

More on central nervous system correlates of virtual reality testing

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ABSTRACT

Polygraphic recordings of EEG and peripheral variables of 10 healthy volunteers taking a VR-based cognitive testing were analysed to describe the phenomenology of short-term and long-term EEG and EP changes and to extract psychophysiological indicators of information processing and adaptation. A non-immersive VR set-up was used to allow exposures to VR of up to 60 min. Auditory-task irrelevant probes proved effective in tracking participants' mental fatigue. Strong negative feedback and motor reactions to them produced well formed event-related potentials including anticipatory components, while other ERPs and alpha EEG changes were noticed to be associated with specific VR events. Finally, sustained EEG changes took place which were correlated with successful or failing cognitive strategies. The neurological equipment produced only negligible additional discomfort to the participants. Psychophysiological investigations should be carried out more intensively by those developing applications for the disabled because are potentially very informative and suitable to tune and optimise important aspects of VR-based paradigms.

1. INTRODUCTION

Virtual environments (VE) are increasingly proposed to assess and treat psychophysiological and cognitive-behavioral disorders (Rose et al., 1997; Rizzo et al., 1997), but surprisingly little is known about their ability to induce transient or sustained psychophysiological modifications in exposed individuals. Knowledge about changes in recordable brain activity may serve several purposes, such as tuning the intensity, the frequency, the timing of a given combination of stimuli to the desired level for a given category of users. On the other hand, VEs can provide psychophysiologicalists an opportunity to experiment new ways of studying human adaptation in more ecological, but nonetheless controlled, conditions. We have suggested (Pugnetti et al., 1996) that psychophysiological studies should precede the clinical application of a VR product to better understand its impact on subjects' physiology and to avoid missing important – either favourable or evil – consequences of exposure to it. The attempt to combine psychophysiological monitoring to VR research, however, is not new. In 1993, Eberhart and Kizakevich briefly described their experiments with healthy volunteers performing tracking tasks in a virtual environment, but gave no precise account of results. Our group (Pugnetti et al., 1994, 1995, 1996) carried out pilot EEG and evoked potentials (EP) studies with an earlier immersive version of our neuropsychological virtual testing scenario, and we were able to show that neat recordings are possible even when subjects wore CRT headsets and magnetic tracking sensors. Nelson et al. (1997) recorded the EEG from subjects interacting with a VE projected on a large screen, which indeed reduces potential sources of interference and the amount of cabling around the subjects. VR is also being implemented into traditional EEG biofeedback in an effort to enhance treatment of specific psychophysiological disorders (Kaiser and Othmer, 2000). A collaboration with UNC has recently given us the opportunity to considerably expand our previous observations, as the ARCANA software has been modified to connect with a new recording equipment and to produce additional stress to the users by degrading the visibility as the number of errors increases (see also Meehan et al., this volume).

2. AIMS AND RATIONALE

The principal aim of this report is to complete the description of the variety of CNS correlates recordable from healthy adults. The paradigm (a classic card sorting test) and the virtual version we devised (Pugnetti et

al., 1995) lend themselves to record transient brain responses (event-related potentials (ERPs), electrooculographic patterns (Eog), phasic EEG rhythmic responses) and tonic EEG changes. In principle, however, any VE can be viewed as a tool to provide complex information and evoke brain responses. Different types of environments, therefore, convey different information and require different types of processing. A combination of a few basic types of VEs that repeats itself a number of times gives the opportunity to record repetitive changes in brain electrical activity due to transient stimulation along with changes that are associated with more durable events such as adaptation to the experimental conditions, learning, and fatigue. We were primarily interested to see whether the EEG reflects the informational content of our two main types of VEs: rooms and hallways. Second, we looked at EP to task irrelevant stimuli as possible indicators of mental adaptation or fatigue during a long lasting exposure to VR, and last, we sought confirmation of our earlier studies on event-related potentials.

