

Neural correlates of disrupted presence: strange disruptions in a naturalistic virtual environment

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Abstract

The concept of presence is commonly related to whether or not a user feels, acts, and reacts as if he/she were in a real familiar environment when using a virtual reality (VR) application. Understanding the neural correlates of presence may provide a foundation for objective measurements and important constraints for theoretical explanations. Here, we focus on the importance of expectations and their violation in several theoretical descriptions of presence in order to investigate neural correlates of disrupted presence. Functional magnetic resonance imaging (fMRI) was used to measure brain activity during execution of everyday tasks in a naturalistic virtual environment (VE). Time periods with disrupted presence were identified using subject reports of strange situations, interpreted as violations of expectations related to the sense of presence. Disrupted presence was associated with increased activity in the frontopolar cortex (FPC), lateral occipito-temporal cortex (LOTC), the temporal poles (TP), and the posterior superior temporal cortex (pSTC). We relate these areas to integration of key aspects of a presence experience, relating the (changing) situation to management of task and goals (FPC), interpretation of visual input (LOTC), emotional evaluation of the context (TP) and possible interactions (pSTC). These results are consistent with an interpretation of disrupted presence as a re-evaluation of key aspects of a subjective mental reality, updating the synchronization with the virtual environment as previous predictions fail. Such a subjective mental reality may also be related to a self-centered type of mentalization, providing a link to accounts of presence building on the self.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Virtual reality—I.3.m [Computer Graphics]: Cognitive science—

1. Introduction

Many of the benefits of virtual reality applications are grounded in the ability to make a user act and react as if in a real, naturalistic, environment. This provides a basis for ecologically valid computer applications and enables naturalistic studies of the freely behaving brain [Mag12]. Ecological validity is especially important for applications relating to how the human brain works in everyday life, for example cognitive training, rehabilitation, or diagnosis [RK05]. In such cases, a primary goal is to allow the cognitive functions of the user to operate as they would in real life. For example, if studying prospective memory using VR, the goal may be to capture the functions that would be at work when setting out to run errands in a real hometown, an everyday task re-

lying heavily on remembering future events [KES*10]. This tendency to act and react as if the VE was real is often related to the concept of *presence*: commonly described as the subjective sense of being "there".

A combination of VR and fMRI has been used in a number of studies over the last decades [ADAD96, BNF*03, HRC*03, LKL04, Mag12, MBD*98, MHQ*03]), but only a few have presented results on the neural correlates of presence. Baumgartner et al. [BSW*08] compared two conditions designed to correspond to high and low presence, respectively. Both conditions were presented as non-interactive roller-coaster rides in a 3D-environment, with a flat track in the low presence condition and spectacular slopes and loops in the high presence condition. Question-

naires were used to relate differences in reported presence to differences in brain activation, across subjects. Restricting initial analysis to the prefrontal cortex based on an a priori hypothesis, activity in bilateral dorsolateral prefrontal cortex (DLPFC) was reported as negatively correlated with the sense of presence. DLPFC activity was further related to down-regulation of the egocentric dorsal visual processing stream and up-regulation of the medial prefrontal cortex (MPFC).

Isolating the effect of presence among condition differences is often challenging [Sjö14]. Bouchard et al. [BTL*09, BTL*10, BDT*12] illustrate one way to focus on the subjective experience by using different narratives to manipulate the sense of presence in a virtual environment that is otherwise identical. The reported effect of a narrative promoting presence is restricted to small clusters in bilateral parahippocampal cortex. Still, it remains unclear how neural correlates of presence should be related to the effect of presence in naturalistic VR applications. For example, none of the studies above allowed the user to interact with the environment.

One way to investigate changes in presence in a naturalistic environment is to focus on the importance of expectations and their violation. The concept of "breaks in presence" has been used to illustrate this relation. Breaks in presence (BIPs) belong to a description of presence as based on the selection of a hypothesis about your environment [SS00, Sla02]. According to this reasoning the subjective sense of presence depends on accepting a hypothesis about the current (possibly virtual) environment as "real", and the key factor in maintaining any belief in such a hypothesis (that is, maintaining presence) is to avoid anything that "disproves" it by violating expectations. A focus on BIPs and expectation violations is particularly appropriate to practical VR applications aiming for ecological validity, since they correspond to what you want to avoid in such applications: moments where you are not (re)acting as if in a real environment. Several theoretical accounts of presence and related phenomena elaborate on the importance of expectations and their violation for achieving and maintaining presence, for example, in terms of predictive coding [SSC11], simulations in the brain [RWWM11, Sjö12], or the importance of being able to rely on expectations and existing motor schemas to be able to "do there" [JCB09, SVS05].

