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Process monitoring and configural display design: a neuroimaging study

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In this paper an investigation is reported of neural imaging of the electrocortical activity involved when users monitored dynamic visual interfaces for process failures. For six different visual displays, the form of the display and the directness of mapping between process parameters and visual form were varied. Performance data showed best results with a configural display that mapped the process parameter most important for failure detection to a simple visual property of the display geometry. In this display condition, performance variability was lowest of all conditions and self-reports of users' monitoring strategy revealed the least variability among users. Neuroimaging results for this display condition revealed that changes in electrocortical activity were most consistent between subjects compared with other displays, while still remaining small in absolute terms. These results are interpreted in the light of previous findings in ecological psychology and control of dynamic systems and implications for their use in dynamic visual display design are outlined.

1. Introduction

The goal of this paper is to determine whether functional neuroimaging techniques might help to corroborate claims about the mental processing invoked with effective vs less-effective visual interfaces. In the last couple of decades, there has been an effort to define principles that will help in the design of maximally effective interfaces for dynamic systems—interfaces that deliver the right information at the right time, in a format that leads the observer to understand its significance. Many researchers have noted the advantages of exploiting the efficiency of the visual system with nomograms (Hutchins 1995) or smart displays (Runeson 1977) that allow observers to extract the significance needed with minimal cognitive effort. For many purposes, then, effective interfaces are almost synonymous with displays that rely principally upon visual perceptual processes rather than memory or computational processes.

The approach to interface design known as Ecological Interface Design (EID) draws on some of these ideas and has attracted recent attention (Vicente and Rasmussen 1992). EID is based on two ideas. First, interface designers should focus on the information the observer needs to know about a system before being concerned about literal representational formats. To achieve this, designers should analyse the work ecology as a structural means-ends hierarchy using Rasmussen's

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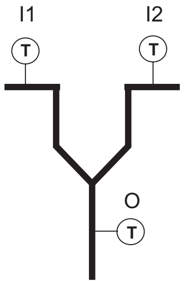
(1985) abstraction hierarchy. Secondly, designers should then seek to support human cognitive work at the most appropriate level of cognitive control—at the skill-, rule- or knowledge-based level of behaviour (SRK: Rasmussen 1983). Three design principles for EID emerge from the SRK behaviour distinction, described by Vicente (2002) thus:

(1) *Skill-based behaviour*—workers should be able to act directly on the interface.
(2) *Rule-based behaviour*—there should be a consistent one-to-one mapping between the work domain constraints and the perceptual information in the interface.
(3) *Knowledge-based behaviour*—the interface should represent the work domain in the form of an abstraction hierarchy to serve as an externalized mental model for problem solving (Vicente 2002: 4).

The problem of finding a representational form that will fit the above constraints has been termed semantic mapping (Woods 1991, Bennett and Flach 1992, Reising and Sanderson 2002). Semantic mapping is the process through which important *relations* and *constraints* in a system are mapped onto the elements of a display, usually a visual display. *Relations* are the physical and mechanical regularities that describe a system's behaviour over time. *Constraints* are boundaries that distinguish what is physically or procedurally possible or desirable from what is impossible or undesirable. Good semantic mapping means that system states (normal and abnormal), relations and constraints can be easily perceived.

There are many examples of faster and more accurate human fault detection performance when displays are developed under ecologically-inspired principles plus semantic mapping (for a review see Vicente 2002). In a simple example that is relevant for the study to be reported here, Buttigieg and Sanderson (1991) required their subjects to monitor a display to determine whether an output of a dynamic process, O, was the average of the two input values, I1 and I2. The intrinsic constraint in the work domain, therefore, was the relation $(I1 + I2)/2 = O$ and the control task was to detect violations of this constraint (see figure 1). Using a set of fixed display formats, Buttigieg and Sanderson (1991) manipulated the cogency of semantic mapping. They found that triangle, bar or shape displays with good semantic mapping supported better detection of constraint violations than the same shapes with poor semantic mapping. Best detection of all was seen with a well semantically-mapped display that was also a configural display. This appeared to be because it



K1

System purpose(s)	Achieve average temperature
Formal constraint(s)	(I1 + I2) / 2 = O
Physical processes	Measure I1 temp
	Measure I2 temp
	Mix fluids
	Measure O temp

Figure 1. A schematic of a simple temperature system (left), and a work domain analysis of the system (right) in which purpose, constraints and processes are identified.

had a visual feature that directly represented the system constraint or property to be monitored, $(I1+I2)/2=O$, or 'K1', rather than representing just the individual elements I1, I2 and O.

Using more complex continuous process microworlds, consistent advantages in performance are found when subjects use displays developed under ecologically-inspired principles. Advantages in fault detection, diagnosis and management accrue to ecological displays, particularly when subjects are called upon to handle unanticipated events (see Vicente 2002).

1.1. *Possible mental processing*

Researchers have attributed the superiority of ecological interfaces for helping users handle unanticipated events to the fact that they let observers pick up information directly through pattern recognition, which is rapid, accurate and low in mental workload. In contrast, more conventional interfaces lead to inferior performance because they force humans to integrate and compare disparate information elements mentally, which is slower, more prone to error and higher in mental workload. Sanderson *et al.* (1989) are just some of many who claim that the advantage of using displays that exploit perceptual invariants lies in the kind of human information processing such displays invoke:

> The goal for display design is to make the invariants of a process directly visible to the operator by mapping the process invariants to features of the display. Under such circumstances efficient perceptual processing (e.g. the pickup of patterns) can be substituted for higher, more demanding cognitive processes (e.g. computation and inference) (Sanderson *et al.* 1989: 186).

At present, such statements represent nothing more than plausible claims. We have no direct, independent, empirically-based evidence of the kind of mental processing invoked when humans use different displays. However, various forms of indirect evidence suggest that such claims may be sound. Pawlak and Vicente (1996) used a dual task paradigm (Wickens 1992) to test the kind of cognitive resources used by subjects when using an ecological vs conventional interface. Their results showed that spatially-demanding tasks performed alongside a system control task lead to worse performance with ecological displays than with conventional displays, indicating that ecological displays absorb visuo-spatial resources. In contrast, verbally-demanding tasks performed alongside a system control task lead to worse performance with conventional displays, indicating that conventional displays absorb verbal-symbolic resources. These results are the only direct empirical evidence to date that different classes of displays make differential demands on cognitive/perceptual resources.

Recent findings with cognitive style provide convergent evidence for differential cortical involvement. Torenvliet *et al.* (1998) used a Holist/Serialist test of cognitive style (Biggs 1987) to demonstrate that the better performers on the DURESS process control microworld are subjects who (a) use the ecological interface and (b) have high Holist scores (i.e. they prefer systems-oriented relational thinking). Interestingly, in quite independent work, Neves (1999) found distinctly different patterns of electrocortical activity when subjects perform well on a Wholist (or simultaneous) task vs an Analytic (or sequential) task. High Wholist performers showed significant right hemisphere frontal and temporal involvement. The pattern of increased amplitude and decreased latency suggested working memory involvement. High Analytic performers show significant left hemisphere occipito-parietal activity, and the pattern of amplitude and latency suggested greater involvement of spatial processing. Overall, Neves' results suggest the sensitivity of neuroimaging techniques to variables similar to those used by Torenvliet *et al.* (1998). Taken together, the above results suggest that neuroimaging may help us test claims being made about mental processing varying with different kinds of visual displays.

