

The Opponent Matters: Elevated fMRI Reward Responses to Winning Against a Human Versus a Computer Opponent During Interactive Video Game Playing

Jari Kätsyri^{1,2}, Riitta Hari^{3,4}, Niklas Ravaja^{1,5,6} and Lauri Nummenmaa^{3,7,8}

¹Center for Knowledge and Innovation Research, Aalto University School of Business, Helsinki, Finland, ²Department of Media Technology, Aalto University School of Science, Espoo, Finland, ³Brain Research Unit, O.V. Lounasmaa Laboratory, Aalto University School of Science, Espoo, Finland, ⁴Advanced Magnetic Imaging Centre, Aalto University School of Science, Espoo, Finland, ⁵Helsinki Institute for Information Technology, Helsinki, Finland, ⁶Department of Social Research, University of Helsinki, Helsinki, Finland ⁷Department of Biomedical Engineering and Computational Science, Aalto University School of Science, Espoo, Finland, and ⁸Turku PET Centre, Turku, Finland

Address correspondence to Jari Kätsyri, Department of Media Technology, Aalto University, P.O. Box 15500, FI 00076 Aalto, Finland.
Email: jari.katsyri@aalto.fi.

Winning against an opponent in a competitive video game can be expected to be more rewarding than losing, especially when the opponent is a fellow human player rather than a computer. We show that winning versus losing in a first-person video game activates the brain's reward circuit and the ventromedial prefrontal cortex (vmPFC) differently depending on the type of the opponent. Participants played a competitive tank shooter game against alleged human and computer opponents while their brain activity was measured with functional magnetic resonance imaging. Brain responses to wins and losses were contrasted by fitting an event-related model to the hemodynamic data. Stronger activation to winning was observed in ventral and dorsal striatum as well as in vmPFC. Activation in ventral striatum was associated with participants' self-ratings of pleasure. During winning, ventral striatum showed stronger functional coupling with right insula, and weaker coupling with dorsal striatum, sensorimotor pre- and postcentral gyri, and visual association cortices. The vmPFC and dorsal striatum responses were stronger to winning when the subject was playing against a human rather than a computer. These results highlight the importance of social context in the neural encoding of reward value.

Keywords: emotion, natural stimulation, reward system, striatum, video game playing

Introduction

Playing video games is a popular leisure-time activity. Most games include specific success- and failure-related events (e.g., winning and losing against one's opponent) that the players strive to achieve and to avoid, respectively. These events trigger pleasant and unpleasant emotional responses (cf. Ravaja et al. 2006a) and may hence function as rewards and punishments. Consequently, games provide a good model for studying motivated behavior.

Playing video games against humans rather than computer-controlled opponents adds an element of social interaction to playing, even when the players are not physically located in the same space (i.e., playing over the internet or LAN). The mere knowledge of playing against another human may evoke a heightened sense of social presence or “being together” (Biocca et al. 2003) with the opponent, and influence how the players interpret the various game events. Although players show generally more positive emotional responses when playing against another human rather than a computer (Ravaja et al. 2006b; Ravaja 2009), the brain networks integrating social information with hedonic value of specific motivational events, such as winning and losing, remain poorly

understood. In the present functional magnetic resonance imaging (fMRI) study, we tested whether winning versus losing against an opponent in a competitive video game activates the brain's reward circuitry, and whether winning against a human compared with a computer player is associated with increased activation in the reward circuit.

Reward Circuit and Video Game Playing

Both animal electrophysiology and human neuroimaging studies indicate that a dopaminergic circuit including mid-brain, striatum, amygdala, and prefrontal cortical regions is involved in processing rewards and supporting motivated behavior (O'Doherty 2004; Bressan and Crippa 2005; Knutson and Cooper 2005; Schultz 2006; Delgado 2007; Hikosaka et al. 2008; Haber and Knutson 2010). Particularly, the ventral striatum, comprising nucleus accumbens (NAcc) and the most ventral parts of putamen and caudate nucleus (Delgado 2007; Haber and Knutson 2010), has been consistently implicated in processing reward, but also the dorsal striatum has been associated with receiving rewards (cf. Delgado 2007). This dopaminergic circuit is also engaged during video game playing, most likely reflecting the rewarding nature of gameplay (Koepp et al. 1998; Hoefft et al. 2008). Within prefrontal cortex, the anterior ventral medial prefrontal cortex (vmPFC) and orbitomedial prefrontal cortex (omPFC) have been associated with processing obtained rewards. However, it has also been proposed that the vmPFC could have a more general role in processing emotions and higher-order cognitive phenomena, such as self-reflection and mentalizing (Amodio and Frith 2006): the vmPFC is engaged during various emotional tasks, whereas cognitive tasks activate more dorsal regions of medial prefrontal cortex (dmPFC) (for a review, see Steele and Lawrie 2004).

Despite considerable evidence for reward processing in the striatum and frontal cortex, the neural basis of reward processing during video game playing remains poorly understood. One positron emission tomography (PET) study (Koepp et al. 1998) has demonstrated increased dopamine release in ventral and dorsal striatum during video game playing, with positive correlation between dopamine release and the success in the game. These results confirm that the dopaminergic reward system is tonically activated during playing, but the lack of temporal resolution of [¹¹C]-PET studies poses limitations on the interpretation of these results with respect to specific events such as single wins and losses.

Only a handful of fMRI studies have tried to tap the brain basis of positive emotions elicited during gameplay. Consistent with the aforementioned PET data, increased NAcc fMRI activations were observed while the subject was playing a simple reaction-time video game (Hoefl et al. 2008); however, brain responses were not measured in relation to specific game events, such as winning or losing. In a recent fMRI study (Mathiak et al. 2011), caudate nucleus activation was suppressed during failures (being eliminated by an opponent) in a violent video game, but—somewhat unexpectedly—also successes (eliminating the opponent) were associated with striatal suppression, including the caudate nuclei. Although a further analysis of the data (Klasen et al. 2012) revealed stronger striatal activation for successes than failures, it is possible that these results could be explained in part by sensorimotor rather than reward processes: the players continued to compete against the remaining computer opponents after successes, whereas they had to stop playing after failures (cf. Mathiak et al. 2011).

Although neural circuits processing social aspects of gameplay have not been studied previously, data from analogous economic decision-making games suggest that vmPFC might play a critical role in social context-dependent reward processing. Responses within vmPFC are elevated in participants who choose to cooperate rather than to compete for limited resources (Rilling et al. 2002, 2004; Decety et al. 2004); furthermore, the vmPFC responses are elevated when participants make decisions against a human rather than a computer partner (Kircher et al. 2009). Consequently, it seems likely that vmPFC processes social, in addition to hedonic, aspects of reward, thus making it a key candidate region for coding opponent-contingent responses to wins and losses during gameplay.

Taken together, prior brain imaging studies suggest that playing video games may engage the dopaminergic brain reward circuit—in particular, the striatum and the vmPFC—but our understanding of the brain reward responses triggered by specific emotional game events remains elusive. Crucially, it is not known how the social context of gameplay influences the neural processing of rewarding and aversive game events, and no prior study has tested how specific game events influence the functional interactions of the reward circuit with other brain regions. Of special interest for reward processing are interactions between the ventral striatum, amygdala, and prefrontal cortex, which are known to have direct anatomical connections (e.g., Kelley 2004; Haber and Knutson 2010). Furthermore, given the indirect connections between ventral and dorsal striatum (Haber and Knutson 2010) and the direct connections from the dorsal striatum to frontal cortex (Parent and Hazrati 1995), the ventral striatum likely interacts also with dorsal striatum, frontal associative cortex, and motor areas. Consistently with these predictions, recent functional imaging studies have demonstrated that reward signals modulate the interconnectivity of the ventral (Passamonti et al. 2009; Stoeckel et al. 2009) and dorsal (Nummenmaa et al. 2012) striatum to both limbic (amygdala, anterior cingulate cortex) and frontal (including somatosensory cortex, premotor cortex, posterior insula, and vmPFC) areas.

The Present Study

In the present study, we addressed the brain basis of reward processing and social aspects of gameplay in the context of a competitive first-person tank shooter game against alleged human and computer opponents during fMRI scanning.

Blood oxygenation-level-dependent (BOLD) signals were measured during the game play and compared between rewarding (win) and aversive (loss) events. Timings of wins and losses were recorded automatically. Thus, we were able to apply conventional event-related, random-effects general linear model (GLM) analysis for testing the effects of rewarding and aversive events on the BOLD signal changes, as well as unraveling the interaction effect with opponent type (human vs. computer) even though the participants were free to play the game in any way they wanted and the occurrences of wins and losses varied across participants.

