Nervous system correlates of virtual reality experience

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ABSTRACT

In recent years several papers have been published in which the effect of exposure to virtual reality (VR) on the activity of the nervous system have been discussed. This area of knowledge is of importance to those interested in VR applications, and especially to those who seek to apply VR to cognitive rehabilitation following brain damage. This paper reviews what is known about the effects on nervous system activity of the interaction with virtual environments, comments on the authors' experience with both normal and neurologically impaired subjects, and outlines a suggested programme for future research.

Keywords: nervous system, psychophysiology, cognition, ARCANA.

1. INTRODUCTION

The search for central nervous system (CNS) correlates of virtual reality (VR) experiences is of considerable importance to those exploring the applicability of this rather new technology to the field of cognitive rehabilitation. The latter is, itself, a rather new clinical discipline that is now emerging as a distinct form of treatment as clinical neuropsychology evolves from its experimental stages. Indeed, the endeavour to integrate a new technology within a new therapeutical methodology that has not yet reached maturity is a typical example of a high risk but potentially highly rewarding operation. Those who seek to do this are well aware of the necessity to obtain as much evidence as possible that VR is psychologically well accepted, physiologically and clinically well tolerated - and cost-effective when applied on a large scale basis.

Though there is little doubt that this evidence will ultimately come from clinical studies, a body of ancillary evidence is available from the results of studies specifically aimed at showing how target brain functions react to this new stimulating technology. Our two centres are making joint efforts to this aim.

2. AN OVERVIEW OF CNS CORRELATES OF VR EXPERIENCES

Besides an indeterminate number of statements made in generic papers in the early days of VR that alluded to the possibility that VR could profoundly affect the brain at the psychological (i.e.) learning and cognition), neurophysiological (i.e. perception) and emotional (i.e. affect, motivation) levels, the bulk of published reports dealing more or less specifically with these issues comes from research undertaken to adapt this technology to work within the range of human sensorimotor constraints - so called 'human factors' (Barfield et al. 1994). This was, and still is, a legitimate preoccupation since early immersive VR systems were shown to cause an excessive workload on human sensory-motor systems, and to produce patterns of stimulation which could not be neurophysiologically coded as 'normal' by the brain. Both factors caused symptoms to appear. The threat to the application of VR was perceived as significant and great efforts have been made to study in greater detail what was causing "cybersickness", - and what should be done to reduce its incidence to a minimum (Biocca, 1992). The issue of VR side-effects has been subject of recent papers and reviews (Pausch et al., 1992) and will not be again addressed here. Rather, we will attempt to underline what has been done to study, by objective means, non-detrimental effects on the brain of VR experiences.

Studies can be classified into two broad categories: 1) physiological studies using VR as a means of putting subjects into a predefined and highly controlled environment, and 2) studies that make use of physiological measurements to assess any bodily reaction to VR. Several pieces of work have been undertaken so far within these two categories. While for the second category of studies the underlying assumption is that the overall pattern of stimulation is still atypical as compared to that provided by the natural environment, the first relies on the closest possible approximation to natural conditions, and this requires a most sophisticated and rare technology. Nonetheless, Eberhart and Kizakevich (1993) have already suggested that VR provides a unique means to undertake physiological studies of human beings under stressful circumstances and have underlined the necessity of taking into serious consideration the biological variability of physiological responses across subjects. This approach has been pursued mostly by military research and training centres, but does not appear to have had yet an impact outside these boundaries. Decety et al. (1994) have used VR to study how the brain is activated during passive observation of complex movements by a virtual hand and by imagination of such movements. They used a PET scan to map functionally activated brain areas. Their study is the best example of how VR can be used to provide highly specified stimulation of a kind that has eluded control so far.

However, VR experiences are not necessarily stressful events. VR can be perceived as almost any kind of real experience depending on a mix of factors (Barfield and Hendrix, 1995). So, the first application of psychophysiological studies is to provide objective data to supplement behavioural data and subjective reports, which are by far the most frequently used measures in VR research. Knowing how and when physiological parameters change during a VR experience can help in the process of tailoring VR applications to an individual’s resources (Durlach, 1994). Clearly, this is even more compelling if the user is an impaired individual or if the VR experience must be prolonged in time. For ethical reasons, the assessment of any VR system devoted to people with disabilities or subjects at risk should include an analysis of its effects on target physiological variables (Whalley, 1995).

