Title.

Human steady-state visually evoked potential topography and attention.

Mark Andrew Schier

8524041
Dedication.

I would like to dedicate this work to all who have suffered brain injury.
Declaration.

This thesis is submitted for the requirements of the degree of Doctor of Philosophy at the University of Melbourne.

It is, to the best of my knowledge, all my own work, except where duly noted in the acknowledgments or text.

I declare that this thesis contains fewer than 100,000 words, exclusive of tables, maps, bibliographies, and appendices. I have not submitted any part of this work for a degree at this or any other University.

Mark Andrew Schier
8524041
Abstract.

This work began with a review of visual spatial selective attention, from a behavioural perspective with particular emphasis placed upon the spotlight model. To complement the behavioural review, the physiological aspects of the visual system were studied to find possible loci of the spotlight. The literature pointed to the pulvinar nucleus of the thalamus, interacting with the parietal and frontal cortices. Some experimental work examined relationships between visual spatial selective attention and event-related potentials (ERPs) recorded from the scalp. The second section of this thesis reviewed the ERP measures relating specifically to the visual modality for their possible application in a visual attentional task. This yielded two independent findings. First, the Probe-ERP paradigm comprising an attentional task being performed by the subject, with a separate stimulus to probe the unused resources within the system. Second, the steady-state evoked response, with the stimulus presented as a small sinusoidal variation around a mean level of contrast. The combination of the Probe-ERP paradigm and the steady-state visually evoked potential (SSVEP) warranted experimental evaluation.

Implementation of the SSVEP required the design and construction of a complete sixty-four channel system, with provision of topographic data presentation, to display potentials across the scalp. This work involved development of computer hardware and instrumentation, software for data collection, analysis, artifact detection, interpolation and topographic display.

After completion of the system, exploratory research involving the SSVEP began. An examination of the relationship between SSVEP and spontaneous EEG activity, particularly in the alpha band (8–13 Hz), indicated that the SSVEP probe activity and spontaneous alpha activity resulted from related, but independent mechanisms.

Two other major experiments followed, involving the Probe-SSVEP with visual vigilance and selective attention. The results indicated that particular regions of the
brain are involved with these activities—including the prefrontal, the right temporal, and the parieto-occipital areas.

As an adjunct to the major experimental work, a small pilot involving a few brain-injured individuals indicated that the technique has promise in examination of clinical populations.
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1. Introduction.

*Human steady-state visually evoked potential topography and attention.*

Evaluation of cognitive processes has a basis in the psychological disciplines, with most emphasis given to behavioural responses to a variety of stimuli in a tester-subject interaction. Examples of this type of testing include pencil and paper tests of *intelligence*, such as the Weschler Adult Intelligence Scale (WAIS), drawing tests such as the complex figure of Rey, maze tracing, and many others too numerous to list. These are referred to as psychometric tests or sometimes as neuropsychological tests. The subject's response is measured to determine whether their response is statistically different from a population of *normal* subjects of matched age and sex. The possibility of subjects influencing the results exists, and tests require either careful construction, or methods of validating the results, to minimise such occurrences.

Other approaches to measuring cognitive responses have used more independent measures, such as reaction time or electroencephalographic (EEG) recording, in an attempt to provide a more objective measurement. These techniques have achieved a variety of success and failure.

Reaction time relies upon co-operation from the subject during the task to make the measure. EEG measures rely upon subject co-operation to affix electrodes, but not as much on the subject's physical response. EEG and event-related potential (ERP) responses show mixed success with cognitive changes.

ERPs are electrical potentials recorded from the scalp in response to an event. The event may be purely a physical stimulus, or it may have some cognitive relevance. Some ERPs show sensitivity to different cognitive events, such as attention, and many studies have explored this sensitivity with transient stimuli. Few studies have used steady-state stimuli. The responses to visual steady-state stimuli (referred to as
steady-state visually evoked potential or SSVEP) also show dynamic changes that are different to the recordings of transient responses.

A refinement of the ERP recording uses a stimulus that is irrelevant to the attentional task to probe the attentional activity. The response to this probe stimulus indexes the resources not directly involved in the attentional task. This so-called Probe-ERP paradigm offers flexibility because of the ability to present the task and stimulus independently and simultaneously. This thesis reports on the use of the Probe-ERP paradigm with a steady-state stimulus during attentional and visual vigilance tasks.

To use the SSVEP and Probe-ERP techniques (or Probe-SSVEP) involved the development of a new data acquisition and analysis system. This system required approximately sixty-four channels to adequately cover the scalp. The system development formed part of a larger project at the Centre for Applied Neurosciences, and I developed several of the original components including the data acquisition software, and contributed to the hardware, and development of other analysis software.

This thesis begins with a review of the effects of selective attention, and a discussion of the properties of the steady-state evoked response, Probe-ERP paradigm and its applications. The fourth chapter describes the hardware, software and other aspects of the instrumentation and sixty-four channel recording system. The final section of the thesis encompasses three experimental chapters dealing with separate aspects and properties of the steady-state Probe-ERP in control subjects, followed by a chapter exploring the usefulness of the technique in recording from brain-injured individuals.
2. **Spatial aspects of visual selective attention.**

This chapter reviews the literature on spatial aspects of visual selective attention. It briefly touches upon the areas of attention, selective attention, and visual selective attention, but does not attempt to review these, except as a method of introducing the main area of spatial aspects of visual selective attention. This review forms the framework for the subsequent experimental chapters.

The review introduces the general topic and defines some concepts used within the review. The review concentrates on two areas. The first contains a review of the behavioural literature, including the various models of visual-spatial selective attention. The second section reviews the physiological literature, to locate the possible mechanism and site of action of visual-spatial selective attention.

### 2.1. Selective Attention.

“Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatter-brained state which in French is called *distraction*, and *Zerstreutheit* in German.”