In this study, we investigate the effects of expectation violations during a simulated everyday task in a naturalistic virtual environment. We do not use any specific manipulation to create expectation violation but focus on the subjective experience, identifying time periods where subjects report that something was "strange" in the virtual reality. Corresponding to an extended effect of BIPs, such time periods can be described as periods of disrupted presence, related to a mismatch between your subjective mental reality and the virtual reality [Sjö12]. We identify such strange time periods using a combination of VR, fMRI, and retrospective verbal reports

(see Spiers and Maguire [SM06a] for a similar approach). As such, this study has a high degree of ecological validity since variations in presence are in a setting where presence is of practical importance for the functioning of the application. Indeed, the fMRI data reported here was recorded while conducting a task designed to study the neural correlates of prospective memory in a naturalistic setting [KES*10].

In a perfect virtual environment, with perfect presence, measured brain activity should correspond exactly to brain activity in a corresponding real setting. Thus, presence-related brain activity would be dictated by the particular task and context [Sjö13, Sjö14]. For example, in the study by Baumgartner increased presence while riding a roller-coaster was related to visual and spatial brain regions [BSW*08] and in the study by Bouchard increased presence related to believing oneself to be in a real room was related to activations in parahippocampal cortex, a brain region known to be involved in spatial/location processing [BDT*12]. A disruption in presence should be related to an increased difference between actual activity and the expected activity for the intended environment and task.

More generally, accounts of presence as related to predictions in hierarchical models implemented in the brain may provide a framework for interpretation of neural correlates of (disrupted) presence. Such accounts suggest that significant disruptions in presence should lead to increased activity higher up in the hierarchy, corresponding to more frontal brain regions [SSC11, Sjö12]. Disrupted presence may also be connected to management of disruptions in a task or task switching. The frontopolar cortex (FPC) has previously been implicated in such task management functions [KH07].

2. Methods

2.1. Population and task

Out of 14 subjects in the initial dataset we selected subjects with at least five strange time periods for the present analysis in order to balance reliable measurement at the individual level with the inclusion of as many participants as possible. Eight subjects fulfilled this criterion. The selected subjects were 19-29 (mean 24) years old, and three were female. All but one were right-handed and all had normal or corrected-to-normal visual acuity. None of the subjects had a history of neurological or psychiatric illness. The study was approved by the ethics committee of Umeå University. All participants gave written informed consent to participate.

The data analyzed for this study was gathered during the performance of a naturalistic prospective memory task in a virtual environment. The basic task consisted of visiting and activating a number of locations in a 3D-model of downtown Umeå (see Figure 1). The experiment was divided into 5 routes. Before each route a list of 4 or 5 tasks (22 in total) was presented to the subjects and the subjects were then

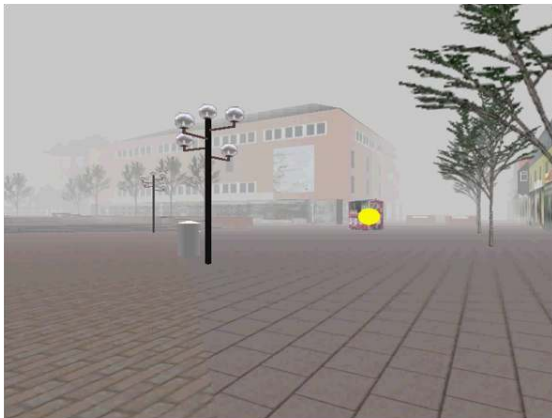
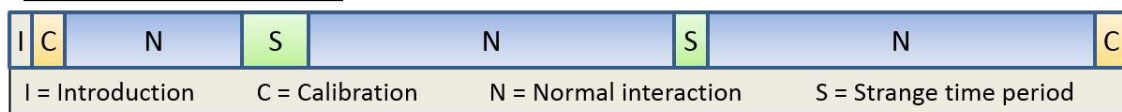
A. Subject view in VE**B. Setup for immersive interaction in MR-scanner****C. Strange periods within a route**

Figure 1: A) Example of subject's view when approaching an interaction target. The yellow circle shows eye tracking and was not displayed to subjects. B) Setup used to enable immersive interaction with the VE from inside of the MR-scanner. C) Calibration time periods were modeled as a regressor of no interest to improve the statistical model.

allowed to navigate the virtual town freely in order to locate and complete these tasks. The present study is based on time periods during this free navigation that correspond to disrupted presence, for example, caused by out of date models in some areas of the virtual town. The design of the prospective memory task is described in detail in Kalpouzos et al. [KES*10].

