fMRI, only a few have begun to investigate the neural activity underlying such subjective gaming experiences: in virtual reality, spatial presence (as measured by the MEC-spatial presence questionnaire (Vorderer et al., 2004)), for example, has been associated with parietal brain areas usually involved in spatial navigation and with parts of the insula involved in body sensation (Baumgartner et al., 2006). Furthermore, the concept of presence was also associated with down-regulation of the right dorso-lateral pre-frontal cortex (DLPFC) and up-regulation of its left counter-part (Baumgartner et al., 2008) as well as with positive correlations in postcentral parietal cortex and insula (Clemente et al., 2014a, 2014b). As for video gameplay, research on the dimension of flow has identified sensory-motor networks to be important (Klasen et al., 2012) and ventrolateral prefrontal cortex (VLPFC), frontal pole area (FPA), and DLPFC showed significant activation during flow states (Yoshida et al., 2014). In addition, reward-related networks were implicated in positive affect (Katsyri et al., 2013a) or pleasantness ratings (Katsyri et al., 2013b) in the context of wining versus loosing. Additionally, participants' affective evaluation of gameplay during computer games labelled as “violent” involved a network consisting of bilateral insula (decreasing positive affect), bilateral vmPFC (increasing *negative affect*), and right precuneus and hippocampus (decreasing negative affect) (Mathiak et al., 2013a). Finally, participants' subjective displeasure was related to increased activity in right precentral gyrus when they played a first person shooter game (Klasen et al., 2008).

Overall, this research already hints at an extensive network of neural processes related to aspects of the subjective gaming experience. However, the aforementioned studies have some important limitations, which will be outlined in the following together with the steps taken in this work to address and overcome them.

First, research so far has focused solely on individual dimensions of the subjective experience, such as affect or flow (Baumgartner et al., 2006, 2008; Clemente et al., 2014a, 2014b), which fails to do justice to the multi-dimensionality of the gaming experience as evidenced by the seven dimensions contained in the GEQ, for example. In the present study, we therefore directly evaluated participants' experience with the GEQ, investigating each of its seven dimensions separately and in a combined analysis.

Second, the assessment of the subjective experience is often done only after a long, extended period of gameplay and experiments (Clemente et al., 2014a, 2014b), which makes it hard for participants to properly recall their experience. Here, we enabled participants to stay concentrated throughout and to provide an accurate and reliable account of their gaming experience by purposefully designing each game session in the present experiment to last only a few minutes. In addition, experience questionnaires were conducted immediately after each of several gameplay conditions in order to aid recall.

Third, studies often lack baseline or contrast conditions (Klasen et al., 2012; Mathiak et al., 2013a) as participants play only one version of the game – this makes it problematic to compare conditions in an experimental setting. Relatedly, when using existing, commercial video games specific elements of the game-play cannot be manipulated, which makes experimental studies difficult. Hence, in order to increase control over the gameplay and to manipulate the subjective experience in an experimental setting, we developed our own set of games. This allowed us to change various elements of gameplay (such as the level of difficulty, the interaction elements, etc.). More specifically, we chose a car driving scenario as this enabled easy modification of specific in-game environmental variables like speed (Jennett et al., 2008), game difficulty (Ulrich et al., 2014), and goal conditions (Klasen et al., 2012) all of which were shown to be associated with the subjective gaming experience.

Fourth, in several studies, participants only were able to play in a fixed or highly-constrained environment (Baumgartner et al., 2006; Baumgartner et al., 2008; Katsyri et al., 2013a, b; Clemente et al., 2014a; Clemente et al., 2014b) that may have made limited the richness of the gaming experience. In our experiment, participants' strategy or tactics were not constrained so as not to bias or limit their experience and to enable them to figure out the driving game environment for themselves.

Finally, several fMRI studies reported univariate analyses only, which have been shown to be less sensitive compared to the newer, multivariate analyses (Coutanche, 2013; Davis and Poldrack, 2013). Therefore, in order to get to a deeper understanding of the involvement of different brain networks in shaping how we experience games, we investigated multivariate correlations between gaming experiences and neural activity across the whole brain. In addition, we related the whole-brain activation maps to meta-analysis-based brain activation maps to aid interpretability and provided a view on how different parts of the brain were able to decode the gaming conditions using a discriminative, searchlight classification.

Based on this setup and prior research, we hypothesize, first, that our specific in-game modifications should be able to manipulate several sub-dimensions of the subjective gaming experience. Second, based on these manipulations, we expect the multivariate analyses to give us a more principled and detailed account of the network of brain areas underlying the different aspects of the gaming experience.

2. Materials and methods

2.1. Game design

We used Unity3D 4.6.1f1 (http://www.unity3D.com a 3D virtual reality development tool) and publicly available 3D- and game-contents to create car game (the assets we based our games on were taken from the following free source: https://www.assetstore.unity3d.com/en/#!/content/10). The car game required participants to complete a course while avoiding obstacles and collecting objects that would award bonus points (see Fig. 1).

There were five different game versions designed to modulate subjective gaming experience (within the limits of the inter-correlations of the GEQ, see below) – a version designed for training, and four conditions of the driving task: baseline, obstacle increase, goal decrease, and speed increase condition, respectively. Since we did not want to train people on the exact same task, the training version contained slightly different contents compared to their experimental versions, but the input and game dynamics were the same across all versions.

In the training version, participants had to achieve a pre-set goal, which was to complete a racecourse with a car in less than 3 min (this training criterion was set after several pilot experiments that were used to tune the difficulty level for the games). Importantly, since the later scanning experiment used a somewhat unusual control button layout (see below), participants were trained to control the vehicle with four adjacent keys (‘asdf’) on the keyboard using their right hand.

In all four experiment versions, participants tried to achieve a high score during 3 min of gameplay. The goal for the games was to collect as many tokens (one point per token) while avoiding obstacles (stones). Tokens for the game consisted of diamonds that were randomly placed on the racing course. Collisions with the obstacles would deduct one penalty point (see Fig. 1). Game scores were saved for each game session and best and worst scores of previous players were shown on the screen to provide additional motivation for players. In addition, the number and timing of all button presses as well as the resulting speed of the car during game play were recorded in order to compare participants' control behavior across conditions.

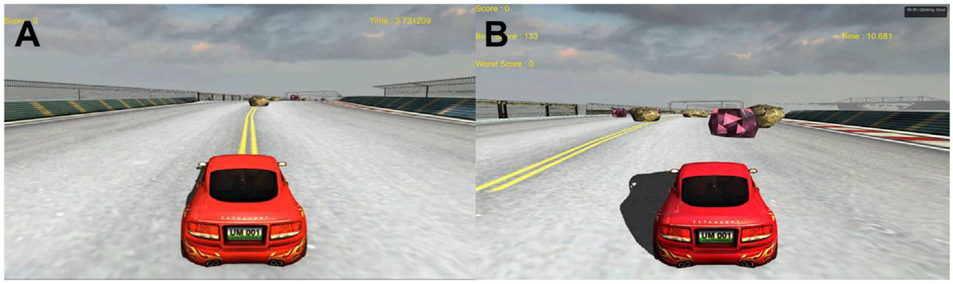

Fig. 1. Screenshot of game play: (A) Baseline condition, (B) Difficult condition – note the increase of stone obstacles.

In the *baseline* condition, the number of obstacles was set to 50 items and the number of collectable tokens was set to 120 items. All other conditions changed in only one parameter compared to the baseline condition: in the *obstacle increase* condition, the number of obstacle was increased to 100 items compared to the baseline condition. In the *goal decrease* condition, the number of tokens was decreased to 10 items compared to the baseline condition. Finally, in the *speed increase* condition, the acceleration speed was set to 1.5x faster compared to the baseline condition.

All game versions used four buttons for control, offering two degrees of freedom for moving the vehicle. Each game was rendered and played back at the native resolution and frame rate of the video goggles (800×600 pixels at 60 Hz).

2.2. Participants

Thirty one right-handed male participants were recruited for our experiment (mean age of 24.8 years (SD = 3.68). All participants were Korea University students and were standard users of computer games with an average playtime of 3.5 h per week spent on computer games (SD = 4.28)). Participants did not report any psychiatric disease, neurological disease or other MRI exclusion criteria. Our study was approved by the local ethical committee at Korea University 1040548-KU-IRB-13-157-A-1(E-P-1). Before scanning, informed consent was obtained and participants were tested for intact stereo vision.