These findings are consistent with the theoretical positions of researchers in this area. They also provide a promising basis to proceed to neuroimaging studies, which have proven to be sensitive to various forms of cognitive and perceptual loading. The application of neurophysiological methods to human factors and ergonomics has been titled *neuroergonomics* (Parasuraman 1998, 2003). Our goal is to use neuroimaging techniques in an attempt to distinguish the cognitive and perceptual processing invoked by different user interfaces used to monitor dynamic systems (Posner and Raichle 1994). We aim to test the hypothesis that ecological displays will lead to monitoring performance mediated by visuo-perceptual areas of the brain, whereas more conventional displays will lead to monitoring performance mediated by areas of the brain involved in higher-order cognitive processes such as reasoning, planning and working memory. Specifically, we propose to use the neuroimaging technique called Steady State Probe Topography (SSPT) in our investigation (Silberstein *et al.* 1990, 1995).

1.2. *Steady state probe topography*

Steady State Probe Topography (SSPT) is a neuroimaging methodology that uses the steady state visually evoked potential (SSVEP). SSPT offers the opportunity of an analysis at high temporal resolution of brain electrical correlates of extended tasks, coupled with noise resistance (Regan 1989, Silberstein 1995). An accepted eliciting stimulus is a uniform visual flicker at a constant frequency superimposed on a computer monitor presenting a cognitive task. Analysis involves examining and interpreting amplitude and phase differences between the input stimulus and scalp readings. Previous studies have reported strong systematic effects of cognitive tasks on the SSVEP (Silberstein *et al.* 1990, 1995). For example, analysing the SSVEP from 64 scalp sites indicated that increased visual vigilance was associated with an occipito/parietal and centro/parietal reduction in the magnitude of the SSVEP elicited by the irrelevant visual flicker. Findings yielded by this technique appear analogous to the regional reductions in α-activity associated with cognitive tasks (Pfurthscheller and Klimesch 1990). The availability of an external reference signal in the stimulus also permits an estimation of changes in SSVEP latency (Line *et al.* 1998).

SSPT has been found to be sensitive to (a) the different phases of a visual vigilance task (Silberstein *et al.* 1990), (b) the need to change strategies during the Wisconsin card sorting task (Silberstein *et al.* 1995), and (c) the use of visual vs auditory modalities in continuous performance tasks (Silberstein *et al.* 1996). It is also sensitive to a variety of clinical differences between subjects.

Compared to Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI), SSPT has a high temporal resolution, providing an image of cortical activity based on readings over a time window typically of 0.77 s. The time window can be shifted to generate dynamic images of changes in cortical activity during a sustained task (Silberstein *et al.* 1990, 1996, Silberstein 1992). Thus, SSPT is uniquely suited to study human interaction with dynamic displays because it lets a researcher capture and visualize electrocortical activity in near to real time. In contrast, Positron Emissions Tomography (PET) provides, at most, one image of cortical activity per minute. Functional MRI (fMRI) provides temporal resolution closer to that of SSPT, but fMRI tracks cerebral blood flow, which is a response to cortical activity that happens at a lag of 2–6 s after the cortical activity. SSPT, therefore, appears to be a good technique for understanding the neuropsychology of human interaction with complex systems through different user interfaces.

The research reported here is the first time that brain imaging techniques such as SSPT have been used to understand human interaction with displays designed to convey information about complex dynamic systems. SSPT data could help to corroborate or disconfirm claims that the configural displays typical of ecological interfaces elicit visual perceptual processing to a greater degree than conventional displays.

1.3. *Rationale for present study*

For the experiments described, we manipulated the display for monitoring a simple hydraulic system. This follows a tradition of research in this area (Sanderson *et al.* 1989, Wickens and Carswell 1995, Bennett *et al.* 1997). Much as the chronometric approach to human information processing has served neuroimaging (Posner and Raichle 1994), so a simple hydraulic system may lend itself to an incremental, additive approach to understanding cortical mediation of human interaction with dynamic systems. Two input streams of water combine in a Y-junction to form a single output stream so that the temperature of the water in the output stream is a combination of the temperaturse in the first and second input streams. To perform the Work Domain Analysis required of EID, we used three levels of abstraction rather than the more usual five (see figure 1):

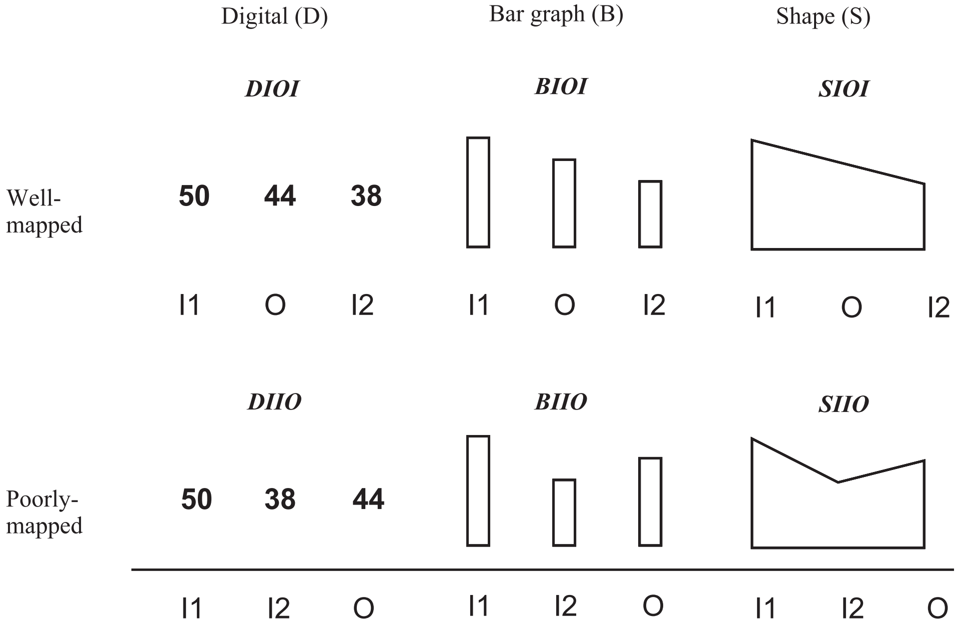


Figure 2. The six display formats for monitoring the temperature system.

- *System Purpose*, where the functional purpose of the system is shown,
- *Formal Constraints*, which show constraints that govern the functioning of the system, and
- *System Functions*, which show the physical functioning of the system.

In the simplest version of the system, which we will explore here, the flowrates of the two input streams are normally equal, so the output temperature is always the average of the two input temperatures: $(I1 + I2)/2 = O$ (see figure 1). The human controller's task was to monitor the process and to indicate if the formal constraint K1—whether the output O is the average of the inputs I1 and I2—is violated.

For the semantic mapping manipulation, digital, bar graph and shape displays were used. There were two ways of mapping the temperature averaging function onto the visual properties of the display (see figure 2). In the well-mapped displays, the output lay between the two inputs so that for both the bar graph and shape displays the output's height would always fall exactly half way between the heights of the two inputs. Under normal conditions, with the shape display this produced an emergent feature of a straight line. With the bar graph display, a straight line could be imagined across the tops of the three bars. Buttigieg and Sanderson (1991) had shown that this mapping (input, output, input or IOI) of the three values led to better performance compared with the corresponding poorly-mapped conditions for each display, in which the output was placed at the right of the two input values (input, input, output or IIO) so that the emergent feature of linearity was removed.