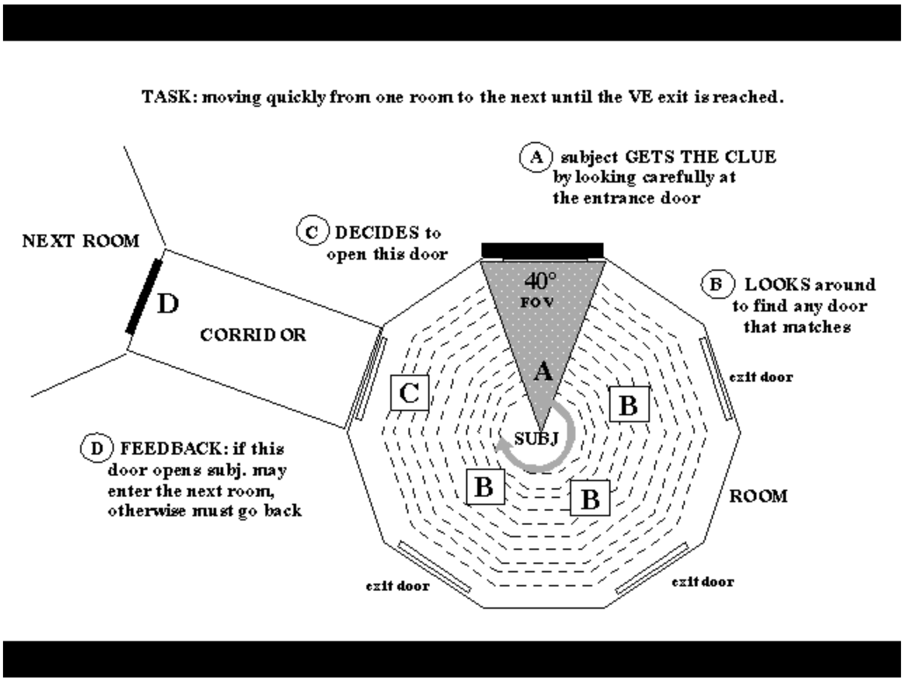

Figure 1. *Top-down schematic view of ARCANA’s virtual environment. A sequence of cognitive and behavioural steps involved in the task is also shown.*

We have followed this approach in developing prototype systems devoted to clinical studies. We will focus particularly on the ARCANA project (Pugnetti et al., 1995) as an example of the way VR can be used to implement a specific cognitive paradigm and to study its physiological correlates. ARCANA’s virtual environment (VE) features only two very simple internal architectural elements: rooms and connecting corridors. While in a room, subjects are supposed to move about by opening one of several possible doors that either lead to the next room or to a dead end corridor. The subject’s task is to proceed by trial and error until he/she finds the door that leads to the outside of the building (figure 1). Cuing is provided by the doors: their variable shapes and colours serve as matching criteria to make correct selections among several alternatives. Each subject is then expected to develop a strategy to avoid the frustration of frequent failure.

Hence, the cognitive requirements of this paradigm appear to be very similar to those of popular tests of categorisation and cognitive flexibility such as the Wisconsin Card Sorting Test (WCST). Our VR setup, however, has important additional requirements because subjects need to explore the virtual space around them, to keep spatial aspects of it within working memory, to master unfamiliar ways to move inside this space that taxes their visuomotor co-ordination, to adapt to a narrowed field of vision which demands an increased reliance upon head rotation to get all the visual information needed, and finally to interpret non-verbal feedback. In addition, information must be handled in a rather abstract form and organised into a strategy which must be checked for correctness at any new choice point, and eventually changed if not successful. This explains why there are really no correlations between the cognitive performance on a battery of standard paper-and-pencil tests and their VR-implemented analogue.

Peculiar to the VR setup for cognitive paradigms is that it allows stimuli to become integral and congruent features of an environment, and that it can be programmed so that specific cognitive events take place within specific contexts and develop on a time scale that is similar, if not identical, to that of normal purposeful behaviour. This puts those interested in assessing brain-behaviour relationships into a very favourable situation. Events flow on a time scale that allows meaningful segmentation of psychophysiological signals, and relationships can be interpreted more confidently because events take place in unambiguous contexts. Because of this, it should be possible to generalise to real life situations with a much greater degree of certainty.