2.3. Procedure

Participants underwent a brief training session to adjust to the controls and to the game mechanics one day before the experiment using the training version of the game. The training session took 3 min and all participants achieved the lap completion criterion in the first session. Before the start of the scanning experiment, participants received standard fMRI instructions. Importantly, they were instructed not to move their head during gameplay so as to avoid motion artifacts. Additional care was taken to adjust the stereo-goggles and to provide dioptric correction for each participant before scanning.

Prior to the actual experimental session, another brief training session was inserted to help participants adjust to controlling the vehicles using the MRI-compatible button box. Control was done – similarly to the previous training session – with the four fingers of the right hand excluding the thumb. The same training context was used as for the previous day, except that gameplay was limited to 1 min. Subsequently, participants were asked whether they were comfortable with vehicle control, which all participants confirmed. Finally, each of the four experimental sessions was run. This included a 30-s resting period and 3 min of actual gameplay. All participants played the baseline condition first followed by the other three conditions in randomized order (counter-balanced across participants).

After each condition, scanning was stopped and participants were required to fill out the GEQ questionnaire on the screen using button presses. As introduced above, the in-game GEQ questionnaire contains seven dimensions (*immersion, flow, competence, tension, challenge, positive affect, negative affect*), with each dimension consisting of two questions that require a −10 to 10 scale (disagree-agree) response. Importantly, in the three post-baseline conditions, participants received information on how they had responded to the baseline condition. To achieve this, the home position of each scrollbar that indicated the numeric value for the responses was initially placed at the value answered for the baseline condition.

2.4. Data acquisition

MRI data were acquired on a SIEMENS-Trio 3T scanner (Siemens Medical Systems, Erlangen, Germany) with a 12-channel SENSE head-coil (Brain-imaging-centre, Korea University, Seoul, South Korea). Structural MRI images of all participants were collected using a T1-weighted, sagittal high-resolution MPRAGE-sequence (repeat time (TR) = 2250 ms, echo time (TE) = 3.65 ms, flip angle (FA) = 9 deg, voxel size = $1 \times 1 \times 1$ mm, 192 axial slices). Functional imaging was performed with a gapless, echo-planar-imaging (EPI) sequence (TR = 3000 ms, TE = 30 ms, FA = 60 deg, voxel size = $2 \times 2 \times 4$ mm). The first 9s of each functional run consisted of dummy scans to allow for steady-state magnetization. Since each game session lasted for exactly 3 min (excluding dummy scans and the baseline resting period), the total number of recorded volumes for each game session was 60.

2.5. Imaging data preprocessing

Data was preprocessed in SPM12 (Wellcome Trust Centre for Neuroimaging, London, UK; http://www.fil.ion.ucl.ac.uk/spm/). First, all scans were realigned to the initial volume, while checking for excessive head translations or rotations. For our data, none of the participants exceeded the threshold of 2 mm/TR. After realignment, the T1 image was co-registered with the mean EPI, and tissue segmentation was performed using the *New Segment* function in SPM. Functional data were then normalized into MNI space and normalized to $2 \times 2 \times 2$ mm using the DARTEL toolbox *normalize* function (Ashburner, 2007) followed by smoothing with a Gaussian kernel of 8 mm FWHM.

2.6. Behavioral data analysis

The measurement of the subjective gaming experience relies on the so-called Game Experience Questionnaire (GEQ), which contains a validated set of seven dimensions or sub-scores that constitute a multidimensional estimate (IJsselsteijn et al., 2013). In the following, we briefly summarize each of the seven dimensions (competence, immersion, flow, tension, challenge, positive affect, and negative affect) in more detail.

Competence was introduced first by White as a feature of performance motivation (White, 1959). In the GEQ, the dimension of *competence* measures one's subjective feelings of how well one did in the game. This is an important factor in the gaming experience, since "good games" have a tendency to improve a players' *competence*, while at the same time keeping them motivated without adding frustration (Gee, 2003). Previous work has shown that a player's motivation is correlated with *competence* (Ryan et al., 2006). Additionally, external game conditions such as display size and resolution (Ni et al., 2006) have been shown to affect *competence*.

Immersion is a term that describes increased engagement and engrossment with a game to the point that one may even forget one's surroundings (Jennett et al., 2008). At this final stage, *immersion* shares features with another closely-related dimension of "presence" (Nacke and Lindley, 2008). Several studies have shown that changes in external game environment affect *immersion*, such as sound (Nacke et al., 2010), point of view (Kallinen et al., 2007) changes in control devices (Lee and Chung, 2013), as well as gaming pace (Jennett et al., 2008).

Flow is a concept related to immersion, defined as a state of concentration in which individuals are so absorbed in an activity that they act with total involvement (Csikszentmihalyi, 1990). In contrast to *flow*, *immersion*, however, is a progressive experience in which *immersed* people may still be aware of their surroundings (Nacke and Lindley, 2008). *Flow* mostly focuses on changes in the player's internal condition. This dimension has been investigated by changing game features or level of difficulty (Ulrich et al., 2014), by introducing a specific event (Nacke et al., 2010; Klasen et al., 2012), or a motivational task (Keller and Bless, 2008).

Tension is a feeling of anxiety and stress that makes it hard to relax. In the context of gaming experience, a feeling of high *tension* is also related to the state of *flow* in which players feel to be part of a gaming situation. A player's *tension* level can be affected by changing traits of the gameplay experience (Nacke and Lindley, 2008), the presence of sound or its pitch (Collins, 2008; Nacke et al., 2010), as well as whether they play alone or are observed by other people (Liu et al., 2012).

A *challenge* is a new or difficult task that tests somebody's ability and skill. Normally, in the game design process, it is vital to match the *challenge* level to the ability of the player (Spronck et al., 2004). Additionally, whether a game presents a *challenge* is also related to competition or interaction with other people (Vorderer et al., 2003) as well as to the gender of the player (Lucas and Sherry, 2004).

Positive and negative affect are components of a persons' well-being (Andrews and Withey, 1976), with *positive affect* connected to feeling enthusiastic, active, and attentive, whereas *negative affect* is characterized by subjective distress and unpleasant feelings (Watson et al., 1988). Increasing *positive affect* is a main goal of game design as it increases motivation and enjoyment (Isen and Reeve, 2005; Lyubomirsky et al., 2005). In contrast, *negative affect* is correlated with stress (Watson, 1988) and hence should be reduced during gameplay. Motivation (Custers and Aarts, 2005), reward anticipation (Knutson et al., 2001), and task performance (Lyubomirsky et al., 2005) were found to be related to *positive affect*, whereas failure, worsened performance (Turner et al., 1998), or loss of the game (Katsyri et al., 2013a) were associated with *negative affect*.

In the present study, the GEQ results were first checked for normality using 28 (7 sub-scores * 4 conditions) Shapiro-Wilk tests and then analyzed for consistency across participants using Cronbach's alpha. In addition, repeated-measure ANOVAs were used to investigate differences across game conditions in terms of GEQ results as well as several in-game metrics (including the average speed of the car, the total achieved score, and the number of button presses during game play). Furthermore, post-hoc analyses of game experiences and in-game metrics were performed to investigate the differences between conditions. Participants' averaged GEQ-subscores were also correlated across the seven different GEQ dimensions to analyze inter-dimension dependencies. ANOVAs and correlations across GEQ sub-scores were corrected for multiple comparisons with a Bonferroni alpha value $= 0.05/7$.

2.7. fMRI data analysis

The main analyses in the paper relied on a standard, general linear model (GLM) with which we obtained participants' *game-condition-specific,* whole-brain activation during gameplay. Since we had four different conditions, the GLM contained four variables in addition to button press data (to regress out the effect of button presses) and six head-motion-related covariates, yielding beta-estimates for each voxel in each condition (similar to (Op de Beeck et al., 2008; Masson et al., 2016)). These beta-estimates were not analyzed per se but formed the basis for the main correlation analyses and a searchlight analysis as explained in the following.