To study how winning and losing in the game modulate the interconnectivity of the reward circuit, we selected the right anteroventral putamen as the region of interest (ROI) for psychophysiological interactions (PPIs) analyses (Friston et al. 1997), given that it has previously been implicated with processing successes and failures during video game play (Mathiak et al. 2011). This analysis allowed us to pinpoint regions with higher neuronal “coupling” with striatum during rewarding than aversive game events. We hypothesized that 1) winning versus losing in the game would evoke elevated activity in vmPFC and striatum, and that 2) these activations would be stronger during playing against a human compared with a computer opponent. Finally, we predicted that 3) the functional interactions of the ventral striatum (right anteroventral putamen) with limbic (amygdala and dorsal striatum) and frontal (motor, premotor, orbital, and medial prefrontal) areas would be modulated by winning versus losing in the game.

Materials and Methods

Participants

The participants were 17 right-handed male volunteers with a mean age of 24.8 years (range 20–33 years) and with abundant experience in playing video games (mean 7.7 h/week, range 1–20 h/week). None had prior experience with the game played in the present study. Their weekly video game playing hours were clearly below the typical cutoff 30 h/week, which has been used to indicate addictive video game playing behavior (Ko et al. 2009; Han et al. 2010). Fourteen participants reported playing first-person shooter games on a regular basis with modest weekly play times (mean 2.9 h, range 0.25–10 h). All participants were Finnish under- or postgraduate university students. Only male participants were recruited because men typically have more experience playing video games, are more motivated to play in social situations, and show higher preference than women for competitive video games (Lucas and Sherry 2004). Participants with self-reported history of neurological or psychiatric disorders were excluded. All participants provided written informed consent as part of a protocol approved by the Ethics Committee of the Helsinki and Uusimaa University District and received monetary compensation for their lost working hours.

Experimental Setup

During scanning, participants played 2 10-min sessions of the first-person tank-shooter game “BZFlag” (an in-house modified version of 2.0.14; <http://bzflag.org>) against alleged human and computer opponents who played the game over a local area network (see below). Figure 1 shows gameplay screenshots and Supplementary Video 1 shows an example of gameplay video. BZFlag was chosen because it is easy to play in the scanner, it is easy to play even without prior experience on similar games, it has realistic 3D graphics, and it is easily modifiable for research purposes because it is an open-source game. The pace of the game was modified to fit the requirements of fMRI analysis (ca. 1–2 win or loss events per minute; see below).

Although the participants were told that they would be playing against human and computer opponents, in reality the actual opponent

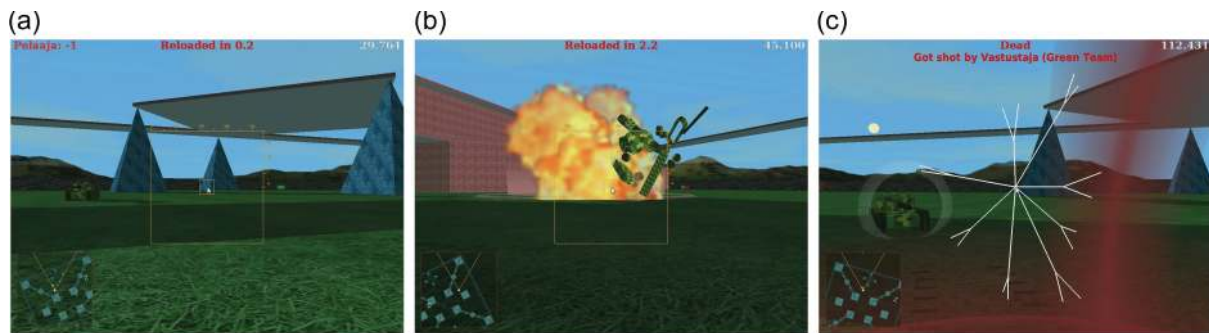


Figure 1. Screen captures from the modified BZFlag game: (a) player is exploring the game environment, (b) player has hit the opponent (win event), and (c) player has been hit by the opponent (loss event). The upper border of the screen containing timers and status messages (e.g. “Ready”) was not visible to the scanned participants.

was always a human player in order to retain a similar difficulty level in both conditions. In other words, we tested whether the knowledge of who is controlling the opponent character influences the brain responses to game events; this methodological choice was feasible as the players did not see or hear each other (cf. implicit audience effect; Fridlund 1991). The same human player (confederate) served as both the human and computer opponent against all players. The video game was modified so that pulse signals from the fMRI scanner triggered the beginning of each game and the timestamps of joystick movements, as well as win and loss events in the game, were automatically logged and time-referenced to the scanner pulses during gameplay.

During each round of the game, the player had to seek and destroy the opponent's tank without himself getting destroyed. Players controlled the game with a magnetic resonance imaging (MRI)-compatible joystick (Current Designs, Inc.; Model HHSC-JOY-1; <http://curdes.com>). They could move freely in the horizontal plane of their environment by moving the joystick, and shoot by pressing the fire button. Shooting was restricted to one shot per 3 s. Figure 1a shows a screen capture from a typical game scene. When the player's shot hit the opponent, the opponent's tank exploded on the screen (win events, Fig. 1b). When the opponent's shot hit the player, the player's visual screen got fractured and the player was unable to move (loss events, Fig. 1c). Whenever either of the players was destroyed, his tank respawned after 6 s at a random location in the battlefield, and the next round began. On average, win events occurred every 35.5 ± 3.2 s (mean \pm SD) and loss events every 39.6 ± 3.3 s. In line with previous studies (in particular, Koeppe et al. 1998), we increased the motivational pull of the game by introducing symmetric monetary rewards and punishments to wins and losses, respectively. Participants were told that they would gain money (+0.33 Euros) when winning and lose money (−0.33 Euros) when losing in the game; in reality, everyone received an equal monetary compensation (30 Euros) when the experiment was finished.

The beginning of the game was synchronized with the acquisition of functional images in the MR scanner. Gameplay was presented via an angled mirror above the participant's eyes, which reflected images back-projected onto a translucent screen in the bore of the magnet behind the participant's head. Game sounds were transmitted to subjects' ears with pneumatic earpieces. Before scanning, each participant's hearing threshold was measured by a standard staircase method (Wetherill and Levitt 1965), and the volume level for game sounds was set to the threshold plus 70 dB, adjusted slightly on the basis of participant feedback when necessary. In the scanner, the participants practiced the game for 5 min before the actual measurement. At the beginning of both sessions, the participants were informed via loudspeakers whether they played against a human or a computer opponent. The order of the human- and computer-opponent sessions was counterbalanced across participants.

Self-Reports and Behavioral Measures

Positive and Negative Affect

Immediately after each game session, the participants were asked to evaluate their playing experience on the positive affect scale (“I felt good” and “I felt content”) and negative affect scale (“I felt bored”

and “I found the game tiresome”) of the Game Experience Questionnaire (Ijsselstein et al. 2008). Evaluations were given on a scale ranging from 1 (not at all) to 5 (extremely). Additionally, participants were asked to rate the overall pleasantness of all win and loss events on a scale ranging from 1 (extremely unpleasant) to 9 (extremely pleasant).

Social Presence

Feelings of social presence during each game session were measured with the Social Presence in Gaming Questionnaire (de Kort et al. 2007), consisting of 17 items tapping empathy (e.g., “I felt connected with the other player”), involvement (e.g., “My actions depended on opponent's actions”), and negative feelings (e.g., “I felt malicious pleasure towards the opponent while playing”). Each item was evaluated on a scale ranging from 1 (not at all) to 5 (extremely). The presentation of all questions following the game session was automated and the responses were given by moving the joystick.

Learning and Performance

To test for potential confounds related to performance and learning, game scores (i.e., numbers of wins minus losses) were computed for early and late game phases (i.e., first and last 5 min) of each session. Furthermore, total accumulated scores were computed for each session and for each participant. Similarly, the following behavioral measures were extracted from the players' and opponent's game logs: forward speed, angular speed (rotation around tank's axis), number of shots, distance from opponent when shooting, and angle in relation to the other player.

Acquisition and Analysis of fMRI Data

Data Acquisition and Preprocessing

Functional and anatomical volumes were collected with a General Electric Signa 3.0 T MRI scanner at the Advanced Magnetic Imaging Centre of Aalto University. Whole-brain functional images were acquired using weighted gradient-echo planar imaging, sensitive to BOLD signal contrast (35 oblique slices without gaps, slice thickness = 4 mm, TR = 2070 ms, TE = 32 ms, FOV = 220 mm, flip angle = 75°, interleaved slice acquisition, 293 volumes per session with a 3.4×3.4 -mm resolution). The first three volumes were discarded to allow for equilibration effects. T_1 -weighted structural images were acquired at a resolution of $1 \times 1 \times 1$ mm³ using a sequence with ASSET calibration. Data from 4 participants with excessive movement artifacts (see below) and data from one participant with repetitive button presses after loss events were removed.