William James wrote these words in 1891 (James 1952). The concept of selecting from the huge range of inputs remains associated with attention as it was then. Luria (1973) described attention as: “The directivity and selectivity of mental processes . . . .”, whereas Kahneman (1973) specifically referred to attention in: “Selective attention consists of the allocation of a limited capacity to the processing of chosen stimuli and to the preparation of the chosen response.”. Moray (1987) defined attention as a broad topic, which includes: “. . . selecting one from several messages, selecting one from several interpretations of information, selecting one from several plans of action, and selecting one from several actions.”. The selective aspects of attention are important but the term attention now encompasses a wider range of concepts, such as:
arousal, alertness, the orienting response, vigilance, reflex attention, and voluntary attention (Posner & Rafal 1985; Butter 1987).

One can use these wider concepts of attention and include them in a model of the overall processing capability of the human brain. This model includes the factors referred to above, and a diagram from Kahneman (1973) is reproduced to illustrate a general processing model of cognitive processes, known as the capacity model.

![Capacity model](image)

Figure 2.1 **Capacity model.**
from Kahneman 1973, p. 10. The available capacity is determined by several factors, including, degree of arousal, voluntary and involuntary direction of attention, and processing demands of current state.

This model has some salient points relating to visual selective attention. Beginning with the response selection: the response is selected from a range of possible activities; for example, a person chooses to read a book, rather than look out a window, or watch a spider; producing the final stage of attention or the output. The preceding stage (allocation policy) has input from several different sources including: *momentary intentions*—such as choosing to glance at a picture on the wall (voluntary); or turning in response to a large flash of light nearby (involuntary—the orienting response); from *enduring dispositions*—such as reading a book (conscious voluntary attention); and feedback of how an output or response is taking place or the *evaluation* of task demands on available capacity. The level of arousal determines the overall capacity, for example; a person has a smaller attentive capacity when drowsy compared with
wide awake (Kahneman 1973). The model addresses visual selective attention and includes, in addition to non-visual selective attention, the other related components; arousal and orienting response, both important in determining the available capacity (Kahneman 1973), but not warranting further consideration in this review.

A large proportion of the selective attention literature deals with auditory and visual selective attention (Rabbitt 1978; Näätäinen 1982; Parasuraman & Davies 1984; Umilta 1988; and for a review of the differences between auditory and visual selective attention see Neumann et al. 1986.). Some of the literature covers other modalities such as the somatosensory, and olfactory systems (Desmedt & Robertson 1977; Hillyard et al. 1984; Michie et al. 1987). Due to the huge body of literature on selective attention, this review only examines the spatial aspects of visual selective attention.

An investigation of the measured behavioural changes associated with visual spatial selective attention, precedes a complementary review of the physiological mechanisms underpinning selective attention. One can consider them as top-down and bottom-up aspects of visual selective attention, in the fashion of Norman & Bobrow (1976). As a basis for understanding visual selective attention, the so-called spotlight model is discussed in detail.

2.2. Visual spatial selective attention.

The visual field of each eye covers a wide area. Horizontally from 60 degrees on nasal side to 104 degrees on temporal side; and vertically from 50 degrees superior to 60 degrees inferior, covering approximately 160 degrees horizontally and 110 degrees vertically. The central area, about 54 minutes of arc in diameter, is the region of high visual acuity known as the fovea (Moses 1975 p. 381). The fovea is generally, but not exclusively, the attended area in the visual field, although one can attend to any part of the visual field covertly, without any associated head or eye movements (Posner & Rafal 1985). The attentional role of the eyes are twofold: one to move the eyes and
bring the area of interest into the high acuity region of the retina; and the other to allocate the processing capacity from one area to another without affecting gaze (Jonides 1980; Jonides 1983). The region of attention is independent of the fovea. 

Van der Heijden (1993) separated the overall visual selective attention literature into those models where position, or spatial location, was special, and those where position was not special. He put forward a parallel model where location information was processed automatically (position system), and other features such as shape or color (identity system) fed information back from a separate processing pathway. When measured, using a reaction time task, the position system possessed an advantage of approximately 200 ms over the identity system during a valid-invalid cued task (Eimer 1993). These findings suggest that the processing of location and identity information are functionally separate, and this review will only examine those studies dealing with location or spatial aspects of visual selective attention.

Several models have been put forward to explain the properties of visual spatial selective attention. They include the parallel-serial model (Jonides 1983) that deals specifically with the movement of attention within the visual field; the spotlight or zoom-lens model, first proposed by Jung in 1954, that deals with the phenomenon of graded spatial attention; and the model of Posner et al. (1984) that deals with the covert movement of attention. The models relate to different methods of examining visual spatial selective attention, and are considered in more detail.

2.3. Spotlight model.

The spotlight is an analogy for the process of focussed attention, with the exclusion of extraneous information. If the visual field is considered a wide expanse of space, then the focus of attention occupies a small area, like a beam of light illuminating only the region of interest, as illustrated in Figure 2.2.
The spotlight describes a small, well-defined focus of attention capable of movement, and fixed upon a particular location within the larger surrounding area (Jung 1954; Hernández-Peón 1964; 1966). The spotlight model allows for differentiation between the focus (high attention area) and the fringe or surround, low—but not zero attention area. Attention is assumed to be primarily allocated to the focus of the spotlight, diminishing in the fringe region, and limited in extent (Yantis & Johnston 1990; Yantis 1992). Several subsequent corollaries have arisen regarding the movement of attention within, and near the spotlight.

1. A movement of attention between locations within the spotlight occurs immediately. In other words, the measured reaction time is no greater than the simple reaction time.

2. A movement of attention to a location outside the spotlight takes time and therefore has a cost associated with the movement. The cost is proportional to the distance moved.

3. A movement of attention between two locations outside the spotlight also has a cost proportional to distance from the spotlight.

(Juola et al. 1987; Egly & Homa 1984; Kiefer & Siple 1987).

The shape of the beam of the spotlight was circular in the original description, but there have been some alternatives advanced, such as: a ring or annulus shaped beam (Juola et al. 1987); a variable focus beam or a zoom-lens (for example, Egly & Homa 1984); and an area with flexible dimension and size (Juola et al. 1991).