3. METHODS

3.1 Participants and procedures

We had 16 healthy volunteers participate in this new experiment; data from 10 of them will be considered here. There were 4 females aged 29.7 ± 3.2 yrs, and 6 males aged 29 ± 4.0 yrs., recruited from the hospital staff, their friends and relatives. Subjects signed an informed consent and were allowed to terminate the session should they feel any discomfort. Before and after the VR session they filled in questionnaires concerning their feelings, symptoms (Regan and Price, 1994) and experience with the system. Subjects were isolated from the recording equipment and handled a joystick while sitting in front of a large (1x1.35 meter) screen on which the VE was projected. To avoid artefacts as much as possible, they were asked to limit sudden gross body movements during the experiment. Before starting, they were hooked up, then calibration procedures took place after which they were given a 10 min practice run that served also as baseline for some of the measurements. The experimental task was to navigate a virtual building in as short a time as possible, as described elsewhere (Mendoza et al., 1998; see also Meehan et al., this volume). Significant events were classified according to previous studies with the same paradigm and triggers released accordingly. They were used for off-line computation of averaged evoked responses and the identification of continuous EEG epochs between two significant events. Stimuli were both visual and auditory. A constant background auditory stimulation with 1500 Hz pure tone pips of about 95 dB nHL was given at a rate of 1.2/sec by two loudspeakers located at a distance of about 2 m. in front of the subjects. Tones served as irrelevant probes to compute auditory evoked responses (AERs) to assess how much subjects were able to concentrate on the main task (Kramer et al., 1995). Task-relevant auditory stimuli (gunshot sounds) were also released at the time of feedback following wrong matches; they were used to compute event-related responses along with any presses of the joystick trigger upon seeing the ball. Any opening/closing of doors and any passage from one environment to another was also marked as a relevant stimulus or event.

3.2 Data recording and processing

We recorded 5 unipolar EEG leads (Fz, Cz, Pz, P3 and P4 all referenced to linked earlobes), 4 unipolar EOGs, 2 dominant forearm arms and 1 facial bipolar EMGs, and peripheral channels as discussed by Meehan et al. (this volume). Signals were sampled at an AD rate of 1000 Hz/channell by a Neuroscan 32 system and monitored both on screen and on paper for the whole duration of the experiment (30 to 60 min. depending on the individual performance). Precise correspondence between physiological events, virtual stimuli and behavioral responses was insured by triggers released by the VE server and recorded along with body signals and videos of the subject and of the VE. Any off-line computation was preceded by appropriate digital filtering and removal of artifacts. A total of 10 recordings were found to contain good quality continuous EEG tracings and were therefore used for this report. Additional data will require further editing due to heavier contamination by artifacts.

4. RESULTS

4.1 AERs to irrelevant probes

Auditory N1-P2 components (peaking at about 100 and 150 ms. from stimulus onset) could be retrieved from the background EEG of all the 10 subjects selected for this analysis. These EP are of supratentorial (mainly cortical) origin but in normal hearing vigilant subjects can be considered as obligatory or automatic responses and are known to be modulated primarily by the physical characteristics of the stimuli. Endogenous factors, however, may also influence their expression to some extent. The AERs recorded during a 3 min. baseline period when subjects practiced with navigation on a demo-VE had greater mean amplitudes than the same