Preprocessing and analysis of fMRI data were performed using SPM8 software package (Wellcome Department of Imaging Neuroscience, London) in Matlab (version 7.10). The EPI images were realigned to the first scan by rigid-body transformations to correct for head movements. Realigned functional volumes were motion-adjusted and outlier volumes were identified based on scan-to-scan movement (0.5-mm change in head position) and global mean BOLD signal (1.3% signal change), and replaced by linear interpolation between

the closest nonoutlier volumes by using ArtRepair toolbox version 4 (<http://spnl.stanford.edu/tools/ArtRepair>; Mazaika et al. 2009). EPI and structural images were coregistered and normalized to the ICBM152 standard template in Montreal Neurological Institute (MNI) space at a $2 \times 2 \times 2\text{-mm}^3$ resolution using linear and nonlinear transformations, and smoothed spatially with a Gaussian isotropic kernel of 6-mm full width half maximum. Four participants whose data had more than 25% outlier volumes (see criteria above) were removed from further analysis. On average, 3.6% of volumes in sessions against a computer opponent and 4.6% of volumes in sessions against human opponent were classified as outliers (nonsignificant difference; $t(11) < 1$).

Regional Effects in the GLM

A random-effects model was implemented using a 2-stage process (first and second level). For each participant, responses to win and loss events were modeled as delta (stick) functions, convolved with the hemodynamic response function (HRF), and analyzed in GLM. Additionally, we calculated joystick movements (i.e., cumulative distances from the central position) during each TR, convolved this time course with the HRF and included it as a regressor to reduce variation in BOLD signal due to sensorimotor planning. The functional data were filtered temporally using an autoregressive (AR-1) model and a high-pass filter with 171.5-s cutoff (i.e., the duration of the longest game rounds). Individual contrast images for the conditions “winning against a human opponent,” “winning against a computer opponent,” “losing against a human opponent,” and “losing against a computer opponent” were generated. The second-level analysis used these contrast images in a new GLM from which statistical images, that is, SPM t -maps, were generated. With balanced designs at the first level (i.e., similar events for each subject, in similar numbers), this second-level analysis closely approximated a true mixed-effects design, with both within- and between-subject variance.

At the second level, the results were subjected to a 2×2 factorial analysis with factors event (win vs. loss) and opponent (human vs. computer), assuming dependency and unequal variances between the levels of both variables. Main effects for “win > loss” and “loss > win” were used to identify brain regions sensitive to winning and losing, and contrasts “human > computer” and “computer > human” were used to find brain regions sensitive to opponent regardless of events. To identify brain regions showing higher activation for human than computer opponents during winning or losing, interaction effect contrasts “win > loss \times human > computer” and “loss > win \times human > computer” were used. When not specified otherwise, a familywise error (FWE) corrected threshold of $P < 0.05$ and minimum cluster size of 20 was used for identifying statistically significantly activated voxels.

Region of Interest Analyses

A priori ROI analyses were conducted for determining the effects of winning and losing against human and computer opponents within striatal and frontal parts of the reward circuit. We approximated—as closely as possible—the functional division of striatum into limbic, associative, and sensorimotor parts (Parent and Hazrati 1995). First, we defined anatomical ROIs for NAcc, caudate nucleus and putamen using the Wake Forest University PickAtlas toolbox (Maldjian et al. 2003). Second, following Martino and et al. (2008) and Postuma and Dagher (2006), we made a priori divisions for the caudate nucleus into ventral ($z \leq 0$) and dorsal ($z > 0$) parts, putamen into anterior ($y > 0$) and posterior ($y \leq 0$) parts, and anterior putamen into ventral ($z \leq -4$) and dorsal ($z > 0$) parts based on MNI space coordinates (cf. Fig. 4a). Given the large number of anatomical landmarks for the reward-sensitive medial prefrontal cortex (mPFC), still without any universally agreed-upon consensus, the coordinates for vmPFC and dmPFC (cf. Fig. 4b; MNI 0, 46, 18 and 0, 28, 31, respectively) were derived from a prior meta-analysis on the role of mPFC in emotional and cognitive processing (Steele and Lawrie 2004). Spherical ROIs with 8-mm radius were drawn around these coordinates. Mean signal changes (in percentage) following win and loss events were calculated within the resulting 8 ROIs (NAcc, ventral caudate nucleus, ventral anterior putamen, dorsal caudate nucleus, dorsal anterior putamen, and posterior putamen; as well as vmPFC and dmPFC).

Functional Connectivity Analysis

We selected the anatomically defined right anteroventral putamen (cf. Fig. 4a) as a main seed ROI for the PPI analyses, given that in a previous fMRI study (Mathiak et al. 2011), the striatal activation peak (MNI coordinates 24, 24, -4) for motivational video game events fell within this region. The time series of each participant was computed by using the first eigenvariate from all raw voxel time series in each ROI. This BOLD time series was deconvolved using the PPI deconvolution parameter defaults in SPM8 (Gitelman et al. 2003) to estimate the neuronal time series for this region. The PPI term (PPI regressor) was calculated as the element-by-element product of the ROI neuronal time series and a vector coding for the main effect of winning versus losing. This product was reconvolved by the canonical HRF. PPI models were run separately for each participant, and contrast images were generated for PPIs. The model also included the main effects of task convolved by the HRF, and the convolved joystick movement regressors as effects of no interest. These models identified regions that had greater or lesser coupling with the striatal source region according to winning versus losing in the game. The obtained contrast images were subsequently entered into second-level GLM analyses. Given that PPI analyses are less optimal for event-related than block-based designs, the statistical significance threshold for analyses was relaxed to $P < 0.05$ FWE-corrected at clusters level ($P < 0.001$, uncorrected for voxel level).

Results

Behavioral Evaluations

Manipulation Check

When questioned explicitly about the opponent after the experiment, none of the participants indicated that they had been aware of playing against the same human opponent throughout the experiment; rather, everyone thought that they had played against computer and human opponents on the corresponding sessions. The confederate opponent was not blind to the experimental conditions, but none of his behavioral measures (see Section “Self-reports and behavioral measures”) showed statistically significant differences between the human versus computer conditions.

Positive and Negative Affect

Behavioral measures for human and computer opponents are presented in Table 1. An analysis with a 2 (affect score:

Table 1

Mean \pm standard error of mean self-rating measures for game sessions played against computer and human opponents

| Behavioral measure | Computer | Human | <i>P</i> |
|------------------------|----------------|----------------|--------------------|
| Affective tone | | | |
| Positive affect | 6.4 \pm 0.5 | 6.8 \pm 0.4 | 0.339 |
| Negative affect | 2.8 \pm 0.4 | 2.4 \pm 0.2 | 0.137 |
| Pleasantness | | | |
| Win events | 7.4 \pm 0.2 | 7.8 \pm 0.3 | 0.638 |
| Loss events | 2.7 \pm 0.4 | 2.8 \pm 0.3 | 0.166 |
| Social presence | | | |
| Empathy | 10.6 \pm 1.3 | 13.6 \pm 0.9 | 0.009** |
| Involvement | 23.1 \pm 1.4 | 25.4 \pm 0.5 | 0.019* |
| Negative feelings | 11.8 \pm 1.2 | 13.2 \pm 1.1 | 0.068 |
| Game scores | | | |
| Total score | 3.3 \pm 1.5 | 0.1 \pm 1.6 | 0.061 ^a |
| Late versus early game | 1.8 \pm 1.0 | 0.9 \pm 1.2 | 0.824 ^a |

P values refer to 2-tailed significances from paired *t*-tests comparing scores between computer and human opponents.

^aWilcoxon signed-rank test.