The first analysis investigated the relationship between the behaviorally-rated, subjective gaming experiences and the whole-brain, neural activity of the participants (as obtained from the beta-estimates). Given four different conditions, $\binom{4}{2} = 6$ pair-wise difference values for each of the behavioral GEQ sub-scores and $\binom{4}{2} = 6$ pair-wise beta-estimate difference values were determined. In order to identify the correlations of interest, the six pair-wise difference values of the behavioral ratings and the neural activity were correlated with each other for every voxel in each participant, yielding a whole-brain correlation map. A second-level group analysis was then used to determine whether the correlation overall was significantly positive or negative using one-sample t-tests to compare the correlation value in each voxel to zero. The resulting p-values were then entered into a standard FDR (false discovery rate) procedure to find significant overall correlations between subjective gaming experience and neural activity in the whole brain (note, that since this procedure was explorative in nature, and was working at the scale of individual voxels, an FDR criterion was used instead of the family-wise-error criterion employed in the subsequent searchlight analyses based on averaging across multiple voxels). This analysis was done for each of the seven sub-scores of the GEQ, yielding seven different whole-brain activation maps.

In order to aid the interpretation of these maps at a broader systems level, we next compared each of the activation maps to term-based activation maps contained in the online resource neurosynth (Yarkoni et al., 2011; http://neurosynth.org/analyses/terms). Neurosynth enables meta-analyses based on automatically extracted feature terms and corresponding activation locations – at the time of writing (08.04.2018), the database had 3107 terms reported in 11406 studies. For this analysis, we gathered the significant activation patterns for each of the seven GEQ dimensions and decoded their most likely functional correlates via correlating it with each of the term-based activation maps in neurosynth. Due to methodological constraints, this "cognitive decoding" function only provides overall correlation values given the whole-brain map of significantly co-activated voxels in each experience and the meta-analysis, whole-brain maps. To analyze the most likely functional associations of each subjective experience, we report the ten highest-correlated features returned by this procedure.

The analyses so far were centered on understanding whole-brain activations of *individual* GEQ dimensions. In order to find brain regions related to the *overall* gaming experience, we next performed another multivariate, whole-brain correlation analysis (Op de Beeck et al., 2008; Bulthe et al., 2014). For this, the seven dimensions of the GEQ questionnaire were first averaged across participants and then used to create a 4×4 distance matrix A, where each cell of the matrix a_{ij} contained the Euclidean distance between the two seven-dimensional vectors for gaming conditions i and j. A similar procedure was conducted for the beta-estimates averaged within a 12 mm radius (corresponding to a 216 voxels volume), yielding a 4×4 distance matrix B. Correlations between A and B were obtained for every voxel and every participant and the resulting p-values were subjected to an FWE criterion in order to determine significant voxels in a group-level analysis. In this analysis, we viewed each of the different game conditions as being located in a seven-dimensional vector-space and we were looking for brain patterns that would capture the overall similarity structure of the four game conditions in this space.

Finally, if the different game conditions resulted in differential brain activity patterns, it should be possible to decode the conditions from those patterns. Hence, as a confirmatory analysis, we ran a decoding searchlight classification, considering the different conditions as our decoding target. A multivoxel pattern analysis based on the *searchmight* toolbox (Pereira and Botvinick, 2011) was used with a 7 × 7 × 7 voxel searchlight and a Gaussian Naïve Bayes (GNB) classifier in order to find voxels that significantly contributed to the decoding of the different gaming conditions. The analysis pipeline is similar to the one used in (Kim et al., 2015) in which the authors investigated differences in brain activations across different types of emotion stimuli.

3. Results

3.1. Behavioral data

Except for one condition, the Shapiro-Wilk tests on the raw GEQ data failed to reach significance: the test returned a p-value of $p = .017$ for the ratings obtained for *tension* in the *goal decrease* condition. Since the QQ-plot did not deviate considerable from the diagonal, the test only highlighted one of the 28 comparison conditions, and the standard ANOVA is robust against small deviations of normality (Miller, 1986), we chose to treat the values in the following as normal.

Cronbach's alpha was then used to test rating consistency across participants for the GEQ, returning $\alpha = 0.895$ for all conditions. This indicates that subjective ratings were highly consistent.

We next used a repeated-measures ANOVA to compare the number of button presses, the speed of the car and the total score across conditions (See Table 1). Results showed significant differences for all measures (number of button presses ($F(3) = 5.215$, $p = .002$), speed ($F(3) = 101.766$, $p < .001$), total score ($F(3) = 191.45$, $p < .001$) indicating differences in control behavior and score across game conditions. Since participants first handled the *baseline* condition, we found that it had the highest number of button presses, as participants became adjusted to the task. In line with the design goals, the *obstacle increase* condition had the lowest speed. In addition, the *goal decrease* condition had the lowest number of button presses, the lowest score, and the highest average speed. Finally, the *speed increase* condition had the highest score compared to other conditions since it was relatively easy to approach targets compared to the other conditions. We performed post-hoc analysis on all measures to confirm the results of ANOVA (see Appendix A).

Next, we analyzed the subjective rating data across conditions. Participants' average ratings of the four game conditions are given in Table 1. With these, repeated measure ANOVAs showed that *competence* ($F(3) = 5.48$, $p = .004$), *tension* ($F(3) = 5.32$, $p = .005$), *negative affect* ($F(3) = 7.41$, $p < .001$), and *positive affect* ($F(3) = 5.84$, $p = .001$) had significant differences across conditions (see Table 1). Again, in line with our design goals, the *obstacle increase* condition showed the lowest *competence, positive affect* with the highest *tension* and *negative affect* ratings. The *goal decrease* condition showed the highest *competence* and *positive affect*, as well as the lowest *tension* ratings. Finally, the *speed increase* condition had the lowest *negative affect* ratings. One should add that for the other dimensions, changes in the subjective experience also conformed to expectations: for example, *immersion* ratings for all non-baseline conditions tended to be higher, and people felt increased *flow* in the *goal decrease* condition.

Next, we evaluated correlations between the different behavioral and control measures shown in Table 1 across participants. For the GEQ dimensions (see Fig. 2), we found the following significant correlations (corrected for multiple comparisons): *competence* correlated with *immersion* ($r = 0.34$, $p < .001$), *positive affect* ($r = 0.59$, $p < .001$), and *tension* ($r = -0.35$, $p < .001$) showing that as *competence* increased, participants also became more immersed, felt more positive and less tense. We also found correlations between *immersion* and *flow* ($r = 0.53$, $p < .001$), *challenge* ($r = 0.72$, $p < .001$), *negative affect* ($r = -0.27$, $p = .003$) as well as *positive affect* ($r = 0.69$, $p < .001$), indicating a relationship between immersive experience and perceived game quality. Similarly, *flow* correlated with *challenge* ($r = .58$, $p < .001$) and *positive affect* ($r = 0.42$, $p < .001$), and *challenge* correlated with *positive affect* ($r = 0.53$, $p < .001$). An increase in *tension* went along with an increase in *negative affect* ($r = 0.57$, $p < .001$), which is in line with expectations about the definition of tension. Overall, the inter-correlations conform to the design criteria and – given the range of correlations obtained – also yield a reasonably independent set of dimensions for the further analyses in this paper.

3.2. fMRI data analysis

Beta-values were correlated for the whole brain with each of the GEQ rating dimensions separately – results of these correlations were then FDR-thresholded at $p < .05$ and results were deemed stable enough if more than 50 voxels in one Brodmann area (BA) survived. Table 2 lists all resulting activations together with their anatomical and peak voxel locations. Our results exclude GEQ dimensions of *competence, tension* and *positive affect* that did not yield reliable clusters with more than 50 voxels.

Fig. 3 visualizes the result of the FDR analysis further with each color encoding one GEQ dimension. In particular, we found that *immersion*,

Table 1
Behavioral data results. SD = standard deviation.