waveforms recorded during a 3 min. period after completion of the VR test when subjects navigated a different VE with no specific instructions (Figure 1 and table 1). Potentials recorded midway during the VR test did not differ significantly from the baseline period. The amplitude of the N1-P2 components measured at the Fz site was especially reduced post-test. The latencies of the principal components of the AER was not changed except for P1 latency which tended to increase after the test (table 1). Two subjects, however, showed clearcut mean N1 latency increases exceeding 10 msec. after VR. All but one subject reduced N1-P2 amplitude after testing. The drop in mean AER amplitude was predicted as a result of previous pilot studies (Pugnetti et al., 1996). The change in brain potentials we observed are comparable to those produced in a relaxed subject by a decrease from optimal level of approximately 30 dB of the intensity of a repetitive short auditory stimulus. The difference between baseline and post-test N1-P2 amplitude correlated with the number of errors made during the VR test (Pearson's coefficient $r = -.64$, $p = .046$, two tailed) but only marginally with the duration of the session; participants who made more errors showed a larger drop in AERs amplitude than those who made less errors. No clear relationship between changes in N1 latency and errors on the VR test was found. These findings do not seem to support the model of allocation of resources, e.g. the notion that brain resources to process irrelevant auditory stimuli were reduced during the VR task, but rather tend to suggest a buildup of mental fatigue after a prolonged exposure to a relatively stressful VE as the primary cause of AER changes. Preliminary analyses did not find significant relationships between AER amplitude changes and changes in total scores on the symptoms checklist, though trends were in the expected direction for symptoms related to mental fatigue. Alternative explanations are also possible and cannot be fully ruled out at this time. For example, a simple adaptation effect may have taken place. Also, the VE employed at post test may have captured subjects' attention differently than that used for the baseline period, though it seems unlikely after a long testing period. Overall, these findings appear to confirm our previous reports (Pugnetti et al., 1996) that the irrelevant probe technique can be used to track subjects' mental state, though a precise definition of the factors involved will need additional analyses.

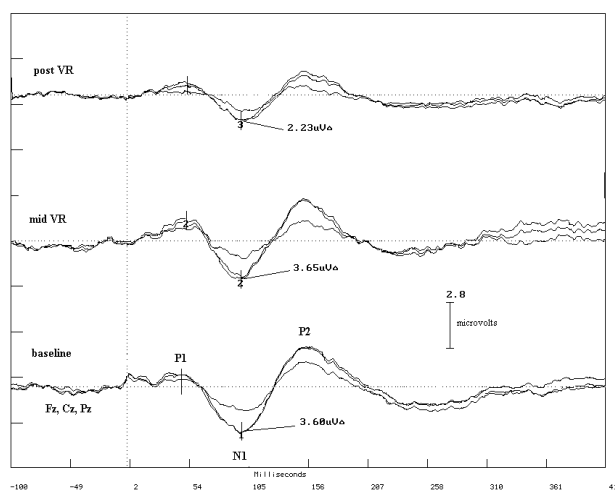


Figure 1. Group averaged evoked responses to auditory irrelevant probes. Superimposed averages from Fz, Cz and Pz electrodes relative to the baseline, mid test, and post test periods; negativity is plotted down.

Table 1. Effect of VR testing on AER group measures

Group measures	Before VR test	After VR test	paired t (df 9)
P1-N1 amplitude (uV.)	4.28 ± 1.84	3.26 ± 1.4	2.48 .03
N1-P2 amplitude (uV.)	6.37 ± 3.33	3.90 ± 1.5	3.25 .01
P1 latency (msec.)	51.0 ± 8.40	58.7 ± 10.8	-2.38 .04
N1 latency (msec.)	95.2 ± 97.9	97.9 ± 3.5	-0.74 n.s.
P2 latency (msec.)	151.5 ± 11.0	152.3 ± 9.2	-0.18 n.s.

4.2 ERPs to task-relevant probes

Clearcut ERPs to negative feedbacks (a combination of visual and auditory stimuli to provide a relatively robust input) were retrieved from all the EEGs analysed so far. These potentials, also known as slow cortical potentials (SCP) or endogenous potentials, are known to originate mainly in cortical structures and in thalamic nuclei. They are generally produced in response to unpredictable or rare events, variations in background stimulation, and periods during which a reaction is anticipated (see Rockstroh et al., 1989, for a comprehensive description of ERPs). The best known is the P300-SW complex (Figure 2). The amplitude of the ERPs we recorded was considerably larger than that of the AERs, but tended to vary over time in individual cases. The effect of experimental variables on the pattern of these slower brainwaves, such as their predictability, changes in the difficulty of the task, in psychophysical stress, or discouragement cannot be defined with any certainty at the moment, and will be the subject of future reports. As subjects were required to press the joystick trigger as quickly as possible after getting the feedback, we were able to record reaction times to single trials and to collect EMGs and corresponding shifts in brain potentials levels. Individual reaction times varied between 300 and 600 msec. (mean 374 ± 130 msec.) after feedback onset.