We are interested in the analysis of ongoing EEG and auditory evoked potentials (EP) of our subjects performing our VR test because its underlying cognitive model is fairly well developed (Perrine, 1993) and substantial research has been already been done on its CNS correlates (Silberstein et al., 1995). Moreover, it has also been found to be an outcome predictor for neuropsychological rehabilitation (Berger et al, 1993).

These analyses can give insights into two aspects of CNS function during VR-based cognitive activity: 1) how it changes as a function of time and performance (i.e. long-term variability), and 2) how specific cognitive steps (i.e. stimulus-response sets) are reflected in short-term changes. We report here the results of interim analyses of ongoing studies.

Figure 2. *An example of 15 second polygraph recording from a subject in a virtual environment. Note the changes in EEG and EOG patterns as the subject stops moving straight and begins visual exploratory activity by turning his head right then left.*

Twelve healthy young subjects participated in the first study assessing EEG changes. Polygraphic recordings of behaving individuals were made by means of a portable 12 channel solid-state memory digital recorder (Micromed Brain Spy). A continuous recording was obtained from 7 scalp unipolar positions 1 EKG, 1 EMG, 1 PNG and 2 EOG channels (figure 2). Each recording session lasted about 1 hour, covering an average of 15 minutes both pre and post VR and 30 minutes of VR testing. EEG signals were sampled at 128Hz and 8 bit resolution, and analysed off-line on a Neuroscan v.3 workstation. Ten of 12 recordings were acceptable in terms of EEG signal quality and biological artifacts. Ocular artifacts on EEG channels were either corrected with a covariance algorithm (Semlitsch et al, 1995) or rejected with loss of the affected data epochs. Myographic artifacts were never found to be prominent on EEG channels. Since subjects participated in the study with their eyes open, the amount of alpha activity over occipital and parietal regions was considered as an index of brain activation. Indeed, the plot of mean alpha power of the 10 subjects against time shows a fairly close inverse relationship with several parameters of performance, such as the time elapsed in each room and the number of errors (figure 3). We interpret this finding either as a correlate of a more automatic mode of cognitive processing or as a progressive build up of mental fatigue. This latter hypothesis seems less likely since the post VR resting EEG did not change from the pre VR level. We may tentatively conclude that learning occurs in this VR setting and that it has central neurophysiological correlates.

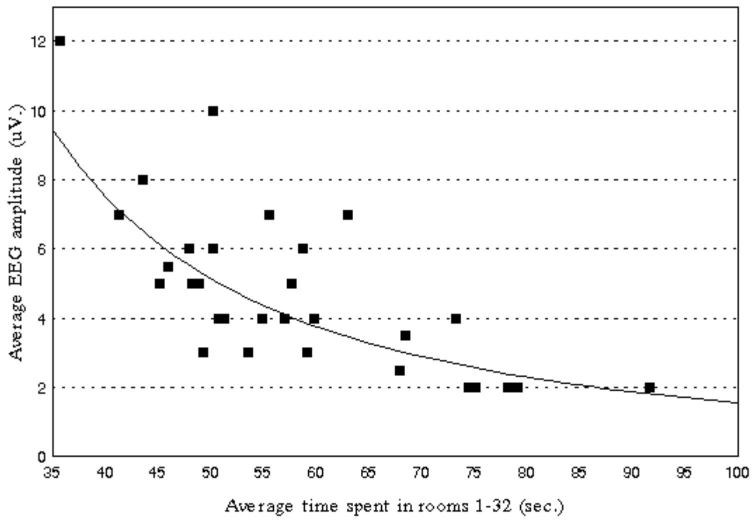

Figure 3. *Plot of EEG alpha amplitude against the time spent in each of 32 rooms. Each point is the average of 10 healthy controls.*