	Baseline	Obstacle increase	Goal decrease	Speed increase
Competence (SD)	−0.15 (4.76)	−1.29 (4.26)	2.12 (3.84)	1.13 (3.36)
Immersion (SD)	1.44 (2.90)	0.40 (3.68)	1.53 (4.17)	1.56 (4.07)
Flow (SD)	0.23 (3.42)	0.40 (3.39)	0.58 (4.28)	1.11 (4.02)
Tension (SD)	−3.10 (3.86)	−1.87 (4.36)	−4.53 (3.82)	−3.92 (3.74)
Challenge (SD)	0.73 (3.01)	1.14 (3.08)	1.06 (4.02)	1.29 (3.73)
Negative affect (SD)	−2.52 (3.20)	−1.34 (4.05)	−3.15 (3.86)	−3.31 (3.53)
Positive affect (SD)	−0.35 (2.89)	−1.26 (3.41)	1.19 (3.76)	−0.26 (3.72)
Game score (SD)	33.35 (9.03)	12.26 (7.55)	4.80 (2.76)	40.45 (13.15)
Speed (SD)	36.11 (7.27)	28.73 (7.21)	50.22 (6.85)	43.38 (9.37)
Button (SD)	275.19 (46.18)	267.35 (48.35)	251.71 (44.07)	270.74 (43.71)

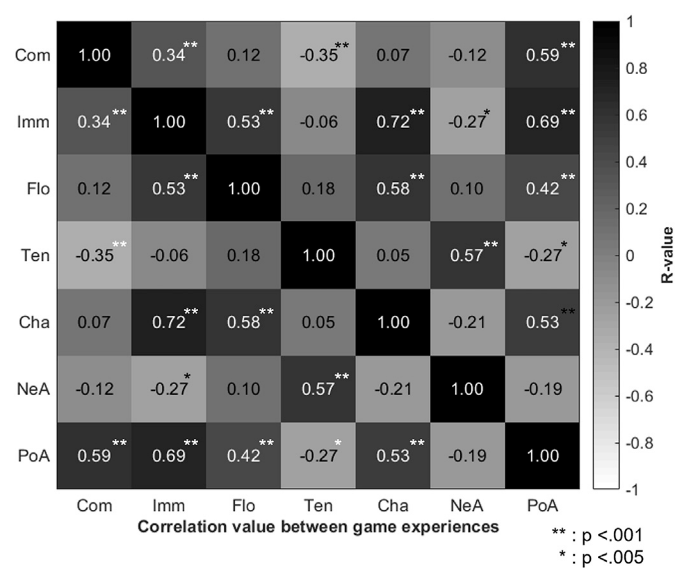

Fig. 2. Correlations between the GEQ rating dimensions (* and ** indicate significant correlations after multiple comparisons; Com = Competence, Imm = Immersion, Flo = Flow, Ten = Tension, Cha = Challenge, NeA=Negative Affect, PoA=Positive Affect).

flow, and *challenge* showed positive correlations with areas both in the dorsal and ventral visual pathway, including middle, superior and inferior occipital gyrus, middle and superior temporal gyrus, inferior and superior parietal lobule, medial, middle, superior and inferior frontal gyrus, pre and postcentral gyrus and additionally, parahippocampal gyrus, paracentral lobule, insula, cuneus and precuneus, lingual gyrus, cingulate gyrus and fusiform gyrus. Furthermore, *flow*, *challenge*, and *negative affect* also had negative correlations in large parts of the visual pathways in similar anatomical locations in addition to angular gyrus, anterior and post cingulate cortex, and caudate (see Table 2).

3.3. Decoding functional correlates of gaming experiences

In order to aid the interpretation of the complex, whole-brain activation maps obtained in the previous analysis, we next decoded feature correlations for the each of the four significant experiences using neurosynth. For this, we correlated the activity patterns shown in Fig. 3 across all meta-analysis maps contained in the database. As can be seen from the resulting feature correlations in Fig. 4, positive correlates of *immersion, flow, challenge* and negative correlates of *negative affect* related features are related to visually- and spatially-related execution as well as attentional processes. Values are especially high for the visual aspects in the ratings. The negative correlates of *flow* and *challenge* seem mostly related to the default mode network.

3.4. Correlational searchlight analysis

Given the widespread pattern observed in the previous analyses, we next conducted a correlational searchlight analysis to identify activity differences across conditions related to the *overall* GEQ experience ratings. Here, the rating profile was used to create a similarity matrix between the four conditions based on Euclidean distances of the seven-dimensional rating vector. The broad visual activation found in some – but not all – of the previous correlation maps was not seen as strongly in this combined analysis. Results highlighted regions such as the cingulate gyrus, cuneus, fusiform gyrus, inferior, superior and middle temporal gyrus, putamen, parahippocampal gyrus, lingual gyrus, post and precentral gyrus and, furthermore, showed broad activation in the frontal part of the brain including in the inferior, superior, medial and middle frontal gyrus and also in the insula (see Table 3, Fig. 5).

3.5. Discriminative searchlight analysis

The discriminative searchlight analysis for *decoding* the four different game conditions showed similar region activation compared to the overall results of the correlational analysis with additional activation in anterior and posterior cingulate cortex, lateral ventricle, thalamus, caudate, inferior parietal lobule, and the precuneus (see Table 4, Figs. 6 and 7). Maximum classification accuracy was found in predominately visual areas (Fig. 6).

4. Discussion

The present study investigated neural correlates of subjective gaming experience as measured by the gaming experience questionnaire (GEQ). Participants played four different car games inside the fMRI scanner and rated their gaming experience after each game. Importantly for our conclusions, both the behavioral and the imaging data analysis were *referenced against the baseline game condition*, which provided us with a robust way to cope with the variation in subjective ratings and experiences in the case of the behavioral data, as well as with a control for the complexity of the visual and motor input that would confound the results otherwise for the imaging data.

Table 2
Location information of group-level correlation analysis. All analyses are $p < .05$ FDR-corrected. See Fig. 3 for visualization of the results and Appendix B to detailed region information.

Positive correlation	Region(AAL)	Peak Voxel	Brodmann Areas	Voxel number
Immersion	cingulate gyrus/cuneus/inferior frontal gyrus/inferior parietal lobule/middle frontal gyrus/middle temporal gyrus/postcentral gyrus/precentral gyrus/precuneus/superior frontal gyrus/superior occipital gyrus/superior parietal lobule/superior temporal gyrus	−14 -94 28	2/6/7/8/9/13/19/40/44/46	2926
Flow	cingulate gyrus/cuneus/fusiform gyrus/inferior frontal gyrus/inferior occipital gyrus/inferior parietal lobule/inferior temporal gyrus/lingual gyrus/medial frontal gyrus/middle frontal gyrus/middle occipital gyrus/middle temporal gyrus/paracentral lobule/parahippocampa gyrus/postcentral gyrus/precentral gyrus/precuneus/superior frontal gyrus/superior parietal lobule	10 -74 2	2/3/4/5/6/7/9/13/17/18/19/20/24/30/31/37/39	11951
Immersion & flow	cuneus/fusiform gyrus/inferior frontal gyrus/inferior occipital gyrus/inferior parietal lobule/inferior temporal gyrus/insula/lingual gyrus/medial frontal gyrus/middle frontal gyrus/middle occipital gyrus/middle temporal gyrus/paracentral lobule/parahippocampal gyrus/postcentral gyrus/precentral gyrus/precuneus/superior occipital gyrus/superior parietal lobule	12 -72 4	2/3/4/6/7/9/17/18/19/30/31/32/37/39/40/44	14330
Flow & Challenge	fusiform gyrus/inferior occipital gyrus/lingual gyrus/middle frontal gyrus/middle occipital gyrus/precentral gyrus/precuneus	30 -80 18	6/7/18/19/37	1671
Negative correlation				
Challenge	angular gyrus/anterior cingulate/caudate/cingulate gyrus/cuneus/inferior frontal gyrus/inferior parietal lobule/insula/lingual gyrus/medial frontal gyrus/middle frontal gyrus/middle temporal gyrus/parahippocampa gyrus/postcentral gyrus/post cingulate/precentral gyrus/precuneus/superior frontal gyrus/superior parietal lobule/superior temporal gyrus/supramarginal gyrus/insula	−50 -70 32	3/4/6/7/8/9/10/13/18/19/21/22/24/30/31/32/38/39/40/41/42/43/45/47	12714
Negative affect	cuneus/fusiform gyrus/inferior frontal gyrus/inferior occipital gyrus/inferior parietal lobule/inferior temporal gyrus/lingual gyrus/medial frontal gyrus/middle frontal gyrus/middle occipital gyrus/middle temporal gyrus/paracentral lobule/parahippocampal gyrus/postcentral gyrus/precentral gyrus/precuneus/superior occipital gyrus/superior parietal lobule	30 -64 -14	3/4/6/7/9/10/13/17/18/19/24/30/31/32/37/39/40/44/46	16041
Challenge & negative affect	inferior frontal gyrus/middle frontal gyrus/middle temporal gyrus/postcentral gyrus/superior temporal gyrus	52 -50 2	8/19/40	1431
Flow & Challenge	anterior cingulate/cingulate gyrus/middle temporal gyrus/posterior cingulate/precuneus	−46 -72 30	10/13/31	415