EMG responses were slightly preceded by a negative shift in SCP following the earlier ERP complex described above, and coincided with a positive shift. Because of the complexity of the stimulation and the absence of a suitable preparatory delay between the feedback and the motor response, it is presently unclear whether the late positivity (LP) on central and parietal leads can be interpreted as a final component of the cortical motor response or as a delayed P300 emerging after the end of a large motor negativity (MP or motor potential). Both components were more evident on central (Cz) and parietal (Pz, P3 and P4) regions. At preliminary analyses, SCP amplitude measures did not correlate with number of errors, duration of the session, and with reaction times, but did correlate significantly with the amplitude of the P1-N1 component of the AERs. This is not surprising as the main stimuli had the same modality, and because both responses reflect psychological concepts (attention) to a greater extent than a single ERP component (Rockstroh et al., 1997). The SCP complex was preceded by a slight negativity arising about 300 msec. before the acoustic stimulus which is evident in the averaged tracings of figure 2. In individual cases this negativity was more pronounced and an alpha-blocking phenomenon was evident in high-alpha subjects (see 4.5). We interpret this component as an anticipatory negativity (AR), as the subjects quickly learned that a negative feedback could occur after the opening of the mid-hallway door. Another long-lasting negativity is also present after the P300 (or LP) component which we tentatively interpret as a pronounced slow wave (SW) typical of a P300-SW complex or as a sustained motor negativity (or a superposition of both) given that several subjects produced multiple trigger responses after the first one in an attempt to delay or reduce the fog.

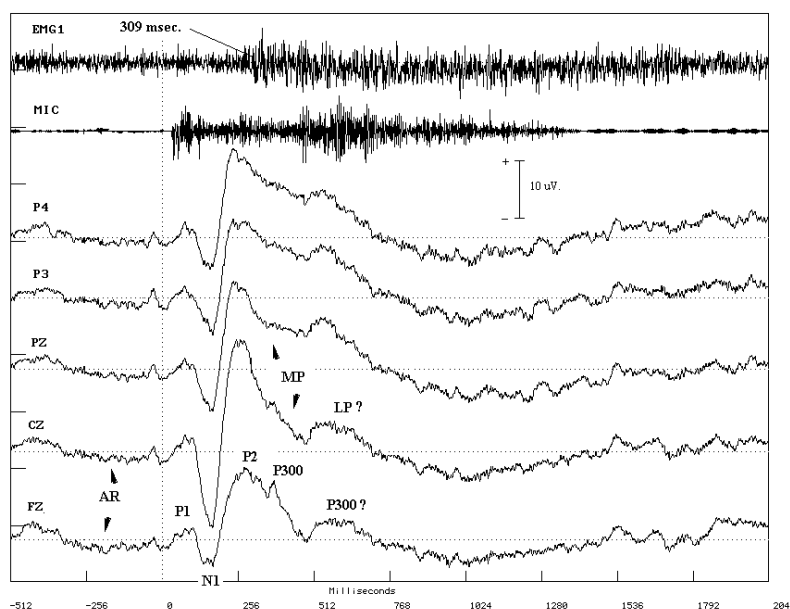


Figure 2. Group averaged ERPs to negative feedback stimuli after a wrong door match. Positivity is plotted upwards. MIC refers to the auditory stimulus (gunshot); EMG1 refers to the surface electromyographic bipolar recording from the flexor digiti muscle of the dominant forearm which was activated to press the trigger of the joystick. Amplitude scale refers only to EP channels.