In the present experiment, a digital condition was used in order to test the sensitivity of the SSPT technique to expected differences in cognitive processes. There was no compelling *a priori* argument for which arrangement of digital values would be well- vs poorly-mapped, so the assignment of arrangements to mappings simply followed the shape and bar graph displays.

The SSPT technique required some procedural differences from those used originally by Buttigieg and Sanderson (1991), which will be described in section 2. Before proceeding to the imaging study, we ran a pilot study without collecting cortical imaging data to ensure that we could replicate and extend the original results. The pilot study established that possibly intrusive aspects of the SSPT technique did not change the way subjects performed the failure-monitoring task.

The goals of the imaging study reported here were as follows:

1. To replicate the main effects and interaction of displays and mappings previously found by Buttigieg and Sanderson (1991).
2. To determine whether there is evidence that (a) well-mapped configural displays lead to electrocortical activity suggestive of perceptual processing, and (b) poorly-mapped digital displays, in particular, to lead to electrocortical activity suggestive of high-workload verbal-symbolic processing.

2. Method

2.1. *Participants*

Participants were 33 members of the Swinburne University community who were paid for their participation in the study. Participants were right-handed with no history of epilepsy and they gave written informed consent to participate.

	Order					
Particip.	1	2	3	4	5	6
1 7 *etc*	1	2	6	3	5	4
2 8 32	2	3	1	4	6	5
3 9 33	3	4	2	5	1	6
4 10	4	5	3	6	2	1
5 11	5	6	4	1	3	2
6 12	6	1	5	2	4	3

Displays	1	SIOI Shape, well-mapped
	2	SIIO Shape, poorly-mapped
	3	BIOI Bar, well-mapped
	4	BIIO Bar, poorly-mapped
	5	DIOI Digits, well-mapped
	6	DIIO Digits, poorly-mapped

Each cell	2 x baseline trials of 4 minutes
	2 x target trials of 4 minutes

Figure 3. Experimental design, showing conditions and counterbalancing.

2.2. *Design*

A within-subjects design was used so that each participant experienced all three displays in both their well- and poorly-mapped configurations, making six conditions overall. Each condition was experienced in the context of a target and baseline task and for a first and second block of trials (see figure 3).

The creation of target and baseline tasks reflected the needs of the SSPT neuroimaging technique and is, therefore, an extension to the original Buttigieg and Sanderson (1991) procedure. People have characteristic resting patterns of cortical activity. As a result, inter-subject variability may swamp small but significant changes in cortical activity for different cognitive tasks. SSPT analyses, therefore, examine the difference in cortical activity between the task of interest (target task) and a task that is similar in every respect except for the most critical cognitive attribute of the task of interest (baseline task). Accordingly, in the present study, the only difference between the target and baseline was as follows.

- *Target task*: Participants monitored for violations of the K1 constraint when I1 varied independently of I2. Usually $I1 \neq I2 \neq O$. Participants judged whether or not O had the correct value given the two different values for I1 and I2.
- *Baseline task*: Participants monitored for violations of the K1 constraint when I1 was always the same value as I2. Usually $I1 = I2 = O$ but in case of a violation, then $(I1 = I2) \neq O$. Participants only had to judge whether or not O was the same as I1 and I2. In all other respects, the task was the same as the target task.

The order of conditions always conformed to a Latin Square design so that across participants each display would be experienced at all serial positions and would be immediately preceded and followed by all other experimental conditions (see figure 3). Within each condition, the baseline task always preceded the target task.

For both the pilot and imaging studies, the experiment was divided over 2 days. On day 1, participants received the instructions and performed the first three conditions of the experinent. On day 2, participants completed the final three conditions.

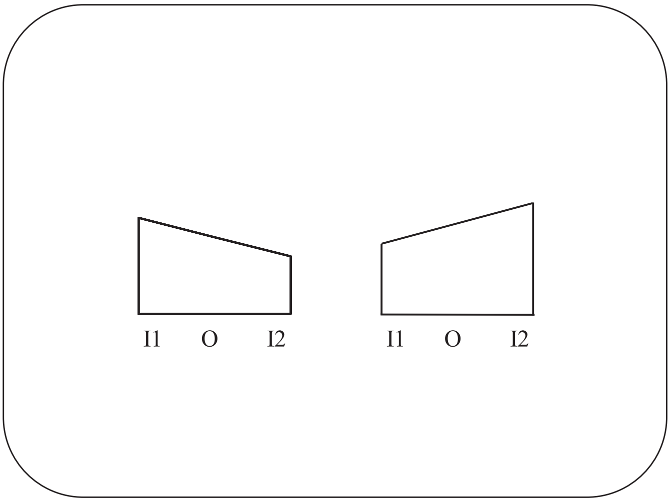


Figure 4. How the display looked to participants. Participants monitored two displays of the same kind.

2.3. *Tasks*

2.3.1. *Failure detection task*: The failure detection task was the same across target and baseline tasks. Participants monitored two independent hydraulic systems that were displayed side-by-side on a computer screen (see figure 4). For each system, participants had to detect whenever the output temperature was no longer be the average of the two inputs $[O \neq (I1 + I2)/2]$ but instead gradually became greater or less than expected. If there was a failure in the left or right process, the participant pressed the left or right button on a response box, respectively. If the response was correct (hit), a large green check mark appeared in the centre of the screen. If the response was incorrect (false alarm or miss), a large red cross appeared in the centre of the screen.

Within each display condition (see figure 3) there were two baseline blocks and two target blocks of 4 min each. There were seven or eight failures within each block. At the end of each block, participants were given feedback on their reaction time and accuracy in the format shown in figure 5. They were asked to ensure that their score fell into upper rightmost part of the box, as shown in figure 5. The Euclidean distance between the origin of the graph and the result for each block was called the 'score' and was used as a performance measure in the analysis (see section 3).

Participants were not instructed in how to perform the task, but were simply asked to judge whether the output was the average of the two inputs. There was a slight variation for the digital conditions. The first 15 participants were instructed not to literally try to perform the mental arithmetic, whereas the instructions for the second 18 participants were brought closer in line with the instructions for all other conditions by not suggesting that any strategy should be avoided.

2.3.2. *Self-report of strategy*: Self-report questionnaires were introduced for the last 18 participants in the experiment. At the end of the four blocks of trials for each display, these participants were asked to report the strategy they had used for the target displays. At the top of the form was a picture of the two processes

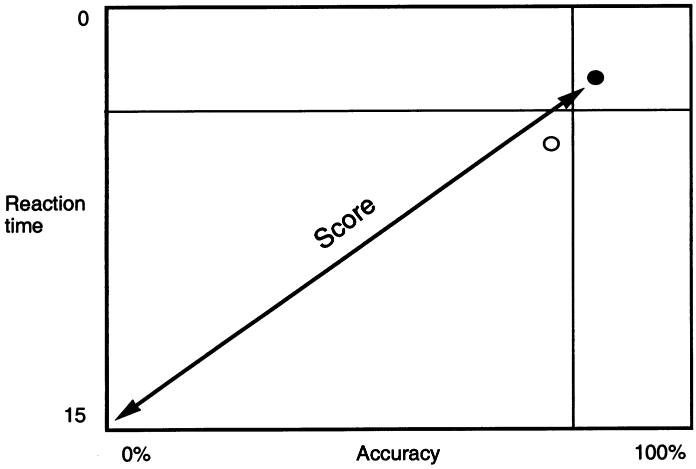


Figure 5. Format of feedback provided to the participants. The diagonal arrow shows how the Score measure was calculated, but was not visible to the participants.

they had been monitoring in the display format they had just experienced. The processes were shown as they would look in a target task, with $I1 \neq I2$. At the bottom of the form was an area where they could write a description of their strategy. Participants were asked to record in both words and pictures the strategy (or strategies) they had used to perform the task, providing as much detail as possible.