It should be noted that the naturalistic nature of the VE is in relation to the limits set by the MR-scanning technology, and in relation to similar previous work. fMRI-scanning is sensitive to even small movements of the head, requiring the subject to lie as still as possible in general. However, the VE corresponds to a familiar real environment, the subjects' hometown, and the conducted tasks correspond to common naturalistic tasks in this environment. Using the hardware described below subjects could conduct these tasks in an immersive and interactive virtual environment within the MR-scanner.

2.2. System and procedure

The MR-compatible hardware used was a combination of hardware delivered by NordicNeuroLab (Bergen, Norway), and hardware developed in-house at the department of Integrative Medical Biology, Umeå University. The visual system consisted of a set of stereoscopic goggles (NordicNeuroLab VisualSystem), 800x600 pixels, horizontal/vertical field of view 30°/23°, with accommodation distance at infin-

ity and a possible diopter correction of -5 to +2 dpt. Eye-tracking was enabled through an integrated camera with an infrared light source, providing a video signal of the right eye. Using these goggles we could immerse the subject in our virtual environment within the MR-scanner. The eye-tracking allowed us to identify events and phases in subject behavior and was instrumental in our investigation of the neural correlates of prospective memory [KES*10].

The VR-software-system was based on Colosseum3D [Bac05], developed at VRlab, Umeå University. A custom-made joystick (right hand) enabled rotation and movement in all directions and allowed the subject to navigate the VE with minimal body movement. Task events were triggered using a pistol-grip MR-compatible button (left hand).

The fMRI data was recorded using a Philips 3.0 tesla imaging device (MR-scanner). The scanning sessions varied in length depending on subject behavior, from a minimum of just under 19 minutes to almost 30 minutes. Scans were collected every 1.5 seconds throughout the session. See Kalpouzos et al. [KES*10] for further details on the system, including fMRI parameters and procedures.

In order to ascertain when subjects experienced disrupted presence we used retrospective verbal reports. This made it possible to investigate the effect of strange situations without further disrupting the prospective memory task under (separate) investigation. Directly after completing the task in the fMRI scanner subjects were taken into an adjacent room and

instructed to recall and report on their thoughts throughout the experiment in relation to a video replay of their previous interaction with the VR environment. The subject decided the pace of the reporting and the video was paused as needed to give the subject time to elaborate. Interventions by the researcher were kept to a minimum, restricted to, for example, prompts for clarification. See Spiers and Maguire [SM06a] for further details on a similar setup.

When transcribing the verbal protocol we focused on utterances that expressed a sensation that something in the virtual environment was "strange". Examples of this include "I would not do this in the real world", "there seems to be something missing here", and "isn't there supposed to be a door along this wall". Initially, we set out to classify utterances into "strange activity" (something happening that felt strange) and "strange environment" (something was strange in the environment) but because of the low number of identified time periods we chose to merge these two categories into a simple "strange" classification covering both types. Reports were matched to subject behavior based on the video in order to determine the time periods related to specific utterances.

2.3. Statistical analysis

For the statistical analysis the brain activity data was treated as a set of volumetric images. The data from each subject consisted of a series of such images (scans) for all time points throughout the experiment. See Beck et al. [BWM*07] for additional background on basic fMRI data-analysis procedures.

The recorded data was analyzed using SPM8 (Wellcome Department of Cognitive Neurology, London, UK) on Matlab 2011 (Mathworks Inc, MA, US). The pre-processing applied to all images included slice-timing correction, realignment, normalization, and smoothing. After resampling, the final voxel size was 2x2x2 mm. To estimate the effect of disrupted presence on brain activity, we used the general linear model (GLM) to create statistical parametric maps with t-statistics. Our primary regressors of interest were *normal* and *strange*, where *strange* corresponds to time periods identified as subjectively strange according to the verbal protocol, and *normal* corresponds to all the time periods with immersive interaction except for the strange time periods. A regressor for the calibration periods before and after the free navigation routes was also included. See figure 1 for an illustration of these time periods during a full route. All regressors were constructed as boxcars convolved with the canonical hemodynamic response function (HRF). We also added regressors of no interest for the motion correction acquired from the realignment pre-processing step. For the estimation of this model we used a high-pass filter with a cutoff of 128 seconds.