Cortical auditory evoked responses were elicited in another study of 10 subjects by releasing footstep sounds binaurally as they operated a pointer (a virtual key) to move forward in the virtual environment. The subjects spent an average of 40% of the time moving inside the VE. Cortical P1-N1-P2 components were measured from the grand averages of artifact-free epochs spanning the whole duration of VR testing. The latter were compared with similar responses elicited during pre- and post-VR periods. While the latter two conditions yielded comparable results, engaging in the VR task substantially reduced the amplitude of N1-P2 components; no effect was seen on the latency of the responses. This was also an expected result and is interpreted as a correlate of the activation during cognitive processing of cortical areas usually participating in EP production. The ERPs technique we used is similar to the steady state evoked potentials used by Silberstein et al. (1995) and to the ‘tracer strategy’ used by John and Eston (1995) and seems particularly promising for studying CNS correlates of mental workload in subjects. For each subject we can generate a function describing the relationship between sound intensity and ERP parameters (e.g. amplitude) in baseline conditions. By analogy, we can then use this function to measure, with the same units, the variations of ERP parameters that we observe during VR when the subject is supposed to be actively engaged in the primary task and only a fraction of his/her processing abilities is devoted to an auditory input which he/she does not have to process actively. It is expected that a heavily involved subject will produce ERPs of smaller amplitude than one who finds the task easier and can process additional inputs at the same time. We have found this to be true by comparing the ERP waveforms obtained during periods of good performance with those of bad performance (figure 4). On two occasions, subjects began to complain of nausea but were able to terminate their VR session. In both, ERPs disappeared completely after malaise onset. We interpret these findings as further supporting the hypothesis that ERP amplitude can be used as an index of saturation of residual cognitive resources left to process concurrent but irrelevant ambient stimuli.

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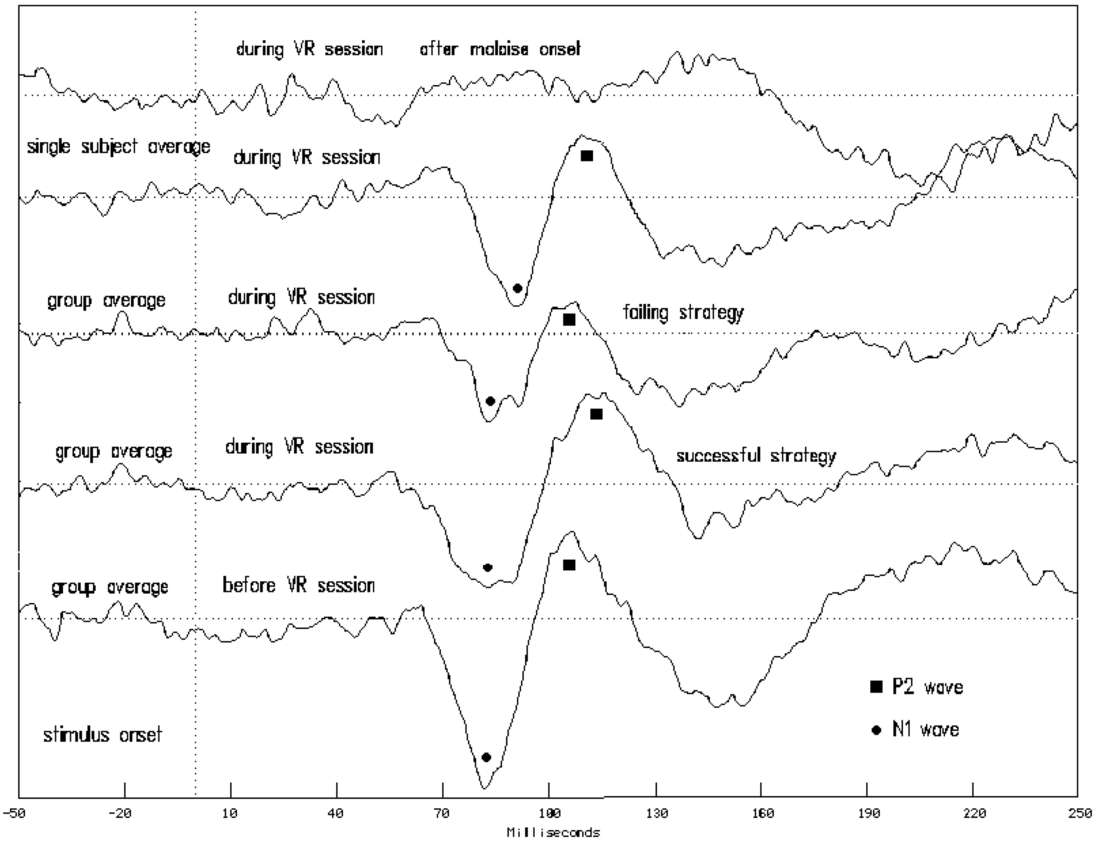