2.4. *Stimuli and apparatus*

2.4.1. *Process functions and displays*: Both experiments were run on a PC with a VGA monitor. A sample of the image participants saw on the screen is shown in figure 4 for the SIOI display. The distance from the left side of the leftmost display to the right side of the rightmost displays was 10.25 cm.

For the shape and bar displays, the two input values, I1 and I2, were driven by a sum of sinusoidal functions at 0.1 and 0.09 Hz for I1 and 0.08 and 0.07 Hz for I2. The values were updated to the screen at 50 Hz. The so-called failure input, I3, was a sum of sinusoidal functions at 0.09 and 0.08 Hz. The tops of the shape and bar displays moved smoothly and continuously as the input and output values changed.

We decided to construct and display the digital display somewhat differently from the shape and bar graphs in order to achieve approximate equivalence in superficial task demands. First, the digital display could not be refreshed at the rate the shape and bar graphs were. Instead, the display had to remain on the screen long enough for all three digits to be read and a true/false judgement to be possible before the display changed. Pilot work suggested that even in the baseline condition this often took more than 1.0 s. Pilot work also suggested that, although variable, visual dwell time for each of the two shape or bar displays monitored was $\sim$1.0–1.5 s. Given this, we decided to update the digital display every 3 s. Sampling all three displays at a rate consistent with the amount of time needed to read digits and make a judgement would sometimes mean that bar and shape displays would appear as successive disjointed snapshots of quite different states.

Secondly, even with the 3-s update of the digital display, the inputs or outputs from the sine functions would often produce the same digital value at the top and bottom of the cycle for several refreshes whereas at the equivalent point with the shape and bar displays, slight movement would still be seen. For the digital display, therefore, chose input values from two zigzag functions with slightly longer cycle times than for the sinusoidal function. This resulted in a succession of values at 3-s intervals that were adequately autocorrelated with the values at the previous interval to be comparable to the smooth movement of the bar and shape displays. With these manipulations, we created series of input values that appeared to capture the temporal demands and input series complexity of the shape and bar displays. As for the shape and bar graph displays, failures were created by ramping in the contribution of a third input series.

Equivalence across the three display conditions could be process equivalence or subjective cognitive equivalence. For this initial study, we chose to replicate the smooth motion of the Buttigieg and Sanderson (1991) shape and bar displays, and for the purposes of comparing SSVEP results to create a digital display that led to a feasible task with the same approximate rate of judgements and approximately the same autocorrelations between successive values on the two inputs and the output. Pilot work with a discrete version of the well-mapped shape display (SIOI-D) has indicated equivalent performance results to the continuous version. A full comparison of discrete presentations of shape, bar and digital displays would provide an answer to a slightly different, but equally valid, question, and is considered for further work.

2.4.2. *Failures within blocks*: Within each display condition of the experiment (see figure 3) there were two baseline blocks and two target blocks of 4 min each. Each block contained between seven and eight failures. Failures were placed randomly within the block, with the exception of the 5 s at the start and 5 s at the end of the block. Failures were constructed by differentially weighting the true output value and an unrelated function, I3, that had a frequency in the same general range as I1 and I2:

$$\mathrm{O} = k[(\mathrm{I1} + \mathrm{I2})/2] + (1 - k)\mathrm{I3}$$

Under normal conditions, *k* was equal to 1, whereas under abnormal conditions *k* ramped smoothly from 1 to 0 over a period of 15 s. Each failure continued for 15 s or until the correct key was pressed to indicate the failure, at which time the output was set back to its normal value. RT was measured from the point at which evidence for failure was present in the interface. Simultaneous failures in the left and right process (see figure 4) were prevented. Failures were generated this way for both target and baseline conditions.

2.4.3. *Collection of SSPT data*: The visual stimulus used to evoke the SSVEP was a 13 Hz sinusoidal flicker subtending a horizontal angle of 160° and a vertical angle of 90°. As is standard for collecting SSVEP data, participants wore a set of goggles that superimposed the flicker over the viewing field. The flicker was experienced as a soft but quickly flickering red light that fills the visual field.

Brain electrical activity was recorded from electrodes at 64 scalp sites which included all International 10–20 positions with additional sites located midway between 10–20 locations. Participants wore an elasticized cap that held the electrodes in position. SSVEP data are gathered from the electrodes while the participant performs a task, and then are amplified, filtered and stored. The amplitude and phase of the SSVEP signal at each scalp site is determined from the 13 Hz cosine and sine Fourier coefficients, evaluated over a 0.77 s integration window that is then shifted in time and the process repeated. Topographic maps of changes in amplitude and changes in phase of the 13 Hz output signal are created by using an interpolation technique to calculate values between electrode locations (see Silberstein *et al.* 1990, 1995 for more details of the method). SSVEP phase variations are expressed as latency variation.

SSVEP data, being scalp data, are clearly not as exact or as revealing as cortical data would be. While there are techniques available to better localize activity to the cortical surface (e.g. Scherg 1990), the assessment of scalp data, reflecting the summed activity of synchronously active neural populations underlying the scalp (e.g. Kutas and Dale 1997), is a well accepted practice and used extensively in the electrophysiological literature (Picton *et al.* 1995, Kutas and Dale 1997). The advantage of the SSPT technique, in particular, is the ability to monitor fast neural changes continuously, albeit with a reduced spatial resolution. In addition, the SSVEP has been found to be relatively insensitive to artifacts such as muscle activity (EMG), eye movements (EOG), eye blinks and 50 Hz mains interference (Silberstein *et al.* 1993). Moreover, the SSVEP is produced by a diffuse unstructured stimulus (Silberstein 1995) and is, therefore, not as affected by eye position effects, such as those produced by highly structured stimuli (e.g. Hillyard *et al.* 1997). Silberstein *et al.* (1991) showed that the SSVEP was not affected by eye position during the performance of a vigilance task.

In the present paper, we report SSPT results for the monitoring phase of the experiment. Therefore, the differences between conditions will reveal differences in neural activity as participants monitor each kind of display and anticipate certain classes of change to the visual stimulus.

3. Results

3.1. *Performance results*

The performance data collected under imaging conditions—that is, with the electrode cap and 13 Hz flicker—are very similar to prior pilot data taken with six participants who did not wear the electrode cap. The absolute values of RT, accuracy and score and the pattern of results were effectively the same across the pilot and imaging studies. These results cannot prove that the cap and 13 Hz flicker did not disrupt the way participants performed the monitoring task, but they reassure us that the cap and goggles did not affect the speed or accuracy of participants' responding and so provide no *a priori* basis for concern.

For the imaging study, monitoring data for both target and baseline tasks were analysed and are shown in figures 6, 7 and 8. The baseline task was simple and so produced performance close to the performance ceiling, with results similar across displays. Because there was strong non-homogeneity of variance between baseline and target task conditions and because differences in the target data were the principal focus of the study, ANOVAs are presented only for target data. In each case, a three-way ANOVA was performed with the within-subjects factors of display, mapping and practice.