Contrasts for a comparison of *strange* versus *normal* were

constructed for each subject. These single-subject contrasts, representing the effect of disrupted presence, were entered into a group analysis GLM using the "random effects" option in SPM8. Thus, the resulting group-level difference corresponds to the increased brain activity during periods of disrupted presence compared to normal free navigation, treating subjects as a random variable. Large activations are statistical effects that are consistently present across subjects. Voxel threshold was set to $p < 0.001$, uncorrected for multiple comparisons, combined with a cluster threshold of extent ≥ 10 voxels.

3. Results

There were large differences between subjects in how they behaved during free navigation in the virtual environment, and in what they reported verbally about their experience and thoughts throughout the experiment. Including subjects with at least 5 periods of disrupted presence resulted in a dataset of 8 subjects with an average of 9.3 (standard deviation (SD) 3.6) time periods with disrupted presence (strange), with an average duration of 4.3 seconds (SD 1.1 seconds). The length of uninterrupted normal periods within the routes varied greatly, with an average of 59 seconds and a SD of 58 seconds. As a comparison, one route took 182 seconds on average to complete (SD 50 seconds) (compare to Figure 1). The distance moved per second (via free navigation, measured in VE distance units) was significantly decreased ($p=0.02$) in strange time periods (mean 2.3, SD 0.8) compared to normal (mean 3.1, SD 0.4) across the group. There were no significant differences for amount of rotation in the VE, or for eye movements.

Disrupted presence was most strongly associated with increased BOLD signal in the frontopolar cortex (FPC) and in the lateral occipito-temporal cortex (LOTc). Although posterior activations were mostly in LOTc, there was also one smaller cluster in the left inferior parietal cortex. The most dorsal part of the right LOTc cluster encroached on the parietal cortex. There were also smaller clusters in the posterior superior temporal cortex (pSTC) and the temporal poles (TP) in both hemispheres, as well as in left pre- and post-central gyri, orbitofrontal cortex and posterior cingulate gyrus. All these activations were significant at $p < 0.001$ uncorrected with cluster extent ≥ 10 voxels. A surface rendering can be seen in Figure 2 and all identified clusters are listed with t-values and MNI coordinates for peak voxels in Table 1. There were no regions with significantly decreased activity during strange compared to normal.

4. Discussion

While our setup did not deliberately cause any differences in environment or behavior between the strange time periods and normal immersive interaction (normal), there may still be consistent differences related to how subjects react dur-

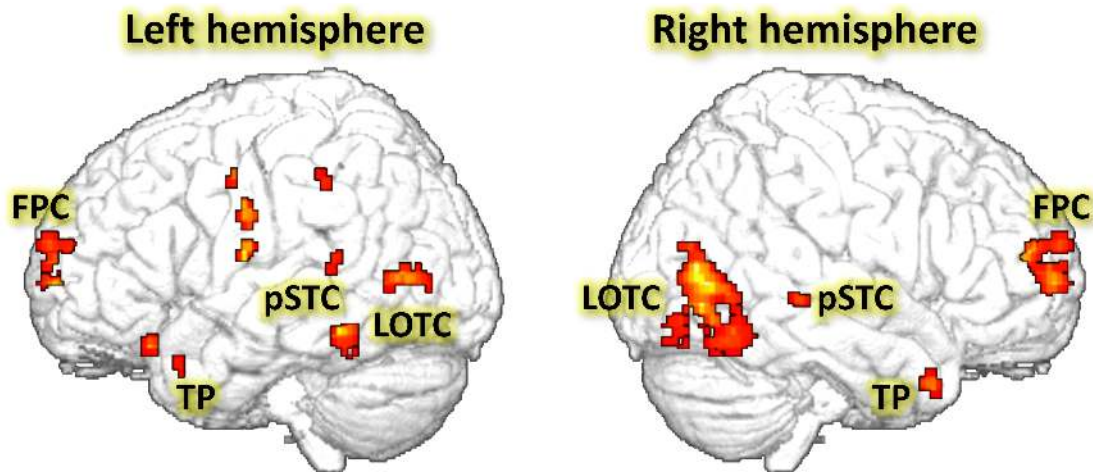


Figure 2: Clusters with increased BOLD signal during periods of disrupted presence (strange compared to normal, $p < 0.001$ uncorrected, cluster extent ≥ 10). Renderings showing activations at a maximum depth of 40 mm projected onto the brain surface, in left and right hemispheres. FPC = frontopolar cortex, LOTC = lateral occipito-temporal cortex, pSTC = posterior superior temporal sulcus, TP = temporal pole.

ing strange periods. The only significant difference in behavior we measured was a decreased in-VR-movement during strange periods. This may be related to BIPs, as an interruption of the current task may cause the subject to "stop and think" and precludes efficient action.