Juola et al. (1987) tested the annulus model of spotlight shape, using a cued reaction time experiment. This was a visual presentation experiment where initially an image
appeared with a central fixation dot and surrounding 1 degree circle. Subsequently a
cue (indicating whether a letter would appear inside or outside the circle) replaced the
image. After the cue, a letter appeared inside or outside the circle. The cue was
designated: valid if the letter appeared at this location; invalid, if the letter appeared
at another location; or neutral, if it conveyed no information regarding location. A
cost-benefit analysis of the reaction time measured the attentional process. A cost was
defined as an increase in reaction time compared to the neutral cue, and a benefit a
decrease in reaction time compared with the neutral cue. The spotlight model predicts
a cost for invalid cues when the target was outside the circle, and a benefit for a valid
cue when the target was inside the circle, whereas the annulus model predicts that
there will be a cost for all invalid cues, and a benefit for all valid cues. Juola et al.'s
(1987) experimental data showed a satisfactory fit to both models, with a closer match
to the spotlight, although this did not reach statistical significance.

To further clarify the nature of the spotlight, Posner et al. (1980), tested the
hypothesis that the attentional focus could simultaneously cover two spatially
disparate regions. Subjects attended to cued locations in a visual display, with two
regions of interest: the most probable location, and the second-most probable location.
There was an increased reaction time—that is, cost—if the most probable and
second-most probable locations were non-adjacent, compared with when they were
adjacent. This indicated that the attentional spotlight could not be split in space.
Kiefer and Siple (1987) using a pair of cued locations, also found the divided spotlight
model unsupported. Several approaches exist for measuring costs and benefits,
including reaction times and temporal order judgements. They provide similar, but not
identical information regarding the stimulus (Neumann et al. 1993).

One research group, used behavioural measures in one experiment (Müller & Findlay
1987), and reaction times in another (Müller et al. 1985), and claimed to show the
subject's ability to split (or divide) the attentional spotlight by using a similar paradigm
to Posner et al. (1980). Müller et al.'s (1985) experiment consisted of a rectangular
display with attentional locations at each corner. These results showed that when the
most probable and second-most probable locations were non-adjacent, there was no added cost compared to when these locations were adjacent. With only four locations (the four corners of a screen), another interpretation of Müller et al.'s (1985) experiment could be that a unitary spotlight of differing shape encompassed the adjacent or non-adjacent locations respectively, as illustrated in Figure 2.3.

![Figure 2.3 Spotlight explanation of shapes on a monitor.](image)
The left panel shows the spotlight encompassing two adjacent locations. The centre panel shows the spotlight encompassing two non-adjacent locations. The right panel shows the spotlight encompassing all four monitor locations.

Thus reaction time data supports the unitary nature of spatial attention (that is, one area), and the spotlight as a valid model for selective attention. It is appropriate to examine other characteristics of the spotlight. To determine size and sensitivity of the spotlight, Egly and Homa (1984), designed an experiment that utilised a circular display of letters around a central fixation point. The letters appeared at a radius of 1, 2 or 3 degrees from the fixation point, after a cue. The cue indicated the distance at which a displaced letter would appear. The displaced letter appeared simultaneously with a central letter. The number of errors made by the subject determined the cost or benefit of a reaction in this experiment; a cost indicated by an increase, a benefit by a decrease in the number of errors. The spotlight model's prediction of no benefit (see corollary 1) for a 1 degree target appearing within a 2 or 3 degree diameter was upheld experimentally. With a pair of cued locations, Kiefer and Siple (1987) found that the size of the attended area could be varied, but required more resources, or had a cost as the area increased. These experiments suggest a spotlight with an adjustable focus to distribute the limited capacity over the area of interest.

LaBerge (1983), using a different experimental paradigm of words and groups of letters (non-words), demonstrated similar results. Subjects had to categorise: five
letter words; or the middle letter of five letter non-words. While this took place, subjects were also required to respond with a button press if the digit ‘7’, referred to as a probe, appeared anywhere in the presented letters or group of letters. The mean reaction times indicated that, when categorising the middle letter, in either words or non-words, the closer the probe digit ‘7’ to the central position, the shorter the reaction time, whereas for words, the profile of reaction times as a function of probe position was almost flat. The results were interpreted by LaBerge (1983) as evidence for the existence of a small spotlight beam for the letters, and a large beam for the words, supporting the zoom-lens or variable focus style of spotlight. Further studies regarding the size and selectivity of the spotlight have been carried out with shaped objects.

When examining objects, attention can be directed within the object, as shown by Peterson & Gibson (1991), who used biased Necker Cubes as objects. Necker cubes are ambiguous line cubes which can be perceived in two orientations, either seen as sloping forward and down, or backward and down. When biased, one corner is made unambiguous with shading and solid lines, as illustrated in Figure 2.4.

![Figure 2.4 Necker cubes.](image)

Peterson & Gibson (1991) hypothesised that when attending to the biased corner, only the orientation consistent with the bias could be perceived, but when attending to the diagonally opposite corner, one of two orientations could be perceived. This experiment used as a measure of attention the ability to hold the inconsistent
orientation, by measuring this holding time. A comparison of results made with respect to an unbiased Necker cube, showed that subjects could hold an inconsistent interpretation of the unbiased region within the biased cube to the same degree as in the unbiased cube; whereas the inconsistent interpretation within the biased region was almost impossible to hold. This indicated that the region of bias could be ignored, that is, put outside the region of the spotlight, and the zone of attention could be smaller than 0.8 degrees.