Figure 6 shows the results for RT. There was a significant effect of display, $F(2, 34) = 19.82$, $\mathrm{MSe} = 2.52$, $p < 0.001$, with the Shape display supporting fastest

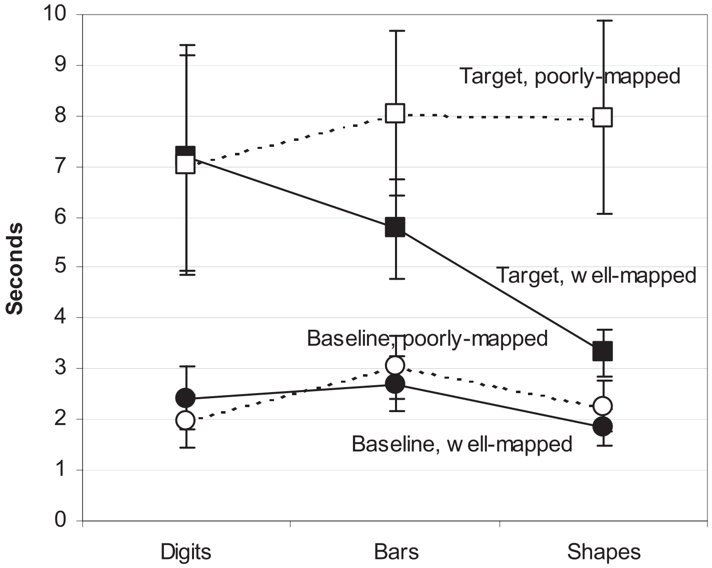


Figure 6. Results for reaction time. Error bars are standard deviation.

responding. Neuman-Keuls comparisons showed that the Shape display was faster than the Bar display, and the Bar display was faster than the Digital display. Mapping was highly significant, $F(1,32) = 199.44$, $\mathrm{MSe} = 4.15$, $p < 0.001$, and showed that participants responded faster with the well-mapped displays. There was no effect of practice. There was a significant interaction between mapping and display, $F(2,64) = 101.87$, $\mathrm{MSe} = 1.86$, $p < 0.001$, which indicated that the advantage of good mapping was particularly strong for the shape display with (the SIOI condition).

Figure 7 shows the results for Accuracy. There was a significant effect of display, $F(2,64) = 89.98$, $\mathrm{MSe} = 0.045$, $p < 0.001$. Neuman-Keuls comparisons showed that the Shape and Bar displays led to faster performance than the Digital display, but there was no difference in performance with the Shape and Bar displays, although the trend was consistent with the RT results. Mapping was significant, $F(1,32) = 30.92$, $\mathrm{MSe} = 0.039$, $p < 0.001$, and showed that participants responded more accurately with well-mapped displays. In addition, there was a small effect of Practice, $F(1,32) = 4.55$, $\mathrm{MSe} = 0.03$, $p < 0.05$. There was also a tendency for mapping and display to interact, $F(2,64) = 2.45$, $\mathrm{MSe} = 0.035$, $0.1 > p > 0.05$, which indicated a tendency for good mapping to improve accuracy more from the digit to the bar to the shape display than was the case with poor mapping.

Finally, figure 8 shows the results for Score. There was a significant effect of display, $F(2,64) = 84.4$, $\mathrm{MSe} = 385.63$, $p < 0.001$. Neuman-Keuls comparisons showed that the Shape display led to better Score results than the Bar display, and the Bar display led to better Score results than the Digital display. Mapping was significant, $F(2,64) = 111.48$, $\mathrm{MSe} = 221.75$, $p < 0.001$, and showed that scores were higher with well-mapped displays. Mapping and display interacted significantly, $F(2,64) = 37.26$, $\mathrm{MSe} = 196.44$, $p < 0.001$, indicating that good mapping led to a very large improvement in scores with the shape display, a large improvement with the Bar display, but very little improvement with the Digital display.

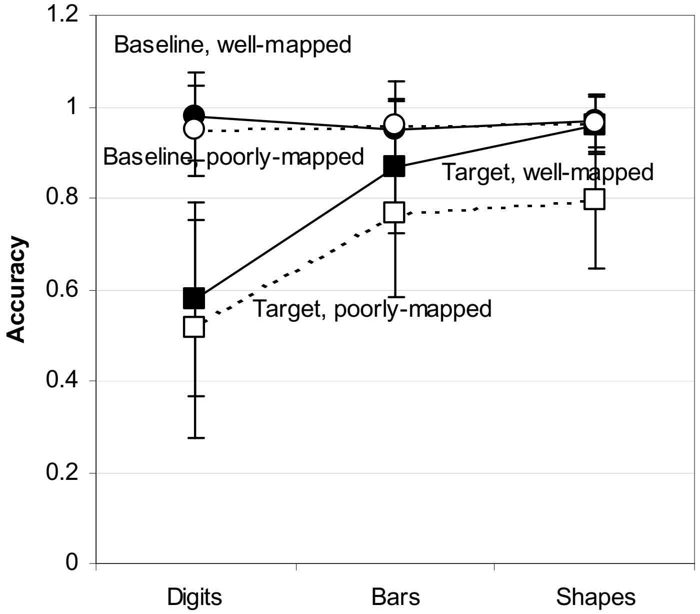


Figure 7. Results for accuracy. Error bars are standard deviation.

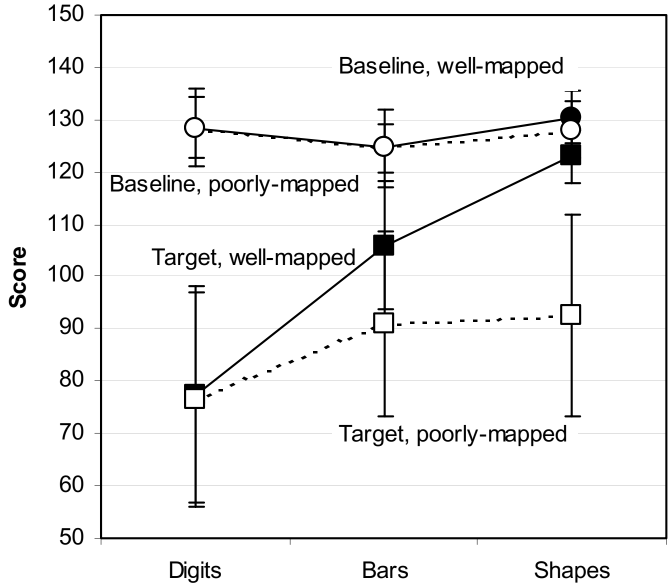


Figure 8. Results for Score. Error bars are standard deviation.

Finally, there was a marginally significant interaction between display, mapping and practice, $F(2, 64) = 2.51$, $\mathrm{MSe} = 189.56$, $0.1 > p > 0.05$, which indicated that with the Bar and Shape displays, practice tended to lead to higher scores, whereas with the Digital displays practice tended to lead to lower scores.