**P* < 0.05.

***P* < 0.01.

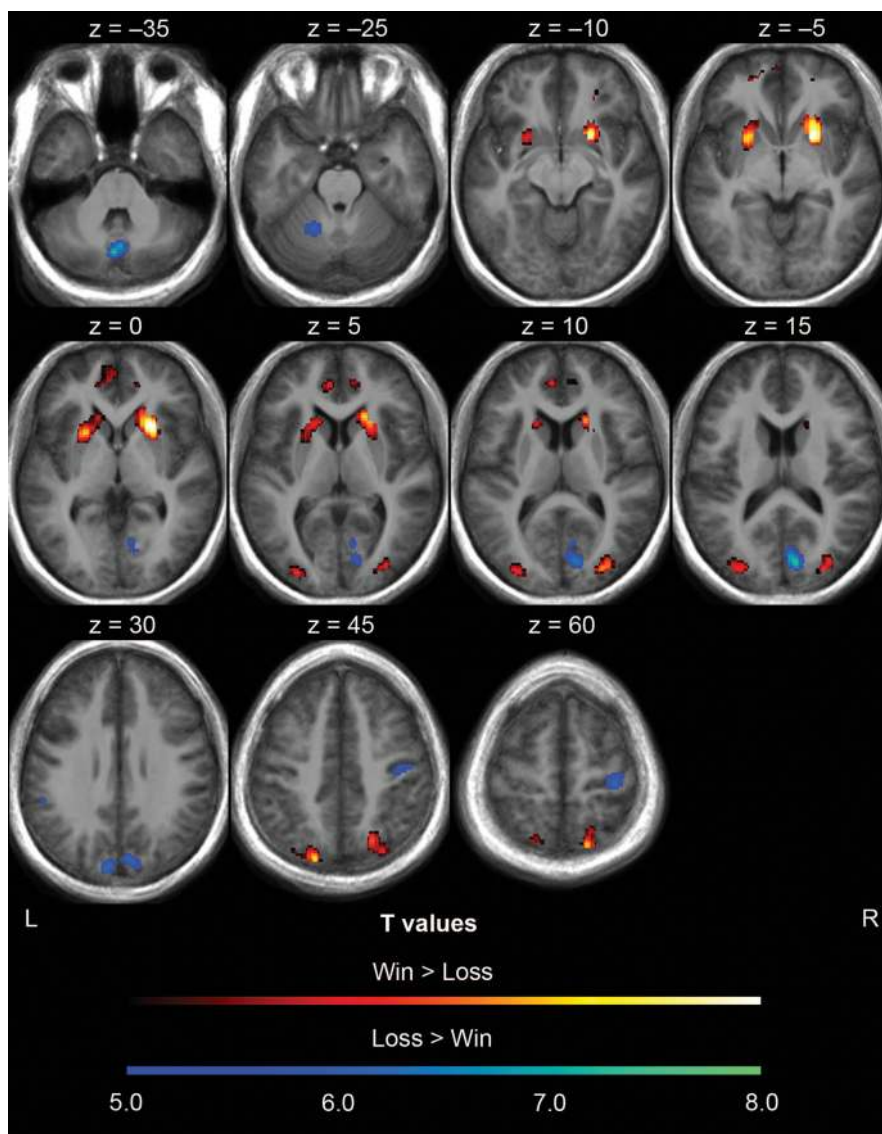


Figure 2. Axial sections showing greater activations to win compared with loss events (red to yellow) and vice versa (blue to turquoise) while playing the game. Data are thresholded at $P < 0.05$ (FWE-corrected). L refers to the left and R to the right hemisphere.

positive/negative affect) $\times 2$ (opponent: human, computer) repeated-measures analysis of variance (ANOVA) confirmed that participants experienced significantly more positive than negative affect while playing the game ($F(1, 11) = 53.40$, $P < 0.001$, Cohen's $d = 4.4$). The interaction between affect score and opponent was not significant ($F(1, 11) = 2.05$, $P = 0.18$). Pleasantness ratings were evaluated with a 2 (event: win, loss) $\times 2$ (opponent: human, computer) repeated measures ANOVA. The results confirmed that win events were rated significantly more pleasant than loss events ($F(1, 11) = 81.87$, $P < 0.001$, $d = 5.5$). The opponent ($F(1, 11) = 1.32$, $P = 0.28$) and the interaction between event and opponent ($F(1, 11) < 1$) did not significantly influence pleasantness evaluations.

Social Presence

Players experienced stronger empathy towards their opponent ($T = 3.35$, $d = 1.0$) and were more involved in the opponent's actions ($T = 2.13$, $d = 0.6$) when playing against a human rather than a computer player (see Table 1).

Performance and Learning

Wilcoxon signed-rank test showed no significant differences between the games played against human and computer opponents in either overall performance (i.e., end scores) or learning within the games (i.e., score differences between the late and early game phases; Table 1). Additional Friedman's ANOVA tests for game scores and players' behavioral measures (see "Self-reports and behavioral measures" section) during the early and late phases of the first and second games also failed to indicate significant learning effects; however, there was a nonsignificant trend toward higher scores during the late versus early games (mean \pm standard error of the mean (SEM) in first and second games: 1.50 ± 0.90 vs. -0.42 ± 0.82 , and 1.67 ± 0.64 vs. 0.75 ± 1.38 ; $\chi^2(3) = 7.34$, $P = 0.06$).

Regional Responses to Winning and Losing

Figure 2 shows brain regions with significant activations for winning compared with losing, and vice versa; Table 2 presents a complete summary of significant activation clusters of

all tested contrasts. Winning activated both subcortical (bilateral putamen and caudate nucleus) and cortical (vmPFC and omPFC) nodes of the reward circuit. Additional activations were observed in the premotor cortex (precentral gyrus). On the contrary, losing elevated activity in the somatosensory cortex (postcentral gyrus), supratemporal auditory cortex, and cerebellum. Furthermore, winning and losing evoked activations within separate regions of the occipital visual cortex and superior parietal lobule. Main effect comparisons between human and computer opponents, and vice versa, did not result in significant activations, suggesting that no brain regions were sensitive to the opponent per se (i.e., regardless of winning or losing).

No significant interaction effects for event \times opponent were observed using the *a priori* statistical threshold. However, using a slightly more lenient threshold $P < 0.05$ (FWE-corrected at cluster level, $P < 0.001$ uncorrected at voxel level), we observed activations for the interaction test “Win >

Loss \times Human > Computer” within precuneus and ventral and dorsal parts of the mPFC (Fig. 3), with these areas being more active when the participants were winning against a human rather than a computer player. For the sake of comparison, we also thresholded the results of the main effect “Win > Loss” using the same threshold and plotted these 2 sets of results in Figure 3. This analysis revealed that ventral medial and right PFC regions responded to winning versus losing, but did not show selectivity for opponent type. On the contrary, ventral and dorsal PFC within the left hemisphere both responded to winning versus losing in general and were selectively more responsive when winning against a human versus computer opponent. Finally, dorsal medial PFC regions responded only to winning against a human and computer opponent. No significant activations were observed for the contrast “Loss > Win \times Human > Computer”.

Region-of-Interest Analysis in Striatum and Frontal Cortex

Although our FWE-corrected full-volume analysis failed to demonstrate differential activations in striatum during win and loss events when the participants were playing against human versus computer opponents, anatomically-based ROI analyses allowed us to test the opponent-dependent activations of different striatal and frontal regions (Fig. 4*a,b*) with higher statistical power. Activations within the ROIs were analyzed with 2 (Event: win, loss) \times 2 (Opponent: human, computer) repeated-measures ANOVAs. An additional factor, hemisphere (left, right), was included in the analyses of bilateral striatal ROIs. Figure 4*c* shows results from the ROI analyses. The main effect of event reached statistical significance ($F > 5.10$, $P < 0.05$, $d > 1.4$) in all other striatal regions except the posterior putamen ($F(1, 11) < 1$), and in ventral ($F(1, 11) = 8.55$, $P = 0.01$, $d = 1.8$) but not in dmPFC ($F(1, 11) < 1$). The interaction effect between event and opponent was significant in dorsal striatum ($F(1, 11) = 7.62$, $P = 0.02$, $d = 1.7$) and in vmPFC ($F(1, 11) = 8.55$, $P = 0.014$, $d = 1.8$), but not in dmPFC ($F(1, 11) = 1.83$, $P = 0.20$). As shown in Figure 4*c*, the signal changes between win and loss events within these regions were larger when the opponent was human rather than computer. The interaction between hemisphere and event was

Table 2

Brain regions showing larger responses to win compared with loss events and vice versa, with further modulation by playing against human versus computer opponent

| Region | Hemisphere | Voxels | Peak <i>T</i> | MNI coordinate | | |
|---|------------|--------|---------------|----------------|----------|----------|
| | | | | <i>x</i> | <i>y</i> | <i>z</i> |
| Win > loss | | | | | | |
| Putamen/caudate nucleus | L | 358 | 7.47 | -24 | 8 | -4 |
| | R | 583 | 8.50 | 22 | 10 | -8 |
| Extrastriate cortex (BA 18, 19) | L | 227 | 7.85 | -30 | -86 | 24 |
| | R | 143 | 6.79 | 32 | -86 | 8 |
| Superior parietal lobule | L | 171 | 7.52 | -20 | -80 | 48 |
| | R | 344 | 7.57 | 24 | -72 | 50 |
| Ventromedial prefrontal cortex | L/R | 130 | 6.58 | -6 | 54 | -4 |
| | R | 21 | 5.76 | 12 | 46 | 6 |
| Loss > win | | | | | | |
| Striate/extrastriate cortex (BA 17–19) | L/R | 469 | 7.53 | 10 | -86 | 18 |
| | R | 27 | 5.67 | 10 | -68 | 2 |
| Postcentral gyrus | R | 181 | 6.28 | 38 | -26 | 62 |
| Superior parietal lobule/postcentral gyrus | R | 46 | 6.46 | 16 | -38 | 74 |
| Cerebellum (Vermis) | L/R | 114 | 7.57 | -4 | -74 | -36 |
| Cerebellum (V/VI) | L | 120 | 6.27 | -18 | -56 | -24 |
| Win > loss: human > computer^a | | | | | | |
| Precuneus | L/R | 363 | 4.57 | 8 | -58 | 36 |
| Medial prefrontal cortex | L/R | 473 | 4.45 | -12 | 50 | 12 |

Note: When not specified otherwise, the data are thresholded at $P < 0.05$ (FWE-corrected).