Schneider (1993) devised an experiment to test certain aspects of the spotlight, and found that the simple spotlight or zoom-lens model could not explain the reduction in benefit when objects overlapped in space. The other parts of the object, outside the focus, were more quickly processed than other objects inside the focus of the spotlight. This indicated that the spotlight metaphor had limitations. In this situation it would seem appropriate to assume that higher order processing overrode the basic spotlight mechanism, due to the feature saliency outside the focus. This is consistent with the explanation of automatic location selection, and feedback identification properties made by van der Heijden (1986; 1993). Duncan (1984) distinguished between object-based, discrimination based, and space-based theories of attention. He found that in experiments using foveal stimuli, of two overlapping objects, that two judgements concerning the same object could be made simultaneously without loss of accuracy, but two judgements concerning different objects could not. This he argued meant that selective attention was made according to objects rather than other factors—they are processed later. These interpretations, however, were not made according to speed or reaction time, but judgement accuracy, and may have actually involved a higher order of perceptual processing. Temporal order judgement and reaction time experiments have been associated with accessing different information (Neumann et al. 1993), and Eimer (1993) reported faster reaction times for position versus object information, and the evidence against the spotlight model is not conclusive.
In a different study, making use of ambiguous figures, Kawabata & Mori (1992) suggested that a two dimensional spatial filtering method provides the mode of operation, at the focus of spatial attention. Along with the theoretical treatment of such a filter, they examined two ambiguous figures: the husband/father-in-law, and the duck/rabbit. In one part of the experiment subjects viewed the figures at specified locations, and reported their perception of the figure. In another part, subjects viewed spatially prefiltered images, and reported their perception of the figure. Their theoretical and perceptual results indicated that the initial location of the centre of the attentional focus was important for the perception of the figure, and provides support for an attentional spotlight with a surrounding spatial filter.

The spotlight has an assumed property of variable size. To investigate interactions between the spotlight size and its sensitivity (as suggested by Egly & Homa 1984), Eriksen & Yeh (1985) designed a series of reaction time experiments where subjects determined the presence of a target letter in a circular display of eight letters, using two conditions: a cued, and a neutral task. The cue indicated the location of the target with 100%, 70% or 40% validity. With 100% validity, all targets appeared at the cued location. With 70% and 40% validity, only 70% and 40% of the targets appeared at the cued location. The subjects were instructed that if the target did not occur at the cued (primary) location, then it would occur at the opposite side of the circle (secondary location). There was a similar validity (100%, 70% or 40%) associated with the secondary location. The experiments showed a benefit, or reduced reaction time, with respect to a neutral task, of being cued to the location, and this benefit decreased as the validity of the cue decreased. The authors interpreted this decrease in benefit with decrease in validity, being caused by subjects increasing the size of the spotlight to satisfactorily perform the task. The reduction in sensitivity of the spotlight associated with increase in its size is consistent with the view that the overall capacity is fixed (Kahneman 1973), and allocated within the spotlight. This supports a continuously variable spotlight, whose *resolving power* is inversely related to the size of the attended field, and is analogous to a zoom lens (Eriksen & St James 1986).
Juola et al. (1991) examined some of the properties of the spotlight, although they did not refer to it as a spotlight. They proposed an attentional area of variable dimensions, location and size. In a series of experiments using circular displays of letters, and varying the size and location of cued information, they showed a poor correlation with a model which had its centre fixed on the fovea, which they termed a *zoom lens*. Likewise experimental data showed a poor correlation with a model that had a small area and scanned, serially the field, which they termed a *spotlight*.

The preferred interpretation was a variable size, with the attentional beam not constrained to include the fovea. In this thesis and discussion, I have extended the concept of the spotlight to include the properties of the zoom lens, where the focus is not constrained to the fovea.

In summary, the spotlight encompasses a region around a focal point, where attention is centred. The central focus is surrounded by a fringe of lower sensitivity. The depth is not fixed in size, but the greater the size, the lower the sensitivity. The focus of the spotlight is free to move anywhere within the visual field, independent of gaze, and the fovea. The next section considers a different model with two modes of operation: a scanning mode, serial in nature, and a general mode, parallel in nature.

### 2.2.2. Serial and parallel processing.

One suggested alternative to the continuously variable, zoom lens, comprises a system with two processing modes (Jonides 1980, 1983; Duncan 1984; Nicoletti & Umilta 1989). This had a general mode, where parallel processing of the visual field occurred, and a focussed mode, where a single region was selected and examined in detail. The processing in the general mode is considered parallel, as all locations are equally attended at a low power, while the processing in the focussed mode is considered serial because only one area of the visual field is examined at any instant at a higher power. There can be almost instantaneous switching between the parallel and serial modes (Jonides 1983). Crick & Koch (1990) proposed a form of awareness, which they termed *fleeting awareness*, which corresponds with the general processing
mode of Jonides. The ability to perform seemingly simultaneous tasks, such as feature gradient detection and form recognition task (Braun & Sagi 1990), may be explained by the switching between the parallel and serial modes. Shulman and Wilson (1987) related these general and focussed modes of processing to local and global information, by examining the response of subjects to an object that had both local and global components (for example, a large capital ‘T’ made up of small capital ‘H’ characters). When the subjects attended to the large letter ‘T’ (global), they more readily detected a simultaneously presented low spatial frequency grating; whereas, when they attended to the small letters ‘H’, they more readily detected a high spatial frequency grating. This phenomenon is readily explained by the two-stage model of Jonides (1980; 1983), and further tests of the validity of this two stage model have been carried out. Adini & Sagi (1992) used Gaussian modulated cosine intensity stimuli (Gabor functions), and found that when subjects attempted to identify the orientation of two simultaneously presented stimuli, there was some indication of parallel processing taking place. Similar speeds of identification for two stimuli when presented overlapping in space, compared with single stimuli, indicates the possible parallel nature of processing. The advantage was also seen for stimuli of the same spatial frequency when separated in space. These results can also be explained by a variable size or spotlight of selective attention.