	Digits		Bars		Shapes	
RT (SD)						
Well-mapped	DIOI	2.2	BIOI	1.0	SIOI	0.5
Poorly-mapped	DIIO	2.2	BIIO	1.6	SIIO	1.9
Accuracy (SD)						
Well-mapped	DIOI	0.21	BIOI	0.15	SIOI	0.06
Poorly-mapped	DIIO	0.24	BIIO	0.19	SIIO	0.15
Score (SD)						
Well-mapped	DIOI	20.9	BIOI	12.1	SIOI	5.1
Poorly-mapped	DIIO	20.5	BIIO	17.7	SIIO	19.2
Distinct strategies						
Well-mapped	DIOI	11	BIOI	6	SIOI	4
Poorly-mapped	DIIO	13	BIIO	7	SIIO	8
SSPT consistency						
Well-mapped	DIOI	4	BIOI	3	SIOI	1
Poorly-mapped	DIIO	4	BIIO	4	SIIO	2

Figure 9. The top three fields show standard deviations across the different displays and mappings. The fourth field shows the number of unique strategies reported out of the 18 participants to whom self-report questionnaires were administered about strategy used. The fifth field rank orders the neuroimaging results from 1 = most consistent changes across subjects within condition to 4 = least consistent changes across subjects within condition.

The results for the digital conditions were the same for all three dependent variables across the first 15 participants and the second 18 participants. This indicated that the shift in emphasis of the instructions, as described in section 2.3, had no effect on performance.

The variability in performance between subjects within each condition followed the means, as is shown by the standard deviations in the top three fields of figure 9. The pattern was the same across RT, accuracy and score. Variability was high and equivalent for digital conditions, whether well- or poorly-mapped. For the bar graph display, there was a slightly larger reduction in variability for the well-mapped display compared with the poorly-mapped display. For the shape display, variability for the poorly-mapped display was as high if not higher than for the other poorly-mapped displays. However, for the well-mapped shape display, variability in performance between subjects was markedly lower in all cases. Although the *F*-tests for our within-subjects design suggest a high level of consistency across participants in how they reacted to changes in Display and Mapping, the less that the constraint K1 was evident in the display, the more idiosyncratic participants' responding became.

3.2. *Self-report results*

Questionnaires seeking a self-report of strategy were administered to the last 18 participants in the study. At the end of the trials for each kind of display, participants were asked to report the strategy they had used for the target trials. From the reports, we identified for each display the strategies reported for performing the task and counted the number of participants reporting that they used each category. Results are shown at the bottom of figure 9. Many more strategies were reported for digits than for bars and shapes, and there were more strategies reported for poorly-mapped than for well-mapped displays. In the well-mapped SIOI display only four distinct strategies were reported, all related to the linearity of the top of the shape. More than half the participants simply reported looking for a break in the line. In the well-mapped bar display (BIOI), many participants reported imagining a line joining the tops of the bar, but several other strategies emerged also.

For the poorly-mapped shape and bar displays (SIIO and BIIO), participants adopted strategies related to determining if the output was between the two input heights or outside the bounds defined by the two input heights. The strategies were often heuristics that reflected only a part of the true relationship to be monitored. For the Digits displays (DIIO and DIOI) as many as 13 strategies are mentioned, with no one strategy generally preferred by participants. The strategies were heuristic rather than exact, many involving partial and idiosyncratic use of number relations.

Taking the most extreme conditions, over three times as many strategies are noted for the DIIO display as for the SIOI display. It is notable that no participants reported literally trying to perform the mental arithmetic. This suggests that the shift in instructions for the digital condition did not promote the use of mental arithmetic, probably because it was too difficult.

3.3. *Neuroimaging results*

The neuroimaging data presented here are only one aspect of the neuroimaging results from this study. In this report, we have focused on neuroimaging during the monitoring phase rather than the response phase of the experiments. Although potentially informative, response-phase neuroimaging data includes—to a degree difficult to discern—idiosyncratic elements associated with making responses.

The SSPT maps shown in figure 10 represent the topology of the scalp, viewed from directly above, with the participant's nose facing upwards. Results are averaged for the 5 s before the onset of the system failure, while participants are monitoring for failures well before they are evident, rather than responding.

In each of the six cells of the experimental design (seen as the cells of figure 10), the top left map shows the amplitude changes in the target task relative to baseline, where hot colours indicate an SSVEP amplitude reduction in the target task compared with baseline, suggestive of greater relative activation in the target task compared with baseline. In the top right map of each cell, hot colours indicate a latency decrease (phase lead) in the target task compared with the baseline task. SSVEP latency reductions index increased neural excitation or reduced neural inhibition, whereas SSVEP latency increases index increased neural inhibition or reduced neural excitation compared with the baseline. A scale is given in the top left that distinguishes the mapping of colours for positive vs negative values. In the following section, we first describe the pattern of statistical significance across the six displays. We then interpret the specific pattern of activity within each display.

3.3.1. *Patterns of statistical significance*: The third map in the lower half of each cell represents the value of Hotelling's T, a multivariate statistic that here takes into account changes in both amplitude and latency. Red/pink values beyond the second white band are significant at $p < 0.05$, having been corrected for the number of measures taken, whereas cooler colours represent non-significant results.

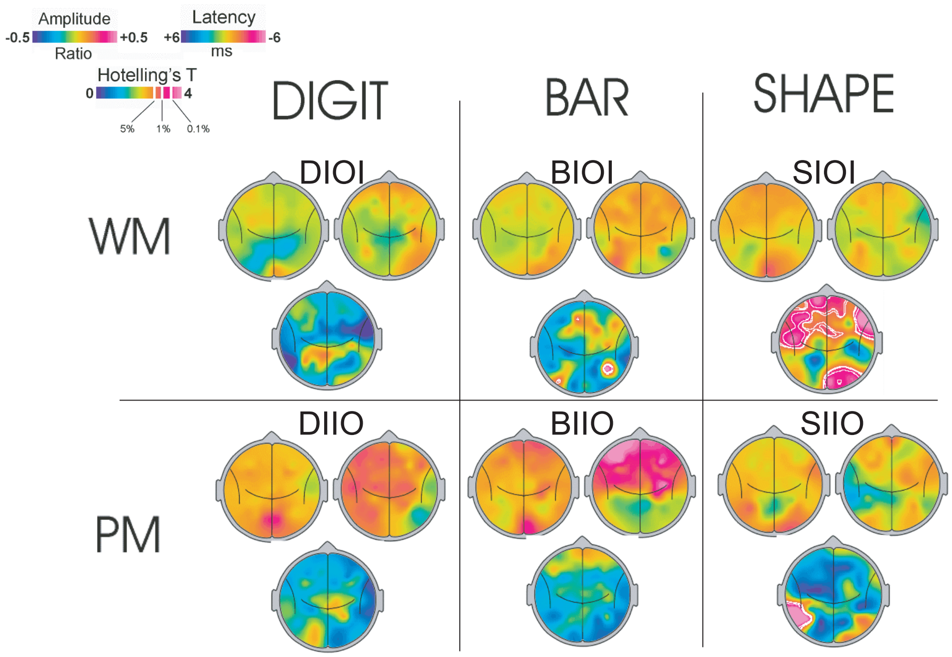


Figure 10. Neuroimaging results, laid out consistently with the experimental design. In each of the six cells of the experimental design, the left image against the black background shows the increase (hot colours) or decrease (cool colours) in amplitude of the target task over the baseline task, and the right image is the latency decrease (hot colours) or increase (cool colours) of the target task over the baseline task. The third map in the lower half of each cell represents the value of Hotelling's T. For the Hotelling's T maps, pink values beyond the second white band are significant at $p < 0.05$, once adjusted for the number of comparisons and maps.