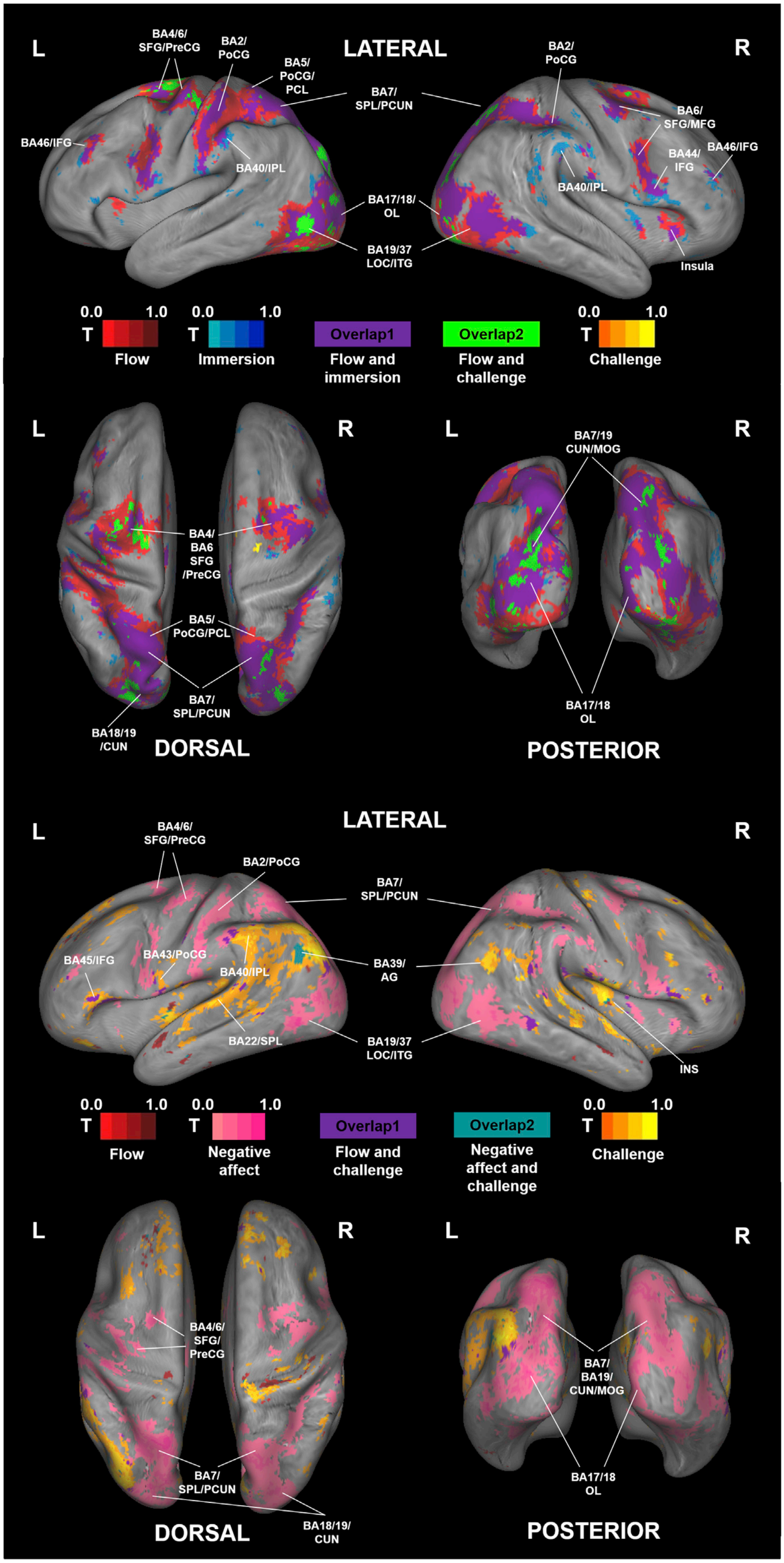

Fig. 3. Correlation between beta estimates and behavioral results. Results were $p < .05$ FDR-corrected. The first two image rows report positive correlations between gaming experiences and brain responses, and the second two image rows report negative correlations between gaming experiences and brain responses. The anatomical labels are abbreviated as follows: IFG, inferior frontal gyrus; SFG, superior frontal gyrus; INS, insula; PreCG, precentral gyrus; PoCG, postcentral gyrus; PCL, paracentral lobule; SPL, superior parietal lobule; PCUN, precuneus; OL, occipital lobe; ITG, inferior temporal gyrus; IPL, inferior parietal lobule; MFG, middle frontal gyrus; CUN, cuneus; MOG, middle occipital gyrus; AG, angular gyrus. All t-values are re-scaled to 0–1 for better comparison.

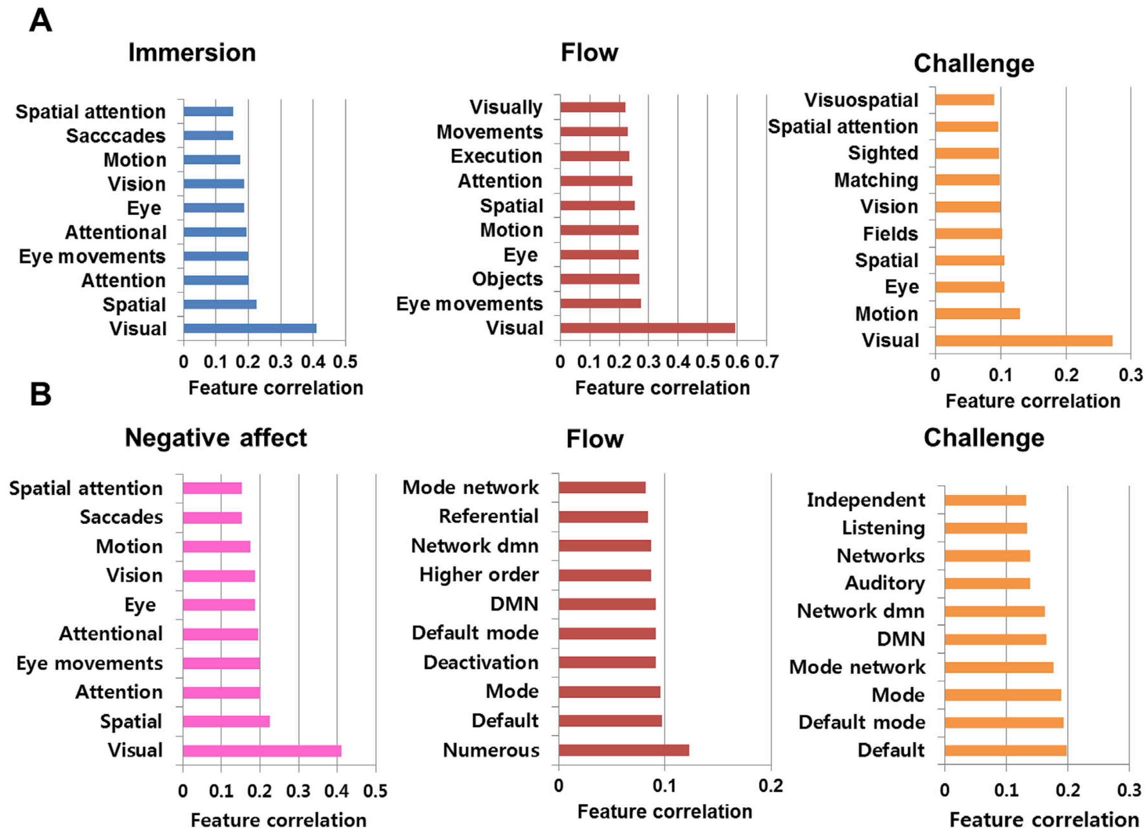

Fig. 4. Associated psychological features using the decode function of neurosynth (Yarkoni et al., 2011) (A) Positive correlation (*Immersion*, *Flow*, *Challenge*). (B) Negative correlation (*Negative affect*, *Flow*, *Challenge*).