^a $P < 0.001$ (uncorrected) for voxels and $P < 0.05$ for clusters (FWE-corrected).

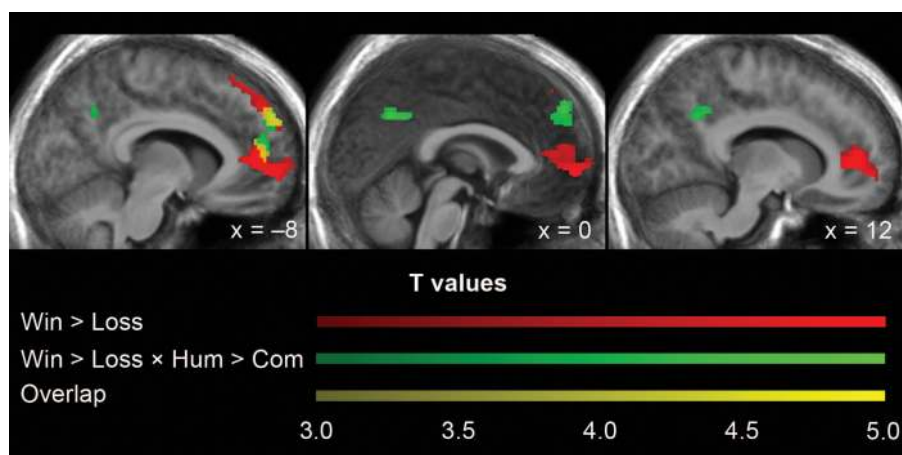


Figure 3. Sagittal sections showing regions with statistically significant activations for the main effect of winning compared with losing (in red), the further modulation of winning versus losing by playing against a human compared with a computer opponent (in green) and to both of these contrasts (in yellow). Data are thresholded at $P < 0.001$, uncorrected (FWE cluster corrected at $P < 0.05$) for visualization purposes.

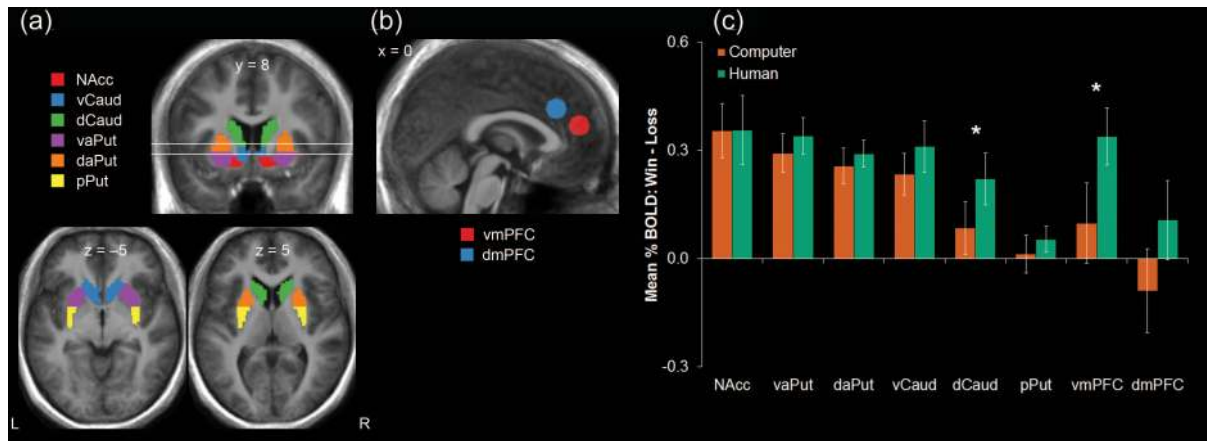


Figure 4. (a) Locations of striatal ROIs, illustrated on a coronal slice and 2 axial slices. The axial slice planes are illustrated as horizontal lines on the coronal slice. (b) Ventral and dorsal medial prefrontal cortex ROI locations, denoting mean activation foci of several emotional and cognitive tasks (Steele and Lawrie 2004), illustrated on a medial sagittal slice. (c) Mean percent signal change values between win and loss events within the ROIs. NAcc, nucleus accumbens; vCaud, ventral caudate; dCaud, dorsal caudate; vaPut, ventral anterior putamen; daPut, dorsal anterior putamen; pPut, posterior putamen; vmPFC, ventromedial prefrontal cortex; dmPFC, dorsomedial prefrontal cortex. Asterisk denotes a significantly ($P < 0.05$) larger signal change for human compared with computer opponent. L refers to the left and R to the right hemisphere.

statistically nonsignificant ($F < 3$, $P > 0.11$) for all other regions except posterior putamen ($F(1, 11) = 18.15$, $P = 0.001$, $d = 2.6$), for which mean per cent signal change values for wins versus losses were greater in the left (mean \pm SEM: 0.08 ± 0.04 ; $F(1, 11) = 4.11$, $P = 0.07$) than in the right hemisphere (-0.01 ± 0.04 ; $F(1, 11) < 1$). The interaction effect between hemisphere, event, and opponent did not reach significance in any region ($F > 1.28$, $P < 0.29$).

To investigate the relationship between participants' striatal and frontal reward responses and the self-reports of feelings of pleasantness, we correlated β weights for winning versus losing in the aforementioned ROIs with pleasantness ratings for winning versus losing. To guard against spurious results due to outliers, nonparametric Spearman's rank correlation tests were employed. As shown in Figure 5, the association between pleasantness and BOLD response was significant only in limbic striatal regions, specifically NAcc and vaPut. Finally, we tested the effects of plausible confounds—that is, game performance and experienced social presence—on the region-of-interest findings reported above by correlating 1) participants' gameplay scores with β values for winning versus losing, and 2) social presence scores for human versus computer opponents with β values for winning against a human versus a computer. The results indicated no statistically significant associations.

Functional Connectivity of the Striatum

The PPI analyses revealed increased coupling between the striatum (i.e., vaPut) and right insula, right inferior frontal gyrus, and cerebellum for winning compared with losing. In contrast, the coupling between the striatum (vaPut) and bilateral precentral gyri, right postcentral gyrus, bilateral superior parietal lobules, bilateral dorsal striatum (anterior putamen and caudate nucleus), and extrastriate cortex increased during losing compared with winning (Fig. 6a and Table 3). Further exploratory comparisons of the functional connectivity patterns between human and computer opponents did not reveal any significant connections that would have been modulated by both events and opponents.

Although the significant positive and negative PPIs indicate relative changes (increases and decreases, respectively) in the

effective connectivity between striatum and the target regions during winning compared with losing, they do not reveal the directions and magnitudes of couplings during either condition. For example, a positive PPI may indicate a change from negative to positive coupling due to winning, increased positive coupling due to winning, as well as increased negative coupling due to losing. To address the direction of the connectivity changes, we first calculated new PPI regressors between the deconvolved neuronal time courses and either win or loss events, for both the striatal seed region and for each of the PPI target regions (i.e., 6-mm spherical ROIs for the activation peaks in Table 3). That is, we repeated our previous procedure for calculating PPI regressors except that win and loss events served separately as the psychological variable in lieu of their interaction (cf. Ashburner et al. 2010).

Next, we calculated correlation coefficients between the obtained time courses for the striatal seed region and each of the target regions, normalized the coefficients with Fisher transformation, and averaged and inverse transformed the results over subjects. This exploratory analysis allowed us to estimate the directions and magnitudes of couplings separately during winning and losing. However, it should be emphasized that the results may slightly deviate from those obtained in the formal PPI analysis, because the original time course of wins versus losses is divided into 2 separate time courses. As shown in Figure 6b, the activity in all the regions depicting negative PPIs always showed a strong positive correlation with the activation of the striatal seed region; however, these correlations were higher during losing than winning. In contrast, the regions showing positive PPIs exhibited smaller correlations with the seed region and an increase for winning compared with losing. In particular, insula showed a negative correlation with striatum during losing and a positive correlation during winning.