Van der Heijden (1989), carried out an extensive analysis on reaction times in a study similar to Jonides’, and found that the location of the cue played a significant role in the allocation of attention. Those cues that occurred in the periphery were processed more automatically than those in the central field. This explanation, however, blurs the orienting response with voluntary selective attention, and should be regarded cautiously. Theeuwes (1993) highlighted the difference between attention that was shifted endogenously (directed to a location by a central arrow or symbolic cue), and exogenously (directed to a location by a peripheral cue). Once again, this blurs distinctions between voluntary attention and the orienting response.
The switching of parallel and serial networks proposed by Jonides (1980; 1983) are supported by other studies. Stoffer (1993) devised an elaborate experiment to cue subjects either with spatial information (size of the cue) or by symbolic information (shape of the cue), to place subjects into a global or local mode of processing. To avoid subjects predicting the cue, 50% neutral cues, 40% valid cues, and 10% invalid cues were used. The results showed comparable reaction times for both symbolic and spatial information. The expected increase in the reaction time for invalid cues compared to valid cues occurred. Examining the results in more detail, Stoffer found that the time between cue and stimulus, changed response to the symbolic and spatial cues. They had similar maximum cost or benefit, but these differed in their relationship to cue-stimulus time. Spatial cues peaked at 400 ms for valid, and symbolic at 600 ms for valid cues. When global and local reaction times were compared, a saving of about 150 ms was seen for maximum benefits—this is consistent with the notion that global processing is the usual operating mode, and unless cued otherwise, it takes about 150 ms to shift from one mode to the other—suggesting that the spotlight takes 150 ms to zoom in. The mechanism for such switching is not clear, but Callaway et al. (1992) provided evidence that cholinergic systems narrowed the effective area of the spotlight, while anticholinergics broadened the area, although the neurotransmitters responsible for the type of attentional processing are not reviewed in this thesis.

Unlike Jonides' instantaneous switching between modes, Stoffer's (1993) data suggest a finite time to shift, perhaps consistent with zooming in of the spotlight.

To explore the lateralisation of the modes of processing, Palmer & Tzeng (1990) used an experimental protocol requiring right-handed subjects to decide if objects were the same or different, and measured reaction time and error rates when the visual stimuli were presented to the right or left visual fields. The reaction-time to right visual field (RVF) stimuli showed an increase with the number of objects presented. The left visual field (LVF) showed neither an increase in reaction time nor error rate with increase in array size. In some they decreased! This is consistent with the right...
hemisphere, or LVF, preferentially favouring global, or parallel processing, and the left hemisphere, or RVF, favouring local, or serial processing. Heilman & van den Abell (1979) found a similar left visual field advantage for reaction time compared to the right visual field.

To compare different modes of processing spatial information, Henderson et al. (1989) designed a complex experiment using the four corners of a monitor, and presented a word or a visual mask at each corner. Subjects fixated upon a central cross, and then examined each location in turn by making a saccade to that location. The order of examination was anti-clockwise beginning at top left corner, and the time spent at each screen position was measured by the gaze position. There were five different modes of presentation referred to as: Full, One, Zoom, One+Next, or One+Last. Full was a full screen presentation, where all words were always present on the screen; One was a single location presented at one time; Zoom was all words presented while gazing at a central fixation point, then only one word at the current gaze location; One+Next was the word presented at the current gaze location and the next location; One+Last was the word presented at the current gaze location and the previous location. There was an advantage of the One+Next display yielding low fixation times on each word comparable with the whole screen display. With the other conditions, (Zoom, One, and One+Last), subjects demonstrated longer fixation times than with the Full screen.

As the series progressed from one word to the next with the fixed order, there was an advantage for processing of the next word (that is, One+Next). The authors argued that a serial model of attention was supported with this experimental paradigm. They discounted a zoom lens model of attention on the basis that there was no advantage in the initial view of the whole display (Zoom mode). The predictable nature of the experiment could have directly produced these results, and the authors acknowledged that this aspect had not been fully explored.

This parallel-serial model is consistent with the spotlight of variable power and size—in the parallel mode, the size is large and the power is small, while in the serial mode power is high and area is small. The parallel-serial model considers these two
extremes as separate operational modes, while the spotlight model places them at opposite ends of a continuum. While it may be advantageous to consider the serial and parallel modes as separate entities, evidence from experiments carried out by Eriksen & Yeh (1985) indicates that the spotlight model with variable power adequately describes the experimental work.

Other models exist apart from the spotlight. Even though the serial-parallel or global-local model explains some experimental findings, the spotlight model is also consistent with these same findings. The issue of whether selection takes place early or late in the sensory processing potentially allows more insight into the nature of the spotlight.

2.2.3. Early and late selection.

Within the framework of the spotlight model, at least two different views exist as to when the selection of the input takes place. These viewpoints include early, late, and hybrid models. There are early selection models, where the selection takes place before any subsequent processing, signifying that the channels are not overloaded with irrelevant information (for example, Treisman 1969; Broadbent 1982; Hoffman et al 1985). These are supported by a finding of increased reaction time with increased cue to target distance (Hillyard & Kutas 1983; Hillyard & Mangun 1986; Mangun & Hillyard 1990). By contrast, late selection assumes that all the sensory information is processed and selection takes place at a higher level (Deutsch & Deutsch 1963; Norman 1968; Shiffrin & Schneider 1977; Bookbinder & Osman 1979). For example, some experiments have demonstrated that reductions in reaction time occurred when the target was distinct from the cue, but related in meaning to the cue. This indicated that processing of the unattended, or distracter, stimulus does take place, and interferes with the processing of the attended or target stimuli (Irwin 1981; Eriksen & Hoffman 1973; Miller 1991) provided that angular separation is small (Broadbent & Broadbent 1990). Late selection blurs the boundaries between attention and perception. Perception takes place later than attention, indicating an activation of an internal representation, or the involvement of memory (Johnston & Dark 1982;
Hybrid theories encompass features of both early and late selection, and generally follow the so-called filter-amplitude model of Treisman (1969). This model provides attenuation rather than total blocking of sensory stimuli from the realm of perception.

Overall, the existence of early or late selection at the expense of the other is not clear, although the hybrid theory of attention leans toward an early selection theory with appropriate feedback from perceptual systems. This information requires integration with the physiological information regarding the location of the spotlight of visual selective attention.

2.2.4. Summary of the spotlight model of attention.

The spatial aspects of visual selective attention can be considered as a spotlight, which is independent of foveal location. It is under conscious control, and can be a narrow, powerful beam; or a broad, less sensitive beam; or somewhere on the continuum between these extremes. While the spotlight model explains visual, spatial selective attention, it should not be automatically applied to other aspects of selective attention without careful examination of the context, and appropriate experimental work.