Table 3
Location information of the correlational searchlight analysis. All analyses are $p < .05$ FWE-corrected. See Fig. 5 for visualization of the results.

Region(AAL)	Peak Voxel	Z-score	Number of voxels
Cingulate gyrus	14 42 6	7.67	1150
Cuneus	2 -84 14	5.41	321
Fusiform gyrus	−32 -56 -14	7.47	150
Insula	−40 -8 12	7.38	1597
Inferior temporal gyrus	−58 -6 -18	6.48	79
Inferior frontal gyrus	−36 26 -4	6.99	1220
Lingual gyrus	28 -62 -10	5.93	323
Medial frontal gyrus	24 34 30	7.61	636
Middle frontal gyrus	−50 -38 -2	4.98	1599
Middle temporal gyrus	−52 -8 -14	8.16	1140
Parahippocampal gyrus	26 -40 -16	6.14	491
Precentral gyrus	46 -14 30	7.84	1260
Postcentral gyrus	−52 -10 16	6.22	364
Putamen	−30 -8 2	7.49	561
Superior frontal gyrus	24 40 28	7.70	750
Superior temporal gyrus	−46 -24 -2	8.25	1187

4.1. Behavioral data across the four conditions

In our study, we found that the different game conditions were able to induce different gaming experiences: behavioral performance, such as car speed and scores, was modulated by the overall number of score and obstacle tokens, as well as the control characteristics of the game. In terms of subjective gaming experiences, for the *obstacle increase* condition, the dimension of *immersion* was significantly decreased, whereas *tension* and *negative affect* were significantly increased. Similarly, in the *goal decrease* condition, *competence* and *positive affect* were increased and *tension* was decreased compared to the baseline conditions. The most likely reason for this is that in the *goal decrease* condition there were fewer targets to collect and participants were able to focus on avoiding obstacles and on driving the car fast. In the *speed increase* condition, the average speed of the car and the overall score were higher, and at the same time participants showed higher *immersion* and lower *tension* and *negative affect*. In this condition, the speed increase helped participants to collect tokens fast, inducing also higher *immersion* – see also Jennett et al. (2008), who found that speed increased *immersion* during game play. The higher score may also explain why participants felt lower *tension* and *negative affect* even though the speed was faster than before, since it was easier to reach the goal.

4.2. Relationship between neural activity and gaming experiences

We next used whole brain correlation analysis to investigate the correlation between neural activity and the subjective gaming experience. *Immersion*, *flow*, *challenge* and *negative affect* showed significant relationships with neural activity, whereas we were not able to find widespread correlations for *competence*, *tension* and *positive affect*.

First, concerning *immersion* and *flow,* we found positive correlations with parts of the dorsal and ventral visual streams, higher-level visual association areas as well as the insula. This is consistent with results from (Klasen et al., 2012), who found that an increased level of concentration and focus led to activity in visual processing areas. Since concentration and focusing on the activity are core components of *flow* (Csikszentmihalyi, 1990), these aspects are linked to the GEQ dimensions we tested.

In addition, we can link the correlations for *immersion* and *flow* observed across a wide range of areas in the dorsal and ventral visual stream to egocentric visual processing of the participants (Gron et al., 2000; Jordan et al., 2004; Baumgartner et al., 2008). Previous studies found, for example, that highly immersive conditions in virtual reality increased parietal brain activity (Baumgartner et al., 2006) and postcentral parietal cortex activation (Clemente et al., 2014a) with the

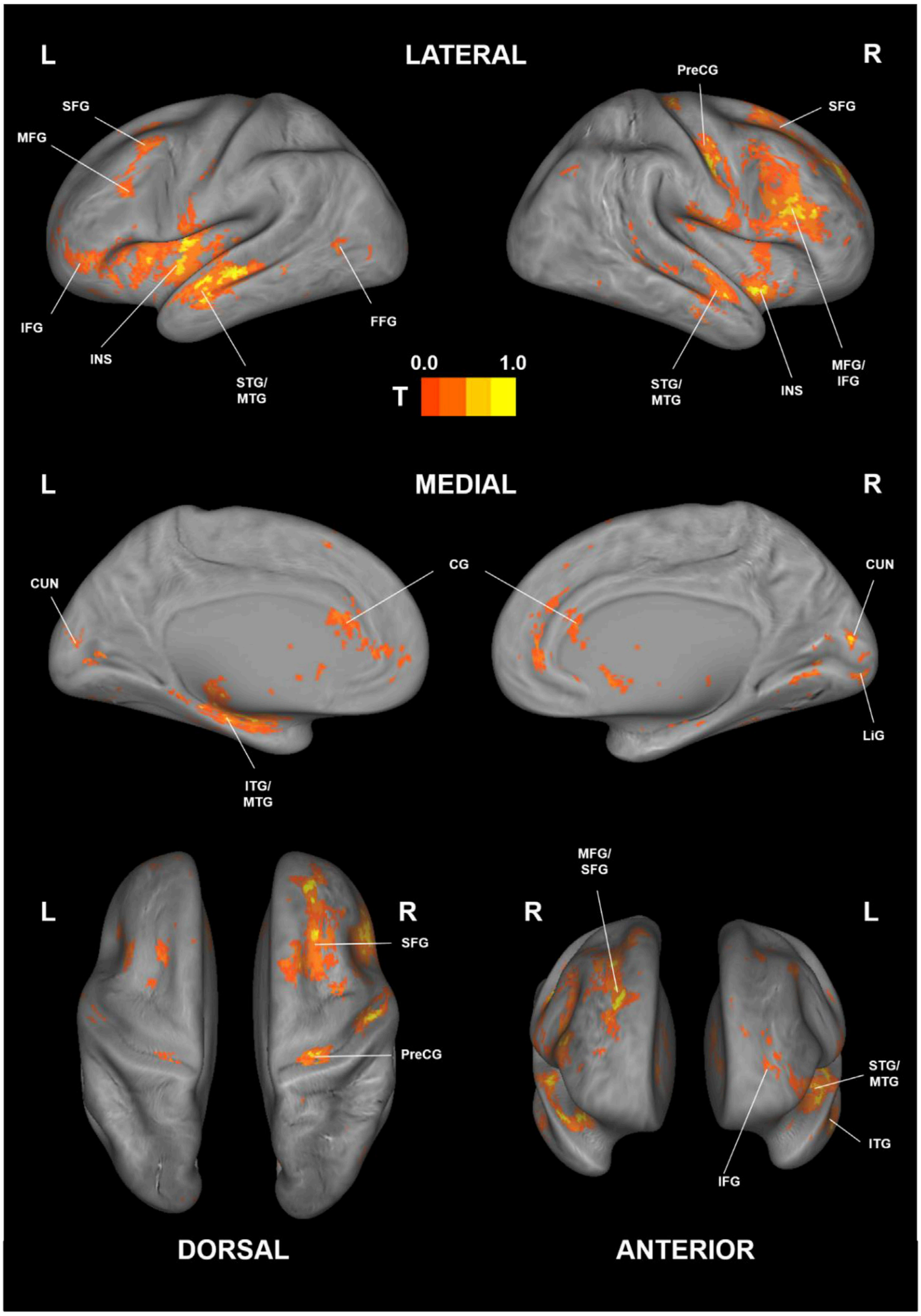

Fig. 5. Correlational searchlight analysis results for correlations of brain activity with overall GEQ dimensions. The anatomical labels are abbreviated as follows: IFG, inferior frontal gyrus; MFG, middle frontal gyrus; SFG, superior frontal gyrus; INS, insula; STG, Superior temporal gyrus; MTG, Middle temporal gyrus; ITG, inferior temporal gyrus; FFG, fusiform gyrus; PreCG, precentral gyrus; CUN, cuneus; CG, cingulate gyrus; LiG, lingual gyrus. Results were $p < .05$ FWE-corrected. All t-values are re-scaled to 0–1 for better comparison.

middle occipital gyrus related to assessing the sense of presence (Ogawa et al., 2013). Additionally, restraining presence or immersiveness correlated with wide-spread decreases in activity in the dorsal visual stream as well as occipital, parietal, and temporal cortices (Baumgartner et al., 2008). Indeed, *immersion*, *flow* and presence as defined in these prior studies are highly inter-related concepts (Draper et al., 1998), for which our results provide additional evidence.