Discussion

For the first time, we were able to delineate brain networks that process rewarding and aversive affective events in a dynamic, competitive video game as a function of the social context of game play. As predicted, we observed 1) greater

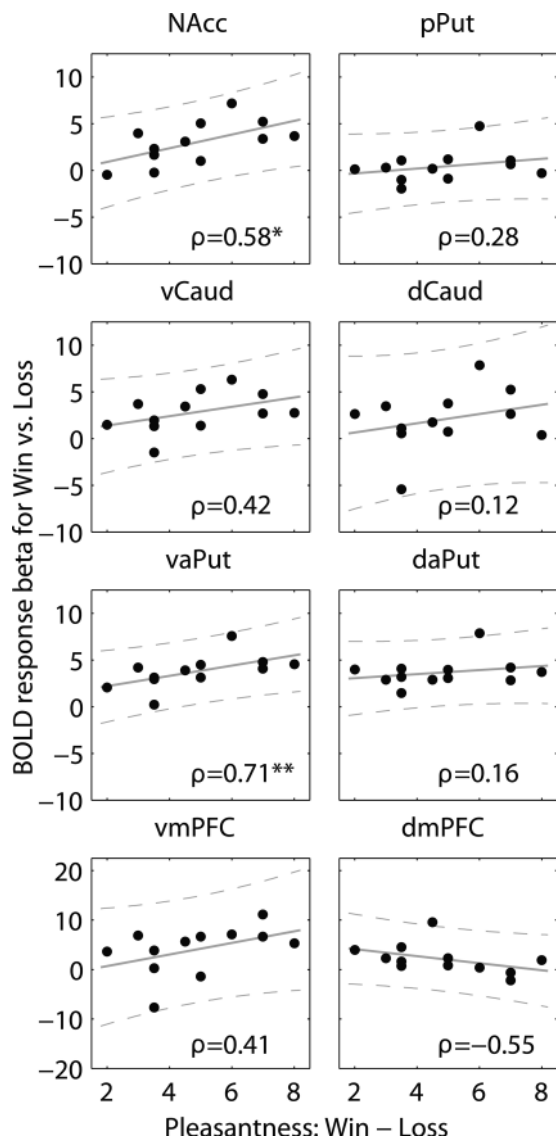


Figure 5. Scatter plots of pleasantness self-ratings versus BOLD responses in striatal (Fig. 4a) and frontal (Fig. 4b) regions of interests for the contrast winning versus losing (Spearman's rank correlation coefficients; * $P < 0.05$, ** $P < 0.01$). Regression lines are shown with 95% confidence intervals.

responses to rewarding compared with aversive game events in the striatal and frontocortical parts of the reward circuit, 2) modulation of the reward activations by the social context, and 3) functional connectivity changes both within the striatum and between the striatum and frontal areas.

Brain Reward Circuit Activations to Video Game Events

Video game playing activates striatal regions involved in affective processing (Hoeft et al. 2008) and triggers striatal dopamine release (Koepp et al. 1998), even when the gameplay itself contains both pleasant and unpleasant events or epochs. Consistently with a recent fMRI study (Klasen et al. 2012), our results demonstrate that specific game events related to winning engage striatum more than those related to losing. Sensorimotor contamination is unlikely, as we regressed out the effects of joystick movements.

In our analyses based on an atlas-based classification, the striatal reward activations occurred within the limbic (NAcc,

ventral caudate, and ventral putamen) and associative (dorsal caudate and putamen) striatum, but not in the sensorimotor (posterior putamen) striatal regions (for the anatomical division of striatum, see Parent and Hazrati 1995). Although the exact anatomical divisions cannot be identified from the available MRI cans, the validity of our atlas-based classification is supported by the striking differences in the reward sensitivity of the subsections of the striatum used in the ROI analysis (cf. Fig. 4c): the sensorimotor striatum showed no discernible sensitivity to winning versus losing, whereas limbic and associative striatal regions were reliably activated by winning in the game.

Although ventral (i.e., limbic) striatum has traditionally been given a central role in processing rewards (e.g., Parent and Hazrati 1995), more recent functional imaging studies have shown that the dorsal striatum is also associated with reward processing (Delgado 2007) and both dorsal and ventral striatal regions show tonic increase in dopaminergic activity during video game playing (Koepp et al. 1998). Consistent with these considerations, our results show that both dorsal and ventral striatum are activated more during rewarding than aversive video game events. Moreover, our functional connectivity results suggest that the ventral and dorsal striatal regions interact during reward processing.

We also found that winning versus losing activated the vmPFC/omPFC, a core cortical region of the reward circuit (Knutson and Cooper 2005; Haber and Knutson 2010). On the contrary, losing versus winning activated the right somatosensory cortex, suggesting that aversive game events had been associated with somatic processing. This interpretation is plausible given that the gameplay was presented from the first-person viewpoint, providing the player a strong embodied impression of getting physically hit by the opponent's missile during the loss events.

Although striatal activations triggered by winning are likely related to hedonic pleasure resulting from winning and receiving rewards, the striatum is also known to code reward expectations and reward prediction errors; that is, associations between actions and rewards, and between obtained and expected reward outcomes (Schultz 2006). In the context of competitive video games, the striatal regions could thus be involved in learning associations between specific behavioral maneuvers and successes in defeating the opponent. Our behavioral data showed only a marginally significant trend for improved game scores from the early to late games, implying that learning during the game play was rather modest, or of such type that it could not be captured with our measures. Moreover, our analyses did not indicate associations between players' performances and striatal activations.

Another confound for our results might be different sensory stimulation during winning and losing. However, even though winning and losing elicited different responses in the auditory and visual cortices, we are not aware of any previous studies that would have suggested striatal activations due to mere nonemotional visual stimulation. Hence, it seems unlikely that the observed striatal activations would have been driven by trivial visual confounds. Most importantly, the critical interaction between human versus computer opponents and win versus loss events was not susceptible to such confounds, given that the visual feedback remained identical regardless of the opponent.

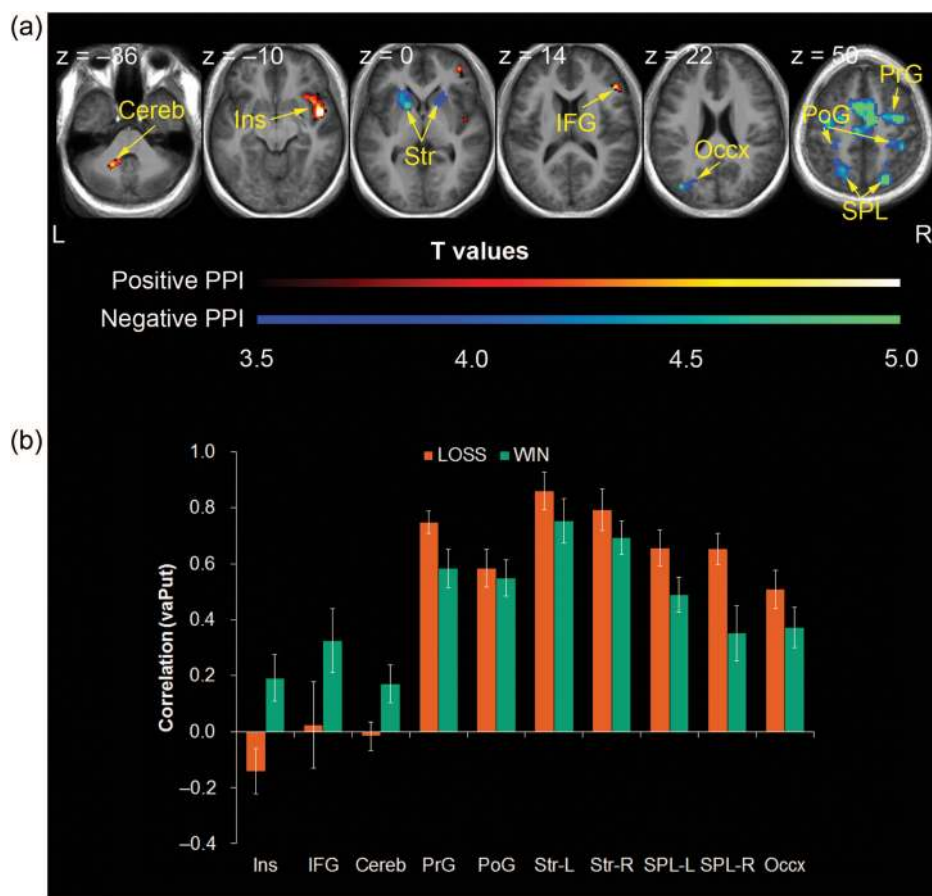


Figure 6. (a) Brain regions showing increased and decreased coupling with right striatum (i.e., ventral anterior putamen) during win versus loss events. Data are thresholded at $P < 0.001$, uncorrected (FWE cluster corrected at $P < 0.05$). (b) Mean correlations (with SEMs) between temporal activations in the striatal seed region and each of the PPI target regions during winning and losing. vaPut, ventral anterior putamen; Ins, insula; IFG, inferior frontal gyrus; Cereb, cerebellum; PrG, precentral gyrus; PoG, postcentral gyrus; Str-L/R, left and right striatum; SPL-L/R, left and right superior parietal lobule; Occx, extrastriate occipital cortex. L refers to the left and R to the right hemisphere.