Compared with normal immersive interaction, disrupted presence led to increased BOLD signal in a number of brain regions including frontal, temporal, parietal, and occipital cortices. The FPC has been previously associated with multi-tasking (interrupting and postponing a current task) and with decision making related to open-ended and ill-structured situations [KH07]. Such cognitive functions match a conception of disrupted presence as a disruption of the current contextual mental simulation, leading to a re-evaluation of input from the environment. The FPC has also been described as "the apex of the executive system underlying decision making" [KH07, p. 595]. This fits well with the view of presence as related to synchronization of a hierarchical and dynamic mental simulations, driven by expectations and associated prediction errors that are fed upwards in the hierarchy as predictions fail at lower levels [SSC11, Sjö12]. By this view, increased activation at the apex of the hierarchy reflects that fundamental assumptions about the current context are challenged, triggering re-evaluation of current interpretations throughout the hierarchy.

The FPC has also been related to mentalizing, that is, detecting and thinking about the mental states of individuals, including thoughts, intentions and emotions. This includes self-awareness and self-perception [FF03, Fri07, MOL*06] and may be related to a form of self-centered mentalizing in the current context.

Olson et al. described the general function of the TP as coupling "emotional responses to highly processed sensory stimuli" and linking high-level representations to "visceral emotional responses" [OPE07]. A connection between the (virtual) context and our emotional responses is a core aspect of a high level of presence. Note that this concerns the general integration of emotions to context. Which emotions are triggered (and to what degree) may vary greatly, potentially explaining why no increase in activity is found in brain areas commonly related to emotions, such as insula and amygdala.

The pSTC is a multimodal region that may be related to many different functions, but one recurring description is involvement in the prediction of complex, often biological, movement and behavior, such as how the body moves. This is an important aspect of mentalizing as it is often used to predict bodily actions of other humans, and the consequences thereof [FF03, Fri07, SM06b]. This function may also support prediction of what actions you yourself have available in the current context, which is also a key aspect of successful presence [Sla09].

Decreased motion during strange periods, together with a lack of significant change in eye-movements, suggest that the large LOTC clusters may be related to attention and the context of the visual stimuli rather than externally driven changes in visual input. Incongruous visual information has been shown to correlate with increased activity in extrastriate cortex [MSB*03], overlapping LOTC. Such an interpretation fits well into a view of disrupted presence as a violation of the "reality hypothesis" and a disruption of the context in which visual information is/was interpreted.

Presence and subjective realism can be related to the

Brain regions	Brodmann area	x	y	z	Peak T	Cluster size
Frontopolar cortex (FPC)	10/32	2	52	18	13.32	226
	10	-16	62	12	6.69	12
Lateral occipito-temporal cortex (LOTTC)	19/37	38	-70	4	12.97	497
	20/37	-46	-46	-14	9.47	81
	19/37	-38	-70	8	8.16	70
Postcentral gyrus	22/43/48	-64	-10	16	10.19	18
	3/4/48	-44	-10	34	8.20	39
Precentral gyrus	6	-34	-6	44	6.83	11
Orbitofrontal cortex	11	-20	26	-20	8.71	16
Temporal pole (TP)	20/38	44	16	-36	7.51	45
	20/38	-34	16	-28	5.26	11
Posterior cingulate gyrus	31	-12	-16	38	7.20	15
Posterior superior temporal cortex (pSTC)	21	46	-34	-2	6.22	12
	22	-56	-44	12	5.50	16
Inferior parietal cortex	40	-48	-40	42	5.51	13

Table 1: Brain regions with significantly increased activity with disrupted presence. Positive x = right, negative x = left. Peak coordinates $[x;y;z]$ in MNI space (Montreal Neurological Institute).

match between a subjective mental reality, corresponding to a hierarchy of dynamic mental simulations, and the virtual environment [Sjö12]. Neural correlates of disrupted presence are likely to vary depending on the specific (virtual) environment and context. In light of this, it is interesting to note that FPC, LOTC, TP and pSTC can all be described as areas providing context and anchoring for mental simulations, relating new percepts to overarching goals (FPC), interpretations of visual input (LOTC), emotional evaluation (TP) and potential interactions (pSTC). In particular, such new percepts may lead to a need to select or switch between multiple tasks (multitasking, FPC), as well as incongruent visual information (LOTC). The possible connection to self-centered mentalizing also highlights the activations in TP and pSTC and suggests a clear link between these results and previous accounts of the self in presence, through visceral personal feelings and possible actions [RM12, Sla09]. In this context, FPC may also be related to personal goals and intentions, given a key role in previous accounts of presence [RWWM11, Riv09].