4.3 ERPs to other significant events

Averaged ERPs could also be identified in response to events that are generally not produced in traditional laboratory studies and that may be more specific for interactive VR environments. As the subjects had to navigate a series of rooms, the opening of doors that led from a hallway to the next room or from a room to a hallway provided a suitable stimulus. During a VR session three such events occurred for each of the 32 rooms visited, for a total of 96 events. The first event occurred when subjects closed the entrance door by looking at it from the center of the room, the second when subjects opened the exit door on their way to the mid-hallway door (in the case of a wrong match) or the door leading to the next room (correct choice), and the third when they entered a new room. The first event was necessary to let the exit doors appear, whereas the other two were necessary to have access to the following environments. The first event had a stronger conditional meaning compared to the other two and was the result of more demanding manoeuvres in the VE. A positive-going potential peaking about 500 msec. before full closure of the entrance door (event 1) was recorded. The ERP seemed to involve to a greater extent posterior regions of the brain, as it was larger on CZ and parietal leads (Figure 3). The relative spread of the averaged waveforms may be explained by a jitter of individual response latencies caused by the fact that the triggering event was not a sharp one, but took some time (about 1 sec.) to develop. No reliable and genuine (e.g. non artifactual) brain responses were produced as subjects entered a new room and when they opened the exit door. We have already described brain responses preceding and following the opening of the mid-hallway door (see 4.2). The ERPs to event 1 may then be associated to the appraisal of the outcome of the positioning manoeuvres necessary to move to the center of the room and turn backwards to face at right angle the entrance door and let it close. This manoeuvre can be extremely difficult in conditions of low visibility, as described in Meehan et al. (this volume).

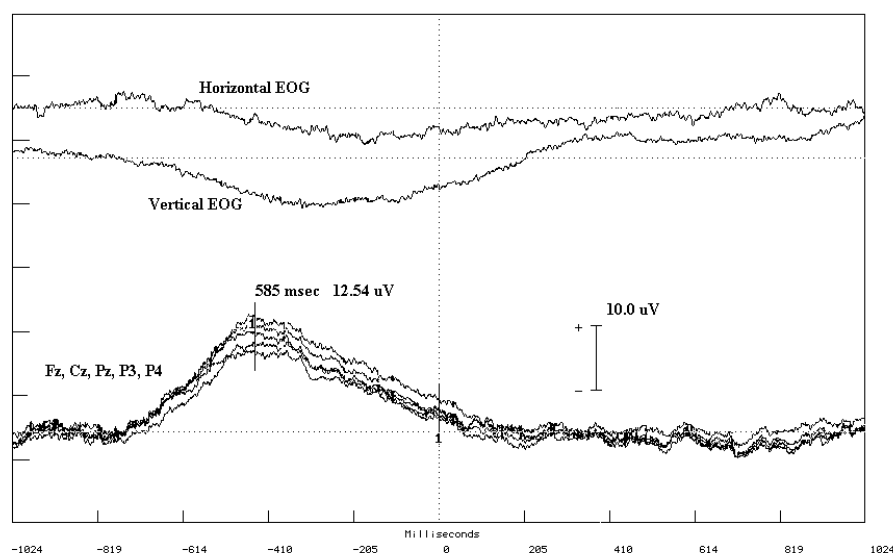


Figure 3. Group averaged ERPs to event 1 as described in the text. Door closure was complete at time 0. Positive peak at 585 msec. from onset of event is larger at posterior recording sites.