Table 3

Brain regions showing positive and negative changes (PPIs) in coupling with right anteroventral putamen during winning compared with losing

| Region | Hemisphere | Voxels | Peak T | MNI coordinate | | |
|-----------------------------------|------------|--------|----------|----------------|-----|-----|
| | | | | x | y | z |
| Positive coupling | | | | | | |
| Insula | R | 487 | 5.91 | 48 | 2 | -10 |
| IFG (BA 10/45) | R | 236 | 4.80 | 50 | 30 | 14 |
| Cerebellum (dentate) | L | 130 | 4.69 | -18 | -54 | -36 |
| Negative coupling | | | | | | |
| Precentral gyrus | L/R | 4507 | 6.48 | 40 | -6 | 50 |
| Postcentral gyrus | R | 294 | 4.88 | 42 | -34 | 52 |
| Superior parietal lobule (BA 5/7) | L | 671 | 5.17 | -24 | -54 | 56 |
| | R | 886 | 6.40 | 22 | -74 | 54 |
| Putamen/caudate nucleus | L | 457 | 5.32 | -16 | 8 | 0 |
| | R | 201 | 4.43 | 16 | 20 | 8 |
| Extrastriate cortex (BA19) | L | 260 | 5.13 | -38 | -78 | 22 |

Note: The data are thresholded at $P < 0.001$ (uncorrected) for voxels and $P < 0.05$ (FWE-corrected) for clusters.

IFG, inferior frontal gyrus

Influence of the Social Context on Brain Responses

Our key finding was that striatal and frontocortical responses to winning versus losing in the game were elevated when the participants thought that they were playing against a human rather than a computer opponent. Specifically, winning compared with losing against a human versus a computer

opponent resulted in additive responses in brain regions that were generally sensitive to winning (dorsal caudate and vmPFC), as well as distinctive responses within dmPFC. We argue that the additive responses within vmPFC to winning against a human versus a computer opponent most likely reflect enhanced reward value, given that this region has been previously associated with emotional (e.g., Steele and Lawrie 2004) and particularly reward processing (Knutson and Cooper 2005; Amodio and Frith 2006; Haber and Knutson 2010). Importantly, a mere “belief” of who was controlling the opponent character was enough to elicit this effect, given that the participants could not see or hear their opponent who was in reality always a human. Thus, subjective interpretations of the social context (rather than the factual context) of the game play significantly influence the reward circuit’s responsiveness.

Despite significant differences in reward-related brain activation, participants reported experiencing similar levels of pleasure while playing against a computer and a human opponent. This lack of significant differences may reflect reward circuit activation that did not give rise to subjective awareness: although speculative, this suggestion is consistent with previous findings showing that even subliminal rewarding and aversive stimuli may influence decision making (cf. Berridge and Kringelbach 2008).

It is possible that some of the frontocortical activations also reflect the engagement of higher-order social reasoning. For example, winning against a human player might involve “Schadenfreude” (malicious pleasure) that is dependent on understanding that another real person feels displeasure over losing, and vmPFC has been previously implicated in such mentalizing processes (Amodio and Frith 2006). A further possibility is that playing against a real person would invoke cognitive inferences about the opponent, for example, regarding how the opponent will adapt his behavior after experiencing a loss. Consistently, dmPFC activation is increased (in superior frontal gyrus) during economic decision making against human compared with computer partners (Kircher et al. 2009). Interestingly, the reported peak activation (MNI coordinates 6, 61, 32) overlapped with the dmPFC cluster that was activated specifically to winning against a human rather than a computer in our study. Similarly, mPFC activation is involved in strategic learning related to the opponent’s beliefs in an economic decision making game (Zhu et al. 2012).

Segregating the effects of social reasoning and reward is difficult, however, because engaging in social interaction with real persons is inherently rewarding (cf. Dunbar 2010). In practice, some subregions within vmPFC may serve a general function in evaluating and/or representing reward value regardless of social reasoning, whereas other subregions may be sensitive to both reward and social reasoning (cf. van den Bos et al. 2007). Taken together, these considerations suggest that although vmPFC activations to win events may have reflected increased reward value, these responses may be modulated by social reasoning and context. However, given that the observed mPFC activations were not associated with either subjective pleasantness nor mentalizing (i.e., self-reported social presence during game play), the exact contribution of the frontal and prefrontal cortex to these tasks needs to be investigated in future studies.

Effective Connectivity of the Striatum

Consistently with our hypothesis, rewarding (winning) and aversive (losing) game events modulated the connectivity between ventral striatum (i.e., right anteroventral putamen) and dorsal striatum, prefrontal (IFG) and sensorimotor cortex, insula, and extrastriate visual cortex. Changes in the functional connectivity between ventral and dorsal striatum are of particular interest. The connectivity was stronger during losing than winning, but nevertheless positive during both events. This interaction between ventral and dorsal striatum may explain the apparent contradiction that the dorsal striatum, which is anatomically connected with associative rather than affective or reward related regions, was activated during reward processing. On the other hand, the same interaction may explain why the ventral striatum, which is anatomically connected with limbic regions, was functionally coupled with primary somatosensory, motor, and visual association areas.

Ventral striatum was functionally coupled to prefrontal cortex only during rewarding game events, and it interacted with a more dorsal and lateral part of the prefrontal cortex than the predicted vmPFC. Given that the dorsolateral prefrontal cortex is typically involved in cognitive tasks (e.g., Steele and Lawrie 2004), this interaction might reflect cognitive modulation of striatal activations. The interaction of

ventral striatum with the right insula was negative during aversive and positive during rewarding events, possibly reflecting interoceptive visceral states (Critchley et al. 2004; Naqvi and Bechara 2009) triggered by the game events; consistently, anatomical connections have been demonstrated between ventral striatum and insula (Chikama et al. 1997).

Conclusions

Rewarding versus aversive events during realistic video game playing evoked elevated responses in the brain’s reward circuit, particularly when the participants were playing the game against a fellow human rather than a computer player. Ventral and dorsal striatum, as well as vmPFC, showed increased activation during rewarding compared with aversive game events, and participants’ self-evaluations of pleasantness were associated with activations in ventral striatum. The differential responses due to the type of opponent were observed in the dorsal striatum, as well as both vmPFC and dmPFC. We propose that the differential activation patterns in striatum and vmPFC reflect higher levels of experienced reward when the participants were winning against a human rather than a computer opponent. Even brief game events thus seem to trigger reward-related neural processing. Exposure to such repeated rewards may explain why computer gaming—particularly against human opponents—is so rewarding.

Supplementary Material

Supplementary material can be found at: <http://www.cercor.oxfordjournals.org/>.

Funding

This work was supported by the aivoAALTO research project of the Aalto University; Academy of Finland (grant numbers #129678, #131483 to RH, #251125 to LN), European Research Council (#232946 to RH), and Emil Aaltonen Foundation (#595100 to JK).

Notes

The authors thank Marita Kattelus for her help with fMRI data acquisition, Cathy Nangini for language checking, and the volunteer participants for making this study possible. *Conflict of Interest:* None declared.

References

- Amodio DM, Frith CD. 2006. Meeting of minds: the medial frontal cortex and social cognition. *Nature Rev Neurosci*. 7:268–277.
- Ashburner J, Barnes G, Chen C-C, Daunizeau J, Flandin G, Friston K, Gitelman D, Kiebel S, Kilner J, Litvak V et al.. 2010. Chapter 33: Psychophysiological Interactions (PPI). In: *SPM8 Manual*. London: UCL, Functional Imaging Laboratory. p. 313–330.
- Berridge KC, Kringelbach ML. 2008. Affective neuroscience of pleasure: reward in humans and animals. *Psychopharmacology*. 199:457–480.
- Biocca F, Harms C, Burgoon J. 2003. Towards a more robust theory and measure of social presence. *Presence Teleop Virt*. 12 (5):456–480.
- Bressan R, Crippa J. 2005. The role of dopamine in reward and pleasure behaviour—review of data from preclinical research. *Acta Psychiatr Scand*. 111(427 Suppl):14–21.