Note that the two perspectives suggested here, anchoring a subjective mental reality, and self-centered mentalizing, are compatible. A subjective mental reality is essentially the same thing as the context in which the self acts and perceives, and mentalizing can be described as the simulation of this context. That is, thinking about the mental states of others is essentially the same thing as simulating their subjective mental reality, in which they may act and perceive the world.

The statistical analysis used in this paper (mass-univariate t -tests) highlights stable differences across the events that together define a condition. Activations related to details of a particular strange time period can be expected to vary and not show up as significant in such an analysis. Brain

areas providing general context and grounding for subjective mental reality simulations, on the other hand, should be consistently activated in association with disrupted presence over different periods and subjects, as subjective reality is re-evaluated and re-grounded.

Previous studies by Spires and Maguire [SM06b], and Moller et al. [MRM07], have a similar experimental setup and present similar results, although they do not investigate presence. The results presented by Moller et al. are preliminary, but overlaps FPC and LOTC, and Spires and Maguire add activations overlapping TP and pSTC to this pattern. On a general level, this illustrates the impact of the specific task and environment for the measured brain activity. In both cases, the attained results may be related to shifting perspectives within a naturalistic environment, during an everyday task. While Spires and Maguire investigate spontaneous mentalizing, and Moller et al. investigated the effects of naturalistic distractions, such as unexpected movements by other characters in the VE, both these events may be related to a shift (of focus and/or attention) away from the current environment and task, and an associated disruption in presence related to this VE.

Baumgartner et al. [BSW*08] established a relation between a reduced sense of presence and increased activity in the DLPFC, an area that was not revealed in our results. Given the large difference in the experimental setup, it is difficult to be confident about the reason for this mismatch. It does, however, seem like our activation in the FPC can be matched to a cluster in MPFC in the study by Baumgartner et al., reported as an area that is up-regulated by the DLPFC and thus related to reduced presence.

This study was not explicitly constructed to investigate effects of (disrupted) presence. This has some drawbacks

but also some rather unusual advantages. Since we do not control what is happening in these strange situations explanations relating to specific cognitive processes are somewhat speculative. However, this approach provides an important complementary perspective to studies comparing levels of presence in constructed conditions. Naturalistic studies of the brain aim to investigate the brain when it operates as if the virtual environment was real, that is, with perfect presence. Any imperfections in the virtual environment may lead to disrupted presence, and pose a potential problem. As such imperfections are subjective and depend on the expectations of the specific user it may be difficult to identify these through outside observation. Checking brain measurements with the neural correlates of disrupted presence in mind may be the most direct and reliable way to address such subjective variation.

An understanding of neural correlates of disrupted presence may also be used to integrate brain-computer interfaces (BCIs) into VR applications. The possibility to detect disrupted presence via brain measurements could be very valuable both during the development of VR applications and in order to detect problems in running applications. It may even be possible to use adaptive BCIs to automatically adjust computer applications in response to variations in presence [Sjö11]. Recent developments toward affordable and commonly available VR [HMR*14] suggest an increasing potential for such applications.

5. Conclusion

The neural correlates of disrupted presence were captured using fMRI and verbal reports of strange time periods during an everyday task in a naturalistic VE. Increased BOLD responses in FPC, TP, pSTC and LOTC can be related to a general understanding of presence by describing these brain areas as representing important types of grounding for subjective mental reality simulations. The neural correlates of (disrupted) presence can be expected to vary depending on the environment and task, but accepting immersive interaction in a naturalistic VE as being present in a real place may be primarily related to specific types of grounding.

Current goals (FPC), interpretations of visual input (LOTc), emotional integration and evaluation (TP), and interaction possibilities (pSTC), are promising candidates for such groundings. This reasoning is also largely compatible with accounts of FPC, TP and pSTC related to mentalizing, as self-centered mentalizing can be described as tightly related to the simulation of a subjective mental reality.

These results complement studies comparing distinct conditions related to different levels of presence. For example, this study has a high degree of ecological validity in relation to actual usage of VR in naturalistic scenarios, suggesting how measurements of brain activity might be used to track presence dynamically.

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