The spotlight model explains the behavioural data, but is unable to shed light on where in the visual system selection takes place. The next section examines this area.

2.3. Physiological aspects.

To introduce the physiological aspects of visual-spatial selective attention, a brief overview of the anatomy of the retinal ganglion cells, and the pathways associated with vision is presented, along with the associated sub-cortical and cortical structures. These structures are examined for a possible role in the process of visual-spatial selective attention by studying brain lesions, evoked potentials, single cell recordings, and animal literature.
2.3.1. Visual Pathways.

Two distinct visual pathways exist from the retina to the cortex, generally referred to as the geniculostriate and mesencephalic pathways. The majority of fibres, after leaving the optic chiasm, travel via the lateral geniculate nucleus (LGN) and arrive at the occipital cortex in area 17 (alternatively labelled V1). This first pathway is known as the geniculostriate or the geniculocalcarine pathway because it begins from the geniculate and proceeds to the striate cortex or calcarine fissure (see Rodieck 1979; Chusid 1979; Poggio 1980). The connections of the geniculostriate pathway to the visual cortex are clearly seen in the diagram 2.5 as the optic radiations. The existence of many cortical visual areas is well documented (see Colby & Duhamel 1991; van Essen et al. 1992; Merigan & Maunsell 1993, for a representative view of those outside the primary visual area 17).

![Diagram of the brain showing optic radiations](image)

**Figure 2.5 Optic radiations.**
This is an inferior view of the brain with the cerebellum and some of the temporal lobes removed for clarity. Note that the optic radiations ‘fan-out’ from the LGN to the striate cortex.
The second pathway travels via the superior colliculus (SC), then the pulvinar nucleus of the thalamus, and arrives at the occipital cortex in areas 18 and 19, and the inferotemporal cortex in areas 20 and 21. This pathway is known as the mesencephalic or the retinotectal pathway as it involves the mesencephalon or midbrain, or the tectum, and then proceeds to the cortex (see Rodieck 1979; Chusid 1979; Poggio 1980). The major structures of the visual system are shown in Figures 2.5 and 2.6.

The two pathways are separate, and have separate retinal connections, cortical connections and functions (Chusid 1979; Lennie 1980). The connections of the pathways to the retinal ganglion cells, and the properties of these ganglion cells will be discussed in the light of the two distinct visual pathways.
2.3.1.1. Retinal ganglion cells.

Within the retina, occur several distinct types of retinal ganglion cells. In cats, these are commonly known as X, Y and W-cells (Fukuda & Stone 1974; Lennie 1980). The W-cells (tonic and phasic cells, sometimes referred to as sluggish-sustained and sluggish-transient) account for 50% of the ganglion cells, the X-cells (brisk-sustained) about 45%, and the Y-cells (brisk-transient) about 5% (Rodieck 1979). These classifications are based upon function, with the X-cells having a sustained response, and the Y-cells having a transient response, whereas the W-cells have a sustained response. Morphologically, the X-cell types correspond to the β type with small somata, and small dendritic structure, and most common in the centralis or fovea area of the retina; the Y-cell types correspond to the α type with large somata, most common in the peripheral retina; and the W-cells correspond to the γ and ε type, have large receptive fields and are found primarily in the peripheral retina (Rodieck 1979).

In the primate, the classification is different: there are A, B, C & E cells, which are roughly analogous to the α, β, γ & ε cells in cats (Leventhal et al. 1981). When describing the function of ganglion cells, it is normal to use the X, Y & W labelling systems, irrespective of species (Rodieck 1979). X-cells have a linear summation; whereas Y-cells have a non-linear summation (Lennie 1980); X-cells have a linear response to time varying gratings, that is, respond at the modulation frequency; Y-cells have a non-linear response and respond at the modulation frequency and harmonics (Shapley & Perry 1986). X-cells have small receptive fields and exhibit centre surround inhibition, Y-cells have large receptive fields, and W-cells have large receptive fields (Enroth-Cugell & Robson 1966; Lennie 1980). The conduction velocities of the various retinal ganglion cells are as follows: X-cells 9–14 m/s; Y-cells 29–39 m/s; W-cells 4–15 m/s (Stone & Fukuda 1974), although in the cat, X-cell and Y-cell latencies overlap at the LGN (So & Shapley 1979). A summary of the properties of the X, Y, and W cells appears in Table 2.1.
Table 2.1 Retinal ganglion cell summary.

<table>
<thead>
<tr>
<th>Property</th>
<th>X-cell</th>
<th>Y-cell</th>
<th>W-cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>response</td>
<td>sustained</td>
<td>transient</td>
<td>sustained</td>
</tr>
<tr>
<td>morphological type</td>
<td>$\beta$ (B)</td>
<td>$\alpha$ (A)</td>
<td>$\gamma, \varepsilon$ (C, E)</td>
</tr>
<tr>
<td>cell body</td>
<td>small</td>
<td>large</td>
<td>very large</td>
</tr>
<tr>
<td>dendrites</td>
<td>small</td>
<td>extensive</td>
<td>varied</td>
</tr>
<tr>
<td>response to gratings</td>
<td>linear</td>
<td>non-linear</td>
<td>mixed</td>
</tr>
<tr>
<td>receptive field</td>
<td>small</td>
<td>large</td>
<td>very large</td>
</tr>
<tr>
<td>conduction velocity (m/s)</td>
<td>9–14</td>
<td>29–35</td>
<td>4–15</td>
</tr>
<tr>
<td>retinal location</td>
<td>central</td>
<td>peripheral</td>
<td>peripheral</td>
</tr>
<tr>
<td>projects to</td>
<td>parvo dLGN &amp;</td>
<td>magno dLGN &amp;</td>
<td>SC &amp; magno dLGN</td>
</tr>
<tr>
<td></td>
<td>magno dLGN</td>
<td>SC</td>
<td></td>
</tr>
</tbody>
</table>

Information in this table summarises the properties of the retinal cells forming the optic nerve. The information is contained in the references cited in this section (Rodieck 1979; Lennie 1980; Stone & Fukuda 1974; Shapley & Perry 1986).