- Chikama M, McFarland NR, Amaral DG, Haber SN. 1997. Insular cortical projections to functional regions of the striatum correlate with cortical cytoarchitectonic organization in the primate. *J Neurosci*. 17(24):9686–9705.
- Critchley HD, Wiens S, Rotshtein P, Ohman A, Dolan RJ. 2004. Neural systems supporting interoceptive awareness. *Nat Neurosci*. 7(2):189–195.
- Decety J, Jackson PL, Sommerville JA, Chaminade T, Meltzoff AN. 2004. The neural bases of cooperation and competition: an fMRI investigation. *NeuroImage*. 23(2):744–751.
- de Kort YAW, Ijsselstein WA, Poels K. 2007. Digital games as social presence technology: development of the social presence in gaming questionnaire (SPGQ). In: *Proceedings of the Presence 2007 Conference*; 2007 October 25–27; Barcelona, Spain. p. 195–203.
- Delgado MR. 2007. Reward-related responses in the human striatum. *Ann NY Acad Sci*. 1104:70–88.
- Dunbar RIM. 2010. The social role of touch in humans and primates: behavioural function and neurobiological mechanisms. *Neurosci Biobehav Rev*. 34:260–268.
- Fridlund AJ. 1991. Sociality of solitary smiling: potentiation by an implicit audience. *J Pers Soc Psychol*. 60(2):229–240.
- Friston KJ, Buechel C, Fink GR, Morris J, Rolls E, Dolan RJ. 1997. Psychophysiological and modulatory interactions in neuroimaging. *NeuroImage*. 6(3):218–229.
- Gitelman DR, Penny WD, Ashburner J, Friston KJ. 2003. Modeling regional and psychophysiological interactions in fMRI: the importance of hemodynamic deconvolution. *NeuroImage*. 19(1):200–207.
- Haber SN, Knutson B. 2010. The reward circuit: linking primate anatomy and human imaging. *Neuropsychopharmacology*. 35(1):4–26.
- Han DH, Hwang JW, Renshaw PF. 2010. Bupropion sustained release treatment decreases craving for video games and cue-induced brain activity in patients with Internet video game addiction. *Exp Clin Psychopharmacol*. 18(4):297–304.
- Hikosaka O, Bromberg-Martin E, Hong S, Matsumoto M. 2008. New insights on the subcortical representation of reward. *Curr Opin Neurobiol*. 18(2):203–208.
- Hoefl F, Watson CL, Kesler SR, Bettinger KE, Reiss AL. 2008. Gender differences in the mesocorticolimbic system during computer game-play. *J Psychiatr Res*. 42(4):253–258.
- Ijsselstein WA, van den Hoogen W, Klimmt C, de Kort Y, Lindley C, Mathiak K, Poels K, Ravaja N, Turpeinen M, Vorderer P. 2008. Measuring the experience of digital game enjoyment. In: *Proceedings of the Measuring Behavior 2008 Conference*; Aug 26–29; Maastricht, The Netherlands.
- Kelley AE. 2004. Ventral striatal control of appetitive motivation: role in ingestive behavior and reward-related learning. *Neurosci Biobehav Rev*. 27:765–776.
- Kircher T, Blümel I, Marjoram D, Lataster T, Krabbendam L, Weber J, van Os J, Krach S. 2009. Online mentalising investigated with functional MRI. *Neurosci Lett*. 454(3):176–181.
- Klasen M, Weber R, Kircher T, Mathiak KA, Mathiak K. 2012. Neural contributions to flow experience during video game playing. *Soc Cogn Affect Neurosci*. 7:485–495.
- Knutson B, Cooper JC. 2005. Functional magnetic resonance imaging of reward prediction. *Curr Opin Neurobiol*. 18(4):411–417.
- Ko CH, Liu GC, Hsiao S, Yen JY, Yang MJ, Lin WC, Yen CF, Chen CS. 2009. Brain activities associated with gaming urge of online gaming addiction. *J Psychiatr Res*. 43(7):739–747.
- Koepp MJ, Gunn RN, Lawrence AD, Cunningham VJ, Dagher A, Jones T, Brooks DJ, Bench CJ, Grasby PM. 1998. Evidence for striatal dopamine release during a video game. *Nature*. 393(6682):266–268.
- Lucas K, Sherry JL. 2004. Sex differences in video game play: a communication-based explanation. *Commun Res*. 31(5):499–523.
- Maldjian JA, Laurienti PJ, Kraft RA, Burdette JH. 2003. An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. *NeuroImage*. 19(3):1233–1239.
- Martino A, Scheres A, Margulies DS, Kelly AMC, Uddin LQ, Shehzad Z, Biswal B, Walters JR, Castellanos FX, Milham MP. 2008. Functional connectivity of human striatum: a resting state fMRI study. *Cereb Cortex*. 18(12):2735–2747.
- Mathiak KA, Klasen M, Weber R, Ackermann H, Shergill SS, Mathiak K. 2011. Reward system and temporal pole contributions to affective evaluation during a first person shooter video game. *BMC Neurosci*. 12:66–76.
- Mazaika PK, Hoefl F, Glover GH, Reiss AL. 2009. Methods and software for fMRI analysis for clinical subjects. Poster session presented at the meeting of Human Brain Mapping 2009, San Francisco, CA.
- Naqvi NH, Bechara A. 2009. The hidden island of addiction: the insula. *Trends Neurosci*. 32(1):56–67.
- Nummenmaa L, Hirvonen J, Hannukainen JC, Immonen H, Lindroos MM, Salminen P, Nuutila P. 2012. Dorsal striatum and its limbic connectivity mediate abnormal anticipatory reward processing in obesity. *PLoS One*. 7(2):e31089.
- O’Doherty JP. 2004. Reward representations and reward-related learning in the human brain: insights from neuroimaging. *Curr Opin Neurobiol*. 14(6):769–776.
- Parent A, Hazrati L-N. 1995. Functional anatomy of the basal ganglia. Part I: The cortico-basal ganglia-thalamo-cortical loop. *Brain Res Rev*. 20(1):91–127.
- Passamonti L, Rowe JB, Schwarzbauer C, Ewbank MP, von dem Hagen E, Calder AJ. 2009. Personality predicts the brain’s response to viewing appetizing foods: the neural basis of a risk factor for overeating. *J Neurosci*. 29(1):43–51.
- Postuma RB, Dagher A. 2006. Basal ganglia functional connectivity based on a meta-analysis of 126 positron emission tomography and functional magnetic resonance imaging publications. *Cereb Cortex*. 16(10):1508–1521.
- Ravaja N. 2009. The psychophysiology of digital gaming: the effect of a non co-located opponent. *Media Psychol*. 12(3):268–294.
- Ravaja N, Saari T, Salminen M, Laarni J, Kallinen K. 2006a. Phasic emotional reactions to video game events: a psychophysiological investigation. *Media Psychol*. 8(4):343–367.
- Ravaja N, Saari T, Turpeinen M, Laarni J, Salminen M, Kivikangas M. 2006b. Spatial presence and emotions during video game playing: does it matter with whom you play? *Presence Teleop Virt*. 15(4):381–392.
- Rilling JK, Gutman DA, Zeh TR, Pagnoni G, Berns GS, Kilts CD. 2002. A neural basis for social cooperation. *Neuron*. 35(2):395–405.
- Rilling JK, Sanfey AG, Aronson JA, Nystrom LE, Cohen JD. 2004. Opposing BOLD responses to reciprocated and unreciprocated altruism in putative reward pathways. *Neuroreport*. 15(16):2539–2543.
- Schultz W. 2006. Behavioral theories and the neurophysiology of reward. *Annu Rev Psychol*. 57:87–115.
- Steele JD, Lawrie SM. 2004. Segregation of cognitive and emotional function in the prefrontal cortex: a stereotactic meta-analysis. *NeuroImage*. 21(3):868–875.
- Stoekel LE, Kim J, Weller RE, Cox JE, Cook EW III, Horwitz B. 2009. Effective connectivity of a reward network in obese women. *Brain Res Bull*. 79(6):388–395.
- van den Bos W, McClure SM, Harris LT, Fiske ST, Cohen JD. 2007. Dissociating affective evaluation and social cognitive processes in the ventral medial prefrontal cortex. *Cogn Affect Behav Neurosci*. 7(4):337–346.
- Wetherill GB, Levitt H. 1965. Sequential estimation of points on a psychometric function. *Br J Math Stat Psychol*. 18:1–10.
- Zhu L, Mathewson KE, Hsu M. 2012. Dissociable neural representations of reinforcement and belief prediction errors underlie strategic learning. *Proc Natl Acad Sci USA*. 109(5):1419–1424.