Figure 4. *Averaged evoked responses to auditory stimuli in healthy subjects. Peak amplitude of N1 and P2 components (Cz location is shown) is reduced during VR experience, especially when subjects find it difficult to deal with the cognitive demands of the task and a consolidated strategy is not yet achieved. The appearance of mild nausea in one subject makes the response impossible to recover. (Note: from bottom to top of figure, averages 1-3 and 4-5 have a different display gain).*

ERP mapping could be obtained from a subject wearing a 19 channel headset. For this experiment, 1500 Hz tones were used as stimuli unrelated to VR events. The average ERP recorded during VR shows a decrease in peak amplitude of N1-P2 components especially over anterior regions (figure 5). This observation suggests that the frontal lobes may be more involved than other brain areas. The literature on neurophysiological correlates of the WCST strongly supports this hypothesis (Weinberger et al., 1986; Silberstein et al. 1995).

We are also looking at short term changes in EEG as correlates of specific cognitive events. A critical one is the period lasting 5 to 8 seconds preceding and following feedback. We have programmed this event to take place always in the corridors (figure 1), where no exploratory activity is needed and where important cognitive activities such as anticipation and evaluation of feedback can occur in a predictable sequence. We have made a distinction between pre and post feedback periods and between positive and negative feedback. Preliminary findings pertain only to a subset of the 286 possible periods across the 9 subjects. The amount of alpha (8-12 Hz) and beta (13-20Hz) frequencies were computed for 30 post-negative feedback 8 second periods and 30 post-negative feedback 8 second periods. Beta activity was significantly increased in epochs following negative feedback as compared to epochs following positive feedback over both frontal and parietal electrodes. In the case of negative feedback, EEG findings have a behavioral correlate in an increase in the time spent in the next room, which we have called “negative feedback-evoked time response”’ (figure 6). This response occurs in more than 70% of the time in healthy subjects and reflects the necessity of a re-evaluation of the strategy after a failure. It is well known that many cognitively impaired subjects lack the capacity to make this re-evaluation and to modify their behaviour accordingly. Hence, we expect to find differences between the ability of healthy and impaired subjects to produce this response and its neurophysiological correlates.

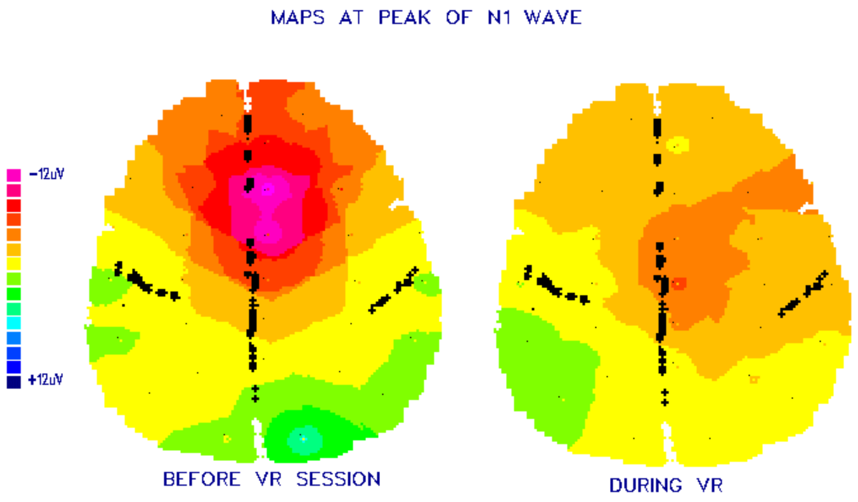

Figure 5. *Colour-coded map showing instantaneous distribution of a subject's peak N1 wave amplitude (uV.) of an auditory ERP recorded from 19 scalp positions before and during a VR session.*