At the optic chiasm, a complex decussation of afferent fibres takes place. Ipsilateral X-cell fibres in the optic tract originate in the temporal field, whereas contralateral fibres originate in the nasal field (Lennie 1980); Ipsilateral Y-cell fibres originate in the temporal field, while contralateral fibres originate in the nasal field and up to 10 degrees of the temporal field (Lennie 1980). All the phasic (W-cell subgroup: sluggish-transient) fibres project contralaterally from the optic chiasm; whereas the tonic (W-cell subgroup: sluggish-sustained) project in a similar nature to the Y-cells (Lennie 1980; Rodieck 1979). W-cells project almost exclusively to the SC, Y-cells project to both the SC & LGN, while X-cells project predominantly to the LGN (Fukuda & Stone 1974).

2.3.1.2. Geniculostriate pathway.

Beyond the optic chiasm, the LGN is the region where ganglion cells synapse, particularly the dorsal aspect or dLGN $^\dagger$ (Lennie 1980). Within the dLGN, a layered arrangement of cells occurs, with the most dorsal layer, lamina 6, receiving input from

$^\dagger$ The ventral aspect of the lateral geniculate nucleus (vLGN) is not considered, because in cats it is involved with eye movements, and does not project to the cortex (Rodieck 1990).
the contralateral eye, and the next layer, lamina 5, receiving input from the ipsilateral eye. All the receptive fields within the dLGN, are organised in a retinal-like fashion. The four most dorsal layers are referred to as parvocellular layers because of the small cells contained within, and X-cells are the most common input to this region, as illustrated in Figure 2.7.

Figure 2.7. The dLGN. This diagram of the macaque dLGN shows the 6 layers. The magnocellular laminae (1 and 2) have the highest contrast sensitivity, while the parvocellular laminae (3–6) have a lower contrast sensitivity. The dorsal most aspect of the dLGN is positioned at the top of this diagram which is reproduced from Shapley et al. 1981, p.544.

In the ventral part of the dLGN, large cells predominate, called the magnocellular region, and Y-cells and W-cells are the most common input (Lennie 1980; Rodieck 1990). The dLGN projects primarily to the striate cortex, situated adjacent to the calcarine fissure, and in primates these fibres project only to area 17 (Rodieck 1979). In primates, within the LGN, the parvocellular region has almost exclusive input from the X-cells, while within the magnocellular region, 75% of the input come from Y-cells, and 25% from X-cells (Shapley 1980; Kaplan & Shapley 1982). In some studies, the term P-cell has been used synonymously with X-cells, and the term M-cell has been used synonymously with Y-cells (Shapley & Perry 1986; Lennie et al. 1990). To avoid confusion, all cells shall be identified within this review. X-cells which project to the parvocellular region have long latencies, while those which project to
the magnocellular region have short latencies (Shapley 1980; Kaplan & Shapley 1982). P-cells show colour sensitivity, with poor spatial contrast responses, while M-cells (with input from both X-cells & Y-cells) show brightness sensitivity (Shapley 1980; Kaplan & Shapley 1982). If the LGN is treated with monomeric acryl amide (a neurotoxicant that preferentially damages P-cells), visual acuity is reduce by a factor of four (Lynch et al. 1992). Other effects of lesions to the P & M regions of the primate LGN are reviewed in Merigan & Maunsell (1993). A factor that functionally separates M and P-cells is the ability, or inability, to respond to phantom contours (Ramachandran & Rogers-Ramachandran 1991). A pattern is constructed of white dots against a pattern of black dots which is visible when stationary; then the pattern is rapidly reversed at a rate where the colour of the dots is no longer distinguishable, and a contour appears (a phantom contour, as it only exists when the pattern is moving). By using contours made from coloured light, the recorded responses were the same as black and white, and Ramachandran & Rogers-Ramachandran (1991) concluded that only the M cells were responsive to the phantom contours. Summaries of the properties of M and P cells appear in Table 2.2.

<table>
<thead>
<tr>
<th>Property</th>
<th>M (X)</th>
<th>M (Y)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>input cell</td>
<td>X</td>
<td>Y</td>
<td>X</td>
</tr>
<tr>
<td>colour effects</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>spatial response (cycles/degree)</td>
<td>5.7</td>
<td>2.2</td>
<td>8</td>
</tr>
<tr>
<td>brightness sensitivity</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
</tbody>
</table>

Table 2.2 M and P cell functions.

The different regions of the dLGN possess functional differences, and contain groups of cells with similar properties (Shapley 1980; Kaplan & Shapley 1982; Lennie et al. 1990).

2.3.1.3. Mesencephalic pathway.

After travelling through the optic chiasm, a representative proportion of all ganglion cells (except X-cells), travels to the SC (Fukuda & Stone 1974). In the superficial layers of the SC, input is from the retina and also from efferent fibres originating in the visual cortex (Rodieck 1990). Fibres from the contralateral eye synapse in the upper
layer, while fibres from the ipsilateral eye synapse in the lower layer (Rodieck 1990). The projections are predominantly contralateral, and the representation is asymmetric—the temporal visual field (nasal hemi-retina) has more representation than the nasal visual field (Rafal et al. 1991). From the SC, projections go to the nuclei of the optic tract, the pulvinar nucleus, and the dLGN.

The fibres which progress to pulvinar nucleus (most posterior region of the thalamus), have connections to the inferior temporal lobe (areas 20 and 21) and the posterior parietal lobe (area 6). In cats, these fibres also travel to the visual areas: 17, 18, and 19 (Rodieck 1979). In humans, however, Walker (1966) traced projections from the pulvinar, and reported that the medial pulvinar projected to the posterior parietal cortex, the lateral pulvinar to the temporo-occipital region, and the inferior pulvinar to the extrastriate region; with no direct connections to the striate cortex.

### 2.3.1.4. Cortical projections.

Many regions of the cerebral cortex receive visual projections, and are indicated in Figure 2.8, and include primary (17), secondary areas (18, 19), and association areas: posterior parietal (5, 7), inferior temporal (20, 21), and the frontal eye fields (8).