The lack of large areas showing strong statistical significance in the patterns of electrocortical changes for all but the SIOI condition and, to a lesser extent, the SIIO condition might at first appear disappointing. However, the pattern of results is probably the most important feature of the present neuroimaging results for the following reasons.

As noted, the well-mapped shape display (SIOI) is the only condition in which the difference in electrocortical activity between target and baseline tasks is statistically significant for much of the cortex. These results occur for the display for which amplitude and phase results suggest there appears to be next to least absolute difference in amplitude between target and baseline tasks and least *absolute* difference in latency between target and baseline tasks. In other words, the Hotelling's T results suggest that when using the SIOI display, participants are highly consistent in showing quite *small* changes in electrocortical activity compared with baseline. Because the experiment used a within-subjects design with the order of presentation of displays counterbalanced across participants in a Latin Square design, the difference in patterns of statistical significance cannot be attributed simply to sampling error, practice effects or carryover effects.

The results for self report and performance variability suggest why we find the above pattern of neuroimaging results—a summary of all data reflecting variability of responding is given in figure 9. For the SIOI display, fewest distinct strategies were reported, yet all reported strategies related in one way or another to monitoring the straight line at the top of the shape for bends or breaks. This suggests that mental activity was probably much more homogeneous in this condition. The theoretical significance of these findings will be outlined in section 4.

3.3.2. *Patterns of electrocortical activity*: Changes in amplitude and latency across the cortex are worthy of notice within displays only when accompanied by statistically significant Hotelling's T results. Notable changes for the six displays are as follows, together with some discussion of their possible meaning.

- *SIOI*: Hotelling's T shows significant changes in the right occipital region, the right frontal-temporal region and the left frontal region. The significant change in the right occipital region appears to be related to a moderate but very localized decrease in SSVEP amplitude (and, therefore, an increase in activation) for the target task over the baseline task, which is probably related generally to visual attention and specifically to the detection of relative angles of line segments. The significant change in the right frontal-temporal regions seems associated with a slight latency decrease in that area. This is similar to Neves' (1999) finding with SSPT of significant right frontal and temporal involvement indicative of spatial processing for good performers on a wholist or simultaneous task. The significant changes in the left frontal area are more diffuse.
- *SIIO*: Hotelling's T shows significant changes in the left temporal-parietal area only. These appear to be related to a moderate decrease in SSVEP amplitude (and, therefore, an increase in activation) for the target display in the left parietal region and a moderate latency increase in the left temporal area. The left parietal decrease in SSVEP amplitude (increase in activation) for the target task is connected with form perception: determining the normality of the SIIO shape requires a more relational judgement than the simple judgement of linear integrity that was needed for the SIOI display. This is similar to Neves' (1999) finding with SSPT of left occipito-parietal involvement for good performers on an analytic task. In addition, the left temporal latency increase found in the SIIO condition may indicate the engagement of inhibitory processes. Again, this is similar to Neves' (1999) SSPT results for an analytic task (embedded figures task). Neves interpreted an increase in left temporal SSVEP latency as the engagement of inhibitory processes needed to suppress responses to an interfering visual stimuli. This interpretation may generalize to the present task. A commonly-reported strategy for detecting violation of the K1 constraint with the SIIO display was to compare the heights of the three uppermost points of the shape while ignoring (inhibiting a response to) the sloping lines joining the points (whose relative slopes would also be adequate for doing the task)—and vice-versa. This result reaches significance probably because the need to establish resistance to interference is common across the two strategies. The lack of left temporal inhibition in BIIO corroborates this interpretation because for BIIO no sloped lines are physically present and, therefore, there is no need to resist interference.
- *BIOI*: Hotelling's T shows significant changes only in a highly localized part of the right parietal region. The right occipital area shows an increase in activation, but unlike the SIOI condition it is not significant.

- *BIIO*: Hotelling's T does not show any significant changes in amplitude or phase for the target over the baseline task. The phase changes in the frontal area, suggestive of excitation in the target task, were not sufficiently consistent to reach significance.
- *DIOI*: Hotelling's T shows no significant changes—indeed, the relative absence even of trends suggests greater variation between participants than for any other display. A comparison of cortical maps for the first 15 participants and the second 18 participants shows no greater difference in the pattern of trends across sub-groups than is the case for the bar and shape displays, for which the shift in instructions was irrelevant. This argues against any claim that the shift in instructions created the variety of strategies and patterns of cortical activity seen.
- *DIIO*: Hotelling's T shows no significant changes. The interpretation of the results is the same as for DIOI.

4. Discussion

In this study, we have replicated and extended the findings of Buttigieg and Sanderson (1991) and so have provided a solid foundation for starting to investigate cortical activity during dynamic display monitoring. In what follows, we discuss the most important aspects of the performance data and then discuss the additional insights provided by neuroimaging data. Finally, we point to the potential applications of neuroimaging techniques in visual display design and indicate questions still remaining.

4.1. *Importance of findings*

4.1.1. *Performance and self-report results*: Our performance results are consistent with an empirical tradition of research on dynamic display design (Sanderson *et al.* 1989, 1992, Buttigieg and Sanderson 1991, Bennett and Flach 1992, Vicente *et al.* 1995). However, our results extend that tradition in several interesting ways.

First, although the baseline task was constructed for the purposes of analysing the SSPT data, it has offered useful insights that have implications for display design. Performance with the well-mapped shape display (SIOI) on the target task scarcely differs from performance on the baseline task. The SIOI display seems to make detecting violations of the K1 constraint so simple in the target task that it is barely more difficult than doing the baseline task—means and variability are very similar. The results indicate that monitoring a straight line that changes its height and orientation (SIOI target task) is as simple as monitoring a straight line that changes its height only (SIOI baseline task)—both are supported by a display with a strong and simple 'visual imperative' that points to very few possible strategies. With all other displays, however, the target task of detecting violations of the K1 constraint involves making more complex judgements than the ones needed in the baseline task.

Secondly, the interactions between Display and Mapping for the target task show that if there is poor mapping between the K1 constraint and emergent properties of the visual display, then the shift from a digital to bar to shape display has no effect on RT and has a much smaller effect on score and accuracy than when the mapping is good. The exact form of this interaction is driven by the degree to which the constraint, K1, is directly visible in the display. In SIOI, K1 is directly visible as the straight line at the top of the shape. In BIOI, K1 can be imagined as a straight line across the tops of the bars. In DIOI, DIIO, BIIO and SIIO, K1 must be labouriously extracted from the data. This set of relationships amongst conditions according to how directly the K1 constraint is represented largely accounts for performance in the target task in terms of both absolute level of performing and variability between participants.

Thirdly, for the 18 participants who provided a self-report of strategies, the variety of strategies increased from shape to bar to digits displays, and from well-mapped to poorly-mapped displays. The variety of reported strategies reflected the quality and variability of performance quite closely, with fewer strategies generally being associated with better, less variable, performance. These conclusions hold equally whether the reports are related to performance results of all 33 participants or to the results of just the 18 who did the self-report.

4.1.2. *Neuroimaging and low variability*: The most important way the present study extends previous research is by adding neuroimaging data from the monitoring phase of the failure detection task. However, the neuroimaging data provided somewhat different information about the effectiveness of display design than we anticipated. We expected to learn more about the differential involvement of cortical areas during monitoring as we varied displays and mappings. Certainly, the results presented in section 3.3 suggest that the electrocortical activity seen with SIOI is consistent with activation of visual attention and detection of line segment angles. Moreover, as also presented in section 3.3, the patterns of cortical involvement in the SIOI and SIIO displays are consistent with results from Neves (1999) for good performers on wholist and analytic tasks, respectively. Our neuroimaging results, therefore, present some parallels with performance results with the DURESS process control microworld from Torenvliet *et al.* (1998), which is encouraging.