4.4 Short-lived rhythmic EEG changes

Phasic spectral changes in ongoing EEG were also considered as indices of moment-to-moment variation in brain arousal levels. It was hypothesized that such changes could occur as a result of the momentary cognitive demands specified by being in a given virtual environment. Alpha (8 to 12 Hz) EEG power over posterior scalp regions was preferred to other spectral variables because of the lower sensitivity of this measure to more anterior sources of artifacts in behaving individuals. Though high amplitude alpha waves are generally suppressed in individuals performing visual tasks, transient increases in these rhythms occur that index brief periods of relative rest in external input processing. We sought to detect whether changes of EEG alpha waves were detectable after the occurrence of significant events. Mean EEG power in the 8 to 12 Hz band was significantly increased over parietal, but sometimes also over more anterior leads, during the 4 seconds following selection of the exit door (event 2 as described before) as compared to the 4 sec preceding this event. No significant changes appeared to be associated to the other two events. Because

alpha waves are known to be associated with idling, we interpret these findings as indicating that the brain was taking short breaks between periods of active processing, such as those occupied to make an important choice. This general interpretation is supported by the finding that the fog (= lower visibility) suppressed the post-event alpha increase (a stress response?) in those who made many errors (see 4.5).

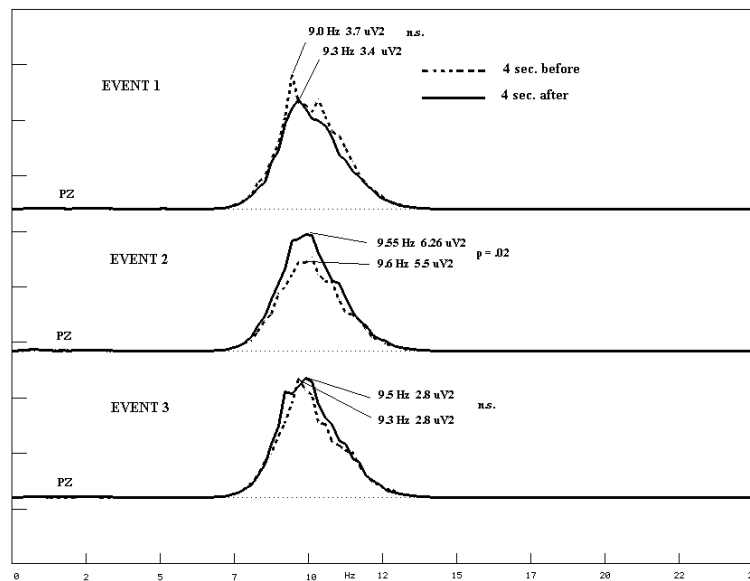


Figure 4. Group averaged alpha (8-12 Hz) power of 4 sec. epochs taken from the Pz electrode before and after events 1 to 3 as described in the text. Y scaling differs between the three pairs of spectra.

4.5 Long-lasting EEG changes

More durable increases or suppressions of EEG rhythms are being studied in connection to changes in testing conditions and subjects' state. Because the latter were dependent on individual characteristics, adaptation to the experimental setup and to performance, results are not described in terms of group findings. Again, measures of alpha power changes were preferred for these analyses. High alpha subjects provide more reliable results as they produce rather sustained rhythmic EEG activity also during active mental processing with eyes open. There were 5 subjects whose mean alpha power in the 8 to 12 frequency range during the test exceeded $3.5 \mu V^2$ (at peak frequency). Two subjects (males) made many errors and their task got very difficult from midtest to the end because of the fog. Three subjects (all females) did very well and did not get any fog during the test. Both bad performers showed a sharp decrease in mean alpha power when fog became incapacitating; one example is shown in Fig. 5B. Of the good performers, two showed a progressive increase in mean alpha power as the number of correct choices increased (Fig. 5A), whereas one did not show any significant change until the end of the test. These findings can be interpreted as further proof that the spectral content of ongoing EEG can be used to monitor dynamic aspects of adaptation to the task and of task learning.

4.6 Other results

All the 10 participants were able to terminate the VR sessions. Total scores on the symptoms checklist showed a moderate mean increase after the session (2.8 ± 1.9 vs. 4.2 ± 4.0 Wilcoxon $Z = -1.3$, $p = .18$, 2-tailed). Only 1 subject complained of mild nausea toward the end of the VR session, but agreed to terminate her test; her data were not included in the present analysis. Two subjects reported discomfort - one mild and the other annoying - caused by the leads and sensors attached to their skin. They were both able to concentrate on the task and did it well. One further subject reported difficulties handling the joystick.