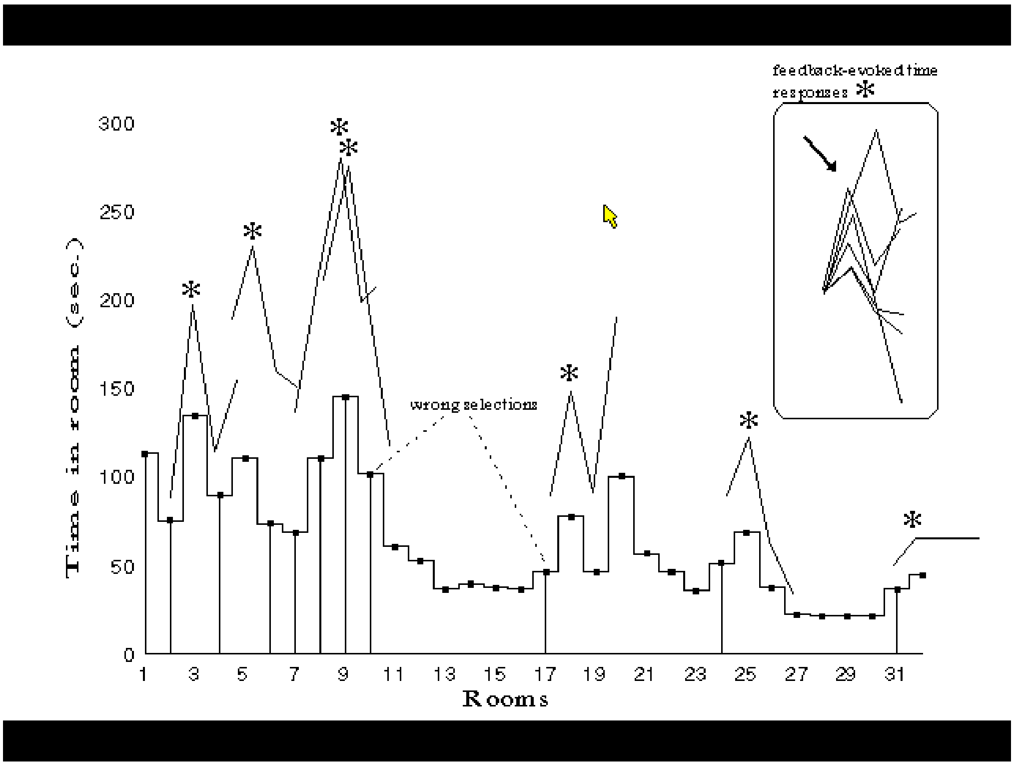

Figure 6. *Plot of time spent in each of ARCANA's consecutive room by a subject. Thin bars indicate when wrong selections occurred. An increase in the time spent in the next room frequently occurs after negative feedback, and is shown in the graph by asterisks.*

In summary, if confirmed and extended by future work and analyses, these findings should have relevance for devising clinically effective VR tools. A similar goal is being pursued by Cole et al. (1995) who have studied multichannel EEG changes prior to and after human interaction with dolphins in order to develop a VR simulator of this therapeutic experience. They have found that EEG spectral peak frequency decreases after real interaction with dolphins and that interhemispheric coherence increases.

Another set of useful data can be obtained by recording EKG changes during a VR experience. As is well known, a tachogram recovered from ECG beat-to-beat analysis is easy to obtain and is useful to assess the degree of physiological stress the subject has experienced (figure 7). This aspect is clearly important to document when dealing with disabilities because we do not want to induce stress for a number of intuitive ethical and medical reasons. Stressful paradigms may affect subjects' performance, acceptance of the technological setup and may delay learning. On the other hand, milder stress may

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facilitate performance in apathetic individuals. We suggest that heart rate changes also be analysed - with the aim of modifying VR applications to match as closely as needed the real-life situations they intend to simulate. We have found heart rate changes to serve as correlates of psychological frustration in sensitive subjects who were failing on their VR task (Pugnetti and Mendozzi, 1994). Also, heart rate changes can underline differences in psychophysiological stress between real and simulated situations. When VR medical applications induce greater changes in physiological parameters than their real counterparts, they probably need to be re-evaluated in terms of psychophysiological and cognitive demands.