However, the degree of *variability* seen in electrocortical activity between subjects is probably the more important story in these data than the specific location of that activity. An interpretation of electrocortical activity can be attempted where there are fewer strategies (SIOI) or strategies that require mutual inhibition (SIIO), but not where there are many disparate strategies as when participants worked with bar graphs or digital displays. A well-mapped configural display such as SIOI draws participants into a very limited set of strategies which are reflected in very similar kinds of electrocortical activity between subjects using SIOI. In contrast, a poorly-mapped non-configural display such as DIIO draws participants into many different strategies so that neuroimaging results suggest no consistent pattern of between-subjects electrocortical activity.

Low variability in SSVEP amplitude and phase between participants, coupled with consistent and high levels of performance, may be a sign of a particularly effective and robust display. As Howie and Vicente (1998) note, regularities in participants' process control behaviour should emerge at the level of abstraction most appropriate for control, as long as participants have information at that level of abstraction. Yu *et al.* (1998) have demonstrated in a process control task that intra-subject variability is minimized at the most appropriate level of abstraction available: at the abstract function level for a participant using the ecological interface but at the physical function level for a participant using the PID interface. Reising and Sanderson (2000) have found similar patterns with *inter*-subject variability. Reising and Sanderson (2000) compared the variability in performance for several variables across an ecological vs a conventional physical mimic interface for a process control task. For participants using the ecological interface, there was less variability around mean values for high-level abstract functions and greater variability around mean values for low-level physical functions than for participants using a conventional interface.

A phenomenon related to these findings might be happening electrocortically. The significant Hotelling's results for SIOI indicate that the SIOI display produces the most consistent between-subjects changes in electrocortical amplitudes and latencies. These changes are significant despite their relatively low *absolute* difference from the electrocortical amplitudes and latencies seen for the SIOI baseline task. In other words, participants show smaller but more consistent changes in electrocortical activity when using SIOI, as opposed to displays such as DIIO. In a manner analogous to conditions under which regularities in process control behaviour emerge, regularities in participants' *electrocortical* activity appear to be emerging when participants are presented with displays providing compelling information at the level of abstraction most appropriate for control.

These results seem to be consistent with a tradition of work within ecological psychology on optimal human–environment fit. Reed *et al.* (1985: 323) have posed the question of how 'a complex neuromuscular system, composed of many degrees of freedom, self-assembles into a simple mode of organization consisting of only a few degrees of freedom ... The answer to this question must include an account of how the system becomes sensitive to relevant dimensions of information that somehow bring new constraints to bear on the system and, thereby, reduce its excess degrees of freedom'. The result of doing so can be to find an optimal point of minimum energy cost. For example, Warren (1982) demonstrated that an optimally climbable stairway for a climber is determined by the fit between the climber's leg length and the riser height of the steps. More overall energy is expended and less subjective preference is expressed by the climber as the riser height increases or decreases relative to an individual climber's leg length from a specific optimum point.

In an analogous way, we might conjecture that the SIOI display very directly shows the observer the relevant dimension of information for performance, and so reduces the degrees of freedom in how the failure detection task might be performed. Because of the effective *engineering* of human–environment fit in SIOI, there is least deviation from a baseline level of electrocortical activity when compared with displays that less effectively engineer a human–environment fit. As patterns of excitation and inhibition become more even and attenuated, the more a move to an automated mode of processing is indicated (Posner and Raichle 1994). Since an important goal of EID is to move processing from 'rule-' and 'knowledge-based' levels to the 'skill-based' level (Vicente and Rasmussen 1992), our results suggested that this goal has been achieved for the SIOI display.

In summary, our results indicate that the pattern of electrocortical activity for a well-mapped configural display (SIOI) reflects the lower number of strategies reported and the lower variability in performance. The lower number of strategies appears to reflect, in turn, the fact that for SIOI there is a compelling mapping of the task-relevant emergent feature (the straight line at the top) to the relationships in the underlying process that require monitoring. The right occipital involvement for SIOI in the neuroimaging data appears to support this interpretation. Where the mapping is less compelling, however, many idiosyncratic strategies emerge whose effects can be seen in performance variability and in greater variation in electrocortical activity.

5. Conclusions and implications

We have taken only the first steps of a planned research programme on the imaging of neural activity while humans interact with dynamic visual displays, but we should provide strong caveats. First, no neural imaging technique can independently identify a display as being ‘good’ or ‘bad’. Instead, SSPT yields complex data that need to be interpreted in the context of task context, performance results, self-report, theory and so on. Secondly, SSPT is not a ‘cognition-finding tool’. There is no simple mapping between the location of cortical activity and cognitive process. As with all neural imaging techniques, there are many unanswered questions about how to interpret SSPT data (Silberstein *et al.* 1990, 1996). Temporal patterns, patterns of inter- and intra-subject variability, and an understanding of the influences on different SSVEP parameters must be considered alongside spatial pattern before any interpretation can be undertaken. In addition, SSPT data reflect differences from a baseline task, which must itself be understood for the maps to be meaningful.

Can SSPT studies help interface designers by verifying that a particular display is effective? The present results suggest that an effective visual interface for routine monitoring tasks not only leads to better performance and fewer reported strategies, but also leads to neuroimaging results that are consistent with the general involvement of visual attention and of spatial processing for good performers in a wholist (simultaneous) task (Neves 1999). The present results also suggest that an effective visual interface may also lead to the greatest between-subject consistency in cortical activity and the smallest latency change within-subjects over a baseline level. These results provide preliminary support for claims made about how effective dynamic displays are processed by human operators.

The advantage of a neural imaging technique like SSPT is its high temporal sensitivity, allowing moment-by-moment changes to be registered. For complex tasks that unfold over time, SSPT and techniques like it may be able to help the analyst discriminate moments when tasks and displays produce greater relative consistency in electrical activity between and within subjects, from moments when they produce less relative consistency. In contrast, self-reports of strategy and performance measures such as RT and accuracy have low temporal sensitivity in the sense indicated above and are measured after the event(s) in question.

However, low inter-subject variability in cortical activity may not be *sufficient* to indicate that a display will be effective. A display could have a visual imperative that is actively misleading for the task at hand, inducing similar strategies and low inter-subject variability in cortical activity, but at the same time leading to very poor performance. Moreover, low inter-subject variability in cortical activity may not even be *necessary* for effectiveness. A complex display may promote qualitatively different, but equally effective, strategies for performance. However, for the very simple processes presented here, where an effective display can be used in only one general fashion, lower inter-subject variability may always accompany better performance. The practical implications are that SSPT may eventually be informative for display design, but considerable further validation and conceptual work must be done before it can be considered a valid, let alone independent, tool in the design process.

In summary, we have established that the SSPT technique is sensitive to theoretically-understood and previously-demonstrated differences in the ability of different visual displays to help participants detect system failures. As the sensitivity, interpretability and cost-effectiveness of neuroimaging techniques such as SSPT increases, they may offer a wide variety of insights into the neural processes underlying the use of dynamic visual displays. At that point, neuroimaging techniques could plausibly be exploited to help human factors professionals design and evaluate displays that support more effective and more robust human performance. We have taken the first steps in this direction.

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