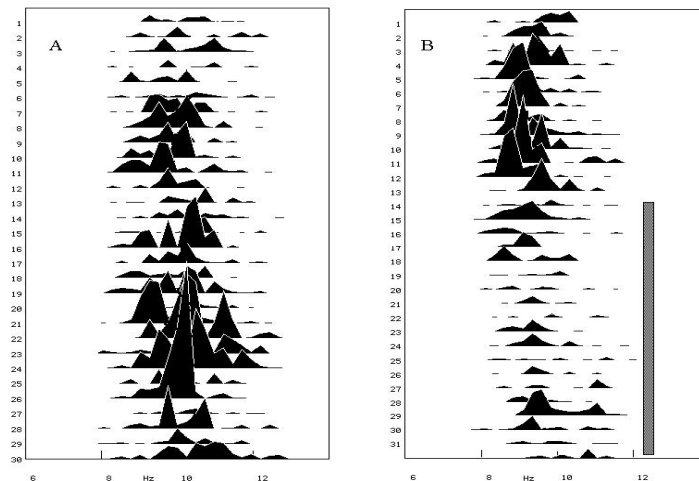


Figure 5. Compressed spectral arrays showing patterns of long lasting changes in EEG alpha (8-12 Hz) power during the VR test. In A (left) a good performer increased her alpha as she overlearned the task. In B (right) a poor performer suppressed his alpha as the task became more and more difficult; vertical bar indicates decreased visibility. Number of successive virtual rooms shown on ordinate.

5. DISCUSSION AND CONCLUSIONS

This study confirmed that monitoring of electrophysiological brain activity of healthy individuals engaged in VR testing is technically feasible without affecting too much their ability to perform. A successful recording of ERPs from behaving individuals exposed to VR has also been recently reported by Bayliss (Bayliss and Ballard, 2000) and by Mager in Basel (Mager, 2000). The range of data obtainable by a careful segmentation of continuous polygraphic tracings is certainly wider than that described in this and in others' reports. Also, inspection of individual records and videos can provide further insight into the rich phenomenology of brain-behaviour correlations during exposure to virtual reality which, however, is difficult to summarize. We believe that relatively simple techniques such as EEG spectral analysis and response averaging are sufficient to provide significant amounts of information, not otherwise obtainable, which can be used to better understand the way our subjects react and adapt to VR. More specifically, we have been able to document both short-term and long-term brainwave changes induced by the participation to our experiment, some of which may have been easily anticipated based on established psychophysiological knowledge (see also Meehan et al., this issue), and others that would have not been easily foreseen and which will require further study to be fully understood. To summarize, event-related potentials and EEG analysis provide useful means to objectively assess - in combination with behavioral observation and rating scales - important issues such as mental fatigue, overall dynamics of learning, orienting reactions to sudden sharp stimulation, anticipation of meaningful events, appraisal of outcome of actions performed to achieve a goal, impact of changes in task difficulty. Though this approach may not appear to have an immediate relevance to VR applications for the disabled, we think that it has relevance for those who must create such applications and to those who must decide how to propose them to disabled users. Without implying any simplistic approach to complicated issues, we just mention a few questions which may be addressed using psychophysiological methods: how long a given VR task should last to achieve an optimal effect (e.g. learning) without stressing inadequately (in either direction) physiological resources? How much the strength of a feedback should vary to maintain an optimal attention to it? When a given event or a consequence of an action become predictable? What is impact of distracting events (either wanted or not) on the processing of the main stimuli? When does a significant mental fatigue really occur? How do we know a subject's attention is really captured on a moment-to-moment basis? What is the impact of mild physical distress induced by the VR setup on our subjects' processing capacities? Is a given brain signal reliable enough to be used to drive specific aspects of the VE, to optimize performance, or to achieve control of assistive devices in simulated situations?

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