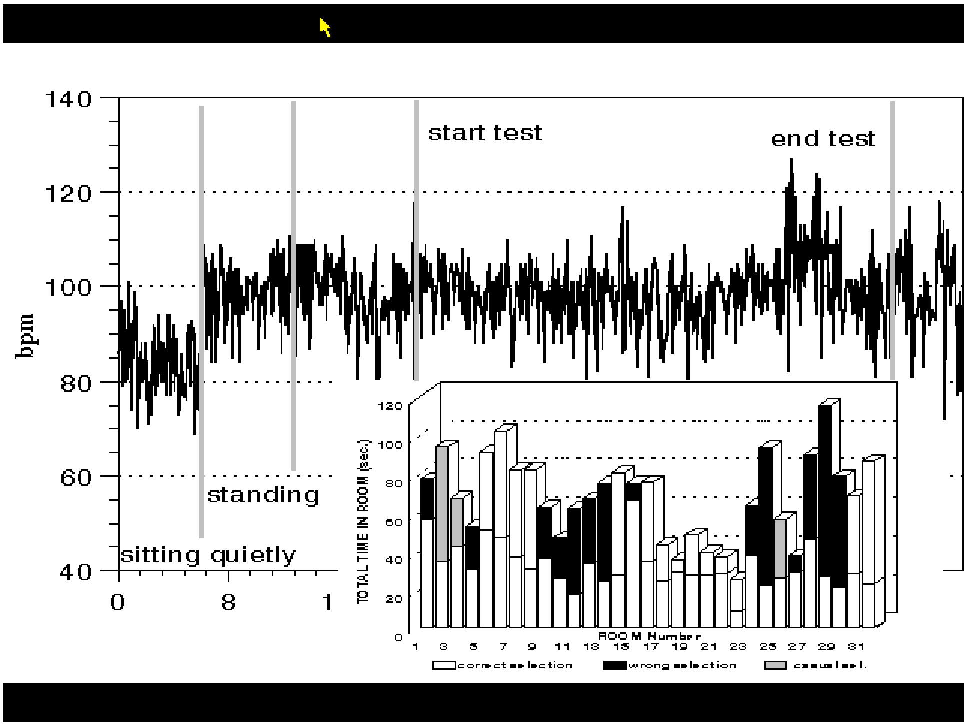

Figure 7. *Plot of mean HR measures taken every 5 seconds in a healthy subject before and during a VR session. The histogram shows time spent in rooms. Black bars indicate wrong selections. Note a HR increase at the times when he was having difficulty finding the right strategy to solve ARCANA's task.*

3. THE FUTURE

A further step in applying VR systems to enhancing learning, enabling communication and assisting cognitive rehabilitation is to bring the experience gained with in-the-field studies with VR into systems capable of modulating critical aspects of the VE in response to biological signal levels. Warner presented both theoretical justification and practical applications of this approach (Warner, 1995) which he calls 'interventional informatics'. Two children with severely disabilities children were enabled to regain control over part of their real environment by means of biosignals and VR associated technologies but, more importantly, their learning abilities were facilitated.

Another most promising rationale for undertaking psychophysiological studies of VR experiences is the implementation of biocybernetic and neurofeedback protocols within VR scenarios. The basic rationale for the former is that by means of on-line biosignal processing (i.e. multichannel EEG) an index of specific mental involvement (e.g. attention) is derived and fed in a closed-loop system to control the amount of items the subject has to pay attention to or control. This approach has being pursued to develop systems such as the EAST, a videogame-based tool intended to demonstrate the concept of rewarding specific brain signal patterns with success at playing. This application is expected to be of value in the treatment of behavioral-cognitive impairments of children with ADD (Pope, 1995). A related application of this concept is expected to emerge within the specific field of neurofeedback to improve the effectiveness of learning voluntary physiological control. According to Budzynski (1995), VR biofeedback has its rationale rooted in the right brain being the mediator of both visuospatial abilities and emotional responses. Bio-VR will act by teaching patients to control emotions via spatial aspects of the VE.

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