As for the correlations for *immersion* and *flow* found in the insula, we can identify two possible sources: first, the insula is known to encode the passage of time (Wittmann et al., 2010) with highly immersed people “losing themselves” in the experiment, hence losing track of time (Jennett et al., 2008). Several studies have implicated the insula also in bodily self-awareness (Tsakiris et al., 2010; Heydrich and Blanke, 2013b). Indeed, in addition to the temporal component, another feature of *immersion* is a loss of one's sense of the surrounding real world (Jennett et al., 2008). Hence, the temporal and spatial properties during immersed gameplay may drive the observed activation in the insula.

Finally, the decoding of functional correlates using neurosynth supported our results that *immersion* and *flow* showed correlation with visuospatial concepts as well as attentional features – all of which are core aspects of *immersion* and *flow*.

Second, we found negative correlations for *negative affect* across both dorsal and ventral visual stream and visual-related areas, with significant overlap with the areas found for *immersion*. The previously-mentioned virtual reality study also found increases in *negative affect* to decrease activity in the precuneus (Baumgartner et al., 2006), similarly to the results observed here. The similarity to the *immersion* results should come as no surprise, given the behavioral correlations we found for *negative affect* with *immersion*. This finding also yields roughly identical decoding of the functional correlates of *negative affect* with *immersion*.

Table 4
Location information of the discriminative searchlight analysis. All analyses are p < .05 FWE-corrected. See Figs. 6 and 7 for visualization of the results.

Region(AAL)	Peak Voxel	Z-score	Number of voxels
Anterior cingulate	4 40 0	7.18	456
Caudate	−34 -16 -12	6.26	136
Cingulate gyrus	18 -44 32	7.18	845
Cuneus	24 -78 18	7.91	1703
Fusiform gyrus	36 -40 -12	6.99	554
Inferior frontal gyrus	36 40 4	7.36	930
Inferior parietal lobule	50 -32 22	6.63	470
Insula	36 14 14	7.72	1204
Lingual gyrus	14 -80 -6	7.54	1355
Medial frontal gyrus	14 28 38	7.18	716
Middle frontal gyrus	−38 0 42	7.18	1751
Middle occipital gyrus	−40 -72 6	7.72	789
Middle temporal gyrus	−46 -64 12	6.81	1722
Parahippocampa gyrus	−34 -40 -12	7.36	824
Postcentral gyrus	−54 -20 16	6.44	854
Posterior cingulate	26 -72 8	7.18	222
Precentral gyrus	30 -12 52	6.26	1709
Precuneus	20 -72 18	7.72	1700
Putamen	−22 16 0	6.63	612
Superior temporal gyrus	−48 -12 0	7.18	1296
Thalamus	−16 -28 10	7.36	635

Third, *challenge* showed positive correlations with parts of premotor cortex, higher-level visual areas and the fusiform gyrus. We know from previous work that setting clear goals – as opposed to diffuse instructions – leads to increased activity in the fusiform area and decreased activity in precueneus (Klasen et al., 2012). This is in line with the results observed in the present study, since the setting of a challenge means that people are aware of what the goal is and how to achieve it. In addition to this, we see activity in the pre-motor areas, which is most likely associated with the increased control inputs that would need to be prepared to tackle the different game conditions.

Fourth, in our study, most of the regions that were negatively correlated with *flow* and *challenge* are part of the default mode network – this is shown in both the whole-brain analysis and in the decoding part (see below). Indeed, previous studies have shown that the default mode network becomes deactivated in goal-oriented tasks and hence is a task-negative network (Fox et al., 2005). Hence, as people became more engaged in the game, chasing the points and avoiding obstacles, the default mode network became more deactivated in these high *challenge* and *flow* situations.

Finally, we were not able to find significant correlations for the dimensions of *competence*, *tension* and *positive affect*. We suggest that whereas our manipulations were able to induce changes in most gaming experience variables, future versions of the game designs should focus on further manipulating both the number of obstacles and number of targets to induce different levels of competence and tension as these two game variables had the largest effect on these dimensions in our behavioral data. Concerning positive affect, it would be possible to look at the contrast between both negative and positive affect, or to specifically introduce reward mechanisms into the game to increase the awareness of a positive outcomes.

4.3. Correlational searchlight analysis

In a subsequent, correlational searchlight analysis, we next used the overall GEQ ratings to decode the different experiences. In this analysis, we also found parts of the ventral visual stream, several frontal regions, as well as the insula which were correlated with the behavioral rating differences. Since this analysis collapses the different GEQ dimensions, we expected the results to reflect the major, broad-scale brain correlates of subjective gaming experiences.

Overall, our results highlight several higher-level areas of the ventral visual pathway, which is consistent with increased demands on object processing in the different conditions (for example, between the goal-decrease and the difficulty-increase conditions). In contrast to the prior correlation analyses, however, the searchlight analysis did not show as much activation in other visually-related areas, which is due to the fact that all seven subjective experience scales were merged in the analysis, resulting in larger influence of other, less visually-related dimensions.

The additional frontal activations that were observed here relate to previous findings on “presence” – the sense of “being-there” in a virtual environment – that has been shown to activate dorso-lateral pre-frontal

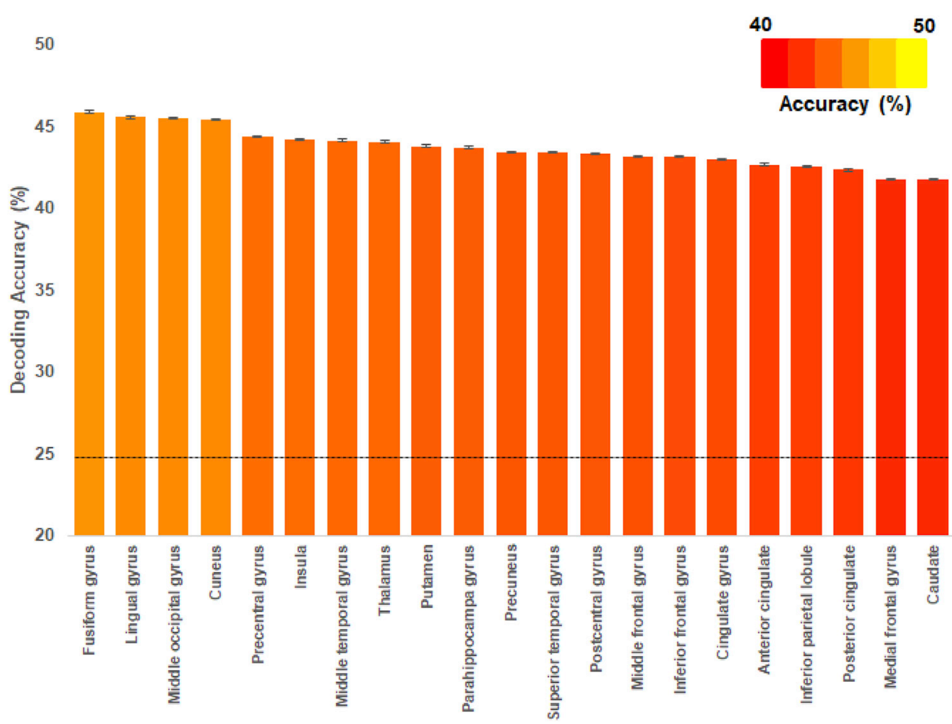

Fig. 6. Average decoding accuracy in the different brain areas. Bars are SEM. The dotted line is the chance level for decoding the four different conditions (=25%).

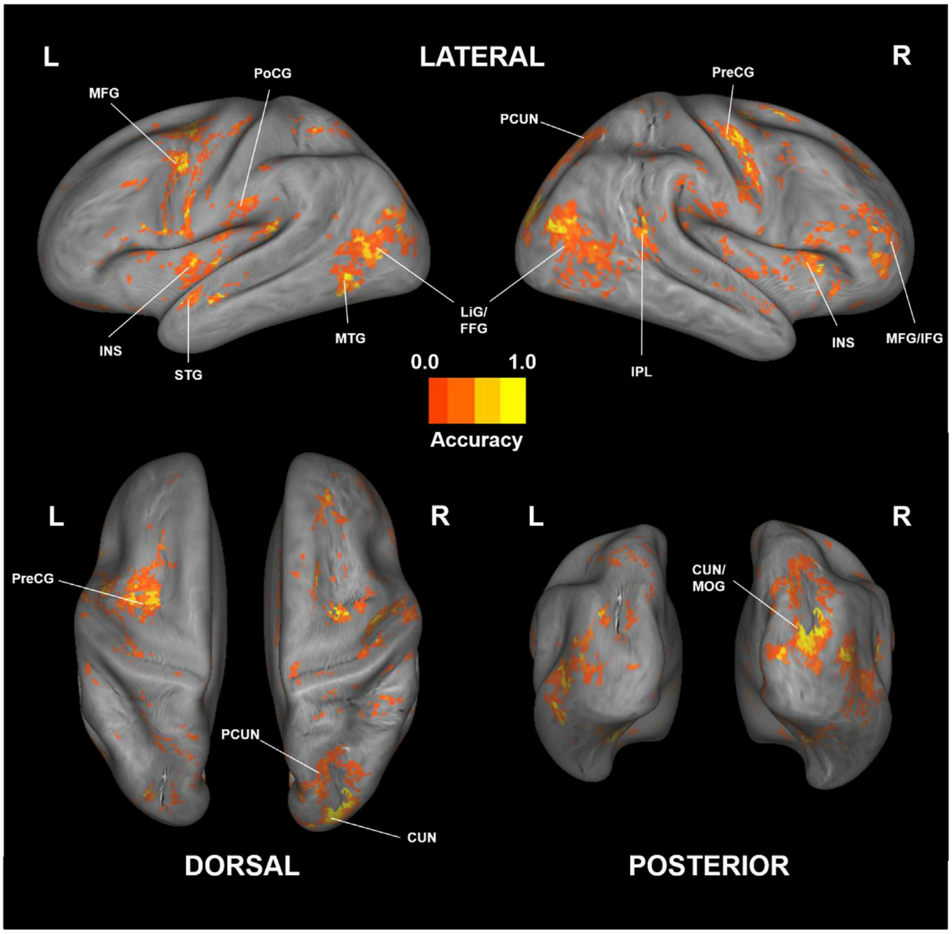

Fig. 7. Discriminative searchlight analysis for brain regions that are able to decode the four different game conditions ($p < .05$ FWE-corrected). The anatomical labels are abbreviated as follows: IFG, inferior frontal gyrus; MFG, middle frontal gyrus; INS, insula; STG, Superior temporal gyrus; MTG, Middle temporal gyrus; LiG, lingual gyrus; FFG, fusiform gyrus; PreCG, precentral gyrus; PoCG, postcentral gyrus; IPL, inferior parietal lobule; CUN, cuneus; PCUN, precuneus. Voxels are shown for accuracy above chance level (=0.25).

cortex (DLPFC) (Baumgartner et al., 2008). It may also be possible to connect this frontal activity to previous studies on emotion regulation (Kim and Hamann, 2007), since achieving the game goals – despite frustration at not collecting the targets or frustration at hitting an obstacle – may involve the up- or down-regulation of emotional processes in order to focus on the tasks at hand. This study showed that increasing and decreasing one's positive and negative emotions are associated with activity in superior frontal and medial gyri – both of which were implicated in our results as well.

With regard to the additional activation in the insula, prior studies have found that posterior insula activity was increased during encoding of the passage of time whereas anterior insula activity was increased during reproduction of time periods (Wittmann et al., 2010) – in our context, more immersed people may “lose themselves” in the game, hence potentially losing track of time when posterior insula activity decreased (Jennett et al., 2008). This may fit also with studies that have implicated increased activity in the posterior insula with increased primary interoceptive bodily self-awareness and increased activity in the anterior insula with increases in self-awareness related to motivational, social and cognitive functions (Tsakiris et al., 2007, 2010; Craig and Craig, 2009; Heydrich and Blanke, 2013a). Lastly, a previous study also showed that bilateral insula activation was inversely related to positive evaluation of the game-play (Mathiak et al., 2013b), indicating a potential role of the affective evaluations in our overall ratings.

4.4. Discriminative searchlight analysis

Finally, we augmented the previous correlational and overall whole-brain analyses with another, discriminative view. When looking for informative brain areas that were able to classify different game conditions, we found – consistent with the correlational, individual analyses – more discriminability in visually-related regions, including middle occipital gyrus, precuneus, and cuneus. In addition, we found that higher-level, visually-related areas – especially the fusiform gyrus – yielded the highest decoding accuracy. We know that the fusiform gyrus plays a role in the transition between lower-level and higher-level visual processing (Weiner and Zilles, 2016) and assists visual processing such as object recognition and visual attention (Caspers et al., 2013; Julian et al., 2014). Interestingly, together with the fusiform gyrus, the lingual gyrus, middle occipital gyrus, and cuneus also have been known for their involvement in visual attention or visuo-spatial attention (for classical studies, see Mangun et al., 1998; Martinez et al., 1999, Hopfinger et al., 2000, for newer work see (Bavelier et al., 2012; Chechlacz et al., 2012; Mayer et al., 2012; Plow et al., 2014)).

Since the largest (visual) changes between the conditions consisted in the increased presence or absence of both obstacles and targets, this may explain the comparatively high accuracy we observed.

Overall, this analysis is another indication that our different games actually resulted in distinct changes in the brain activity that capture aspects of the subjective gaming experiences which were the target of the four game conditions.

5. Conclusion

The present study is to our knowledge the first to use a series of customized games targeting the manipulation of aspects of subjective gaming experience with the goal of charting their related brain networks. Results for individual dimensions yielded different, experience-specific networks of brain areas for several core aspects of the gaming experience questionnaire (GEQ). A correlational whole-brain analysis for a combined measure of subjective experience as well as a discriminative analysis were used to augment the conclusions, highlighting broad-scale visual, spatial, and higher-level processing sites. Although one may assume that different experiences will also engage different brain areas, the specific networks that co-vary with the subjective evaluation have so far not been investigated in detail – data that is provided by our study.

Future studies, however, are needed to examine how the dimensions of competence, tension and positive affect may emerge from imaging data of the gaming experience as these did not show large enough activation clusters in our first whole-brain analysis. For this, one may need to design games that would affect these dimensions even more strongly than in the present study.

Relatedly, the present study only used four different game conditions, leaving room for exploring the full space of the subjective game experience further. Future work is needed to manipulate and measure the gaming experience in a more continuous manner, as this would allow us to conduct detailed regression analysis on the experience measures with different types of game variables and brain activity. Similarly, it would be ideal to obtain subjective data *throughout* the gameplay in order to relate specific events and properties of the game back to changes in brain activity. Providing (multidimensional) feedback during gameplay, however, would become challenging as participants are involved in difficult control tasks, leaving them little to no resources to provide other responses at the same time. One possibility to overcome this issue that still would allow for a multidimensional analysis of the game experience would be to have participants annotate the different dimensions post-scanning as they watch themselves playing the game.

Finally, it would be interesting to extend the current analyses with additional functional connectivity data to provide another view on the brain processes underlying subjective gaming experiences.

Overall, we believe that these results nonetheless are an important first step in investigating higher-level aspects of brain processing beyond the usual paradigms in the field in which mostly passive, non-interactive tasks have been used. Based on these first results, we would like to continue further in charting these aspects in the brain, generalizing to different types of games and environments. Importantly, our approach could be used in the future to test and compare specific populations such as patients with gaming addictions or with disorders related to aggressive, angry, or violent behavior. This would allow us to analyze how their subjective gaming experience and the brain networks engaged in its creation compare to those in a control group, helping us to chart and potentially predict behavioral and neurological health issues. In the broadest sense, our study also provides further insights into the complexity of brain processes happening in more life-like, interactive environments and shows that such settings can be used to map higher-level cognitive and subjective experience in human brain function. We expect future research to continue in closing the gap between controlled experimental settings and real-world settings.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2018.11.061.

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