![Cortical structures](image)

Figure 2.8 Cortical structures.  
A lateral view of the right cerebral cortex, with some of the major visual regions indicated, along with their respective Brodmann numbers.
The primary visual cortex (area 17, also known as V1) has major projections to the prefrontal cortex (areas 18 and 19); and major dorsal and ventral projections. The target and function of these dorsal and ventral projections differ (Goodale & Milner 1992). The ventrally-directed system projects to the inferior temporal lobe. Lesions in the temporal lobe in monkeys cause a severe impairment in object discrimination based upon their features (Desimone & Ungerleider 1989), including loss of face discrimination (Desimone 1991). The dorsally-directed system is involved functionally in spatial perception. This system projects to the posterior parietal lobe and in monkeys, lesions in this region cause an impairment in spatial tasks, but do not affect object discrimination (Desimone & Ungerleider 1989). Other anatomical evidence of pathways comes from fluorescent tracer studies. These show that the posterior parietal cortex, in the Rhesus monkey, receives inputs from the pulvinar and dorsomedial nuclei (Schmahmann & Pandya 1990). In macaques, when the M-cells are selectively blocked in the dLGN (by injection of lidocaine), the responses in the cortex to motion stimuli disappear; while when both the M and P-cells are blocked in the dLGN the response to colour or form disappears (Ferrera et al. 1992). This indicates that the M-cell and P-cell pathways process different types of visual information, and that the P-cell system remains exclusive for the processing of movements. Akshoomoff & Courchesne (1992) provide some evidence that even the cerebellum may play a role in the covert orientation of attention.

Within the visual system, the structure of the optimum stimulus varies with recording location; for example, in the retina, a ganglion cell is only responsive to light placed in a small area known as the receptive field (Moses 1975), whereas in the inferior temporal lobe, a cell may only respond to a complex spatial and temporal pattern (Richmond et al. 1987) or to a face (Desimone 1991; Harries & Perrett 1991). This integration and selection of spatial location is examined in the following sections, in an attempt to locate the site(s) of action of the spotlight.

The overview of anatomical structures and pathways ends here. The sections following review the role of various regions in the processing of visual spatial selective
attention. The locus of attention in space could feasibly exist anywhere within the visual system. A search of the literature relating to visual spatial selective attention within the visual system follows.

2.3.2. The retina and optic tract.

After the retina, the first synapses in the visual system are in the brainstem; the geniculostriate system synapsing in the dLGN; and the mesencephalic system in the SC (see Poggio 1980). These two regions also receive input from the cortex, vestibular and auditory nuclei, and from other nuclei within the visual system (Rodieck 1979). Because of this confluence of pathways, it is feasible to suggest that selection takes place at this level. The evidence for spatial selection will now be examined.

With a spatial selective attention task, Eason et al. (1983) showed that there was a change in the B-wave of the electroretinogram (ERG), which is due to changes in the retina. The B-wave reflects activity of the Müller cells in the dark adapted eye (Armington 1974). The B-wave activity was recorded in humans and occurs earlier than has been recorded in the cat. The changes to the B-wave indicate some form of modulation of the visual system at an early level. Hackley (1993) found that the blink reflex to either an acoustic or cutaneous stimulus varied if the subject attended to one stimulus or the other. This reflex is an involuntary response, but still appears to contain a small component influenced by selective attention. Hackley (1993) hedges, arguing against both a peripheral gating, and a strong automatic theory, and opts for a partial mix of both, based upon results from cross-modality experiments. Moving away from the retina to the optic nerve, some other results have been obtained.

In 1959, Palestini et al., recording from the retinal ganglion cells in the optic nerve of the cat observed that potentials in response to a flash of light were attenuated in amplitude when a white rat appeared in the visual field. The reduction in amplitude depended upon the novelty value of the stimulus, and habituated within 15–30 seconds. These visual evoked potentials diminished when a stimulus of a different modality was presented (olfaction: the smell of fish). These studies indicated
descending influences upon the visual pathways, which have an effect on selective attention. Näätänen (1975) criticised Palestini et al.'s 1959 study because of an absence of any control for the effects of habituation. There is a possibility that the responses were due to some orienting mechanism rather than selective attention—these aspects are sometimes difficult to separate (see section 2.1), but nevertheless, the results show a modulation in the activity of cells as early as the optic tract.

2.3.3 The thalamus and midbrain.

The next region along the visual pathway is the thalamus, and around the thalamus there exists a layer of cells with extensive inhibitory collaterals known as the thalamic reticular complex, or reticularis-nucleus-thalami (Walker 1966; Crick 1984). Crick identified this as the site of the searchlight, but provided no evidence to support his claim. The cells of the thalamic reticular nucleus inhibit the adjacent thalamic nuclei—when the reticular cells are firing at maximum rate, the thalamic cells' firing rate slows significantly (Schlag & Waszak 1970; 1971), possibly gating some of the stimuli travelling through the thalamus. Yingling and Skinner in 1977 examined the effect at the thalamic level of selective attention in anaesthetised cats by recording the cortical evoked response to electrical stimuli in the optic tract. When a region of the reticular complex adjacent to the LGN was stimulated (with a 20 ms burst of 250 Hz activity), the cortical response evoked by optic tract stimulation was abolished. This effect was only seen with stimulation of the reticular complex, and was not seen with stimulation of either the LGN or the optic radiations (see Figures 2.5 and 2.6). This indicated that a localised effect of selection of incoming visual information took place. The effects have also been reported in the rat (French et al. 1985), and other species. Using awake dogs, with an over-learned response to food, Young et al. (1971) examined the effect of stimulating the optic radiations with a pair of pulses and recording the evoked response in the cortex. They found that when a light was switched on (a previously over-learned signal for food), the magnitude of the cortical response to the pulses was diminished compared to a control condition. These data are not directly comparable
with Yingling and Skinner's (1977) data, but do support the concept of gating of irrelevant information at the level of the thalamus. Yingling & Skinner also reported that the thalamic reticular nuclei are specific in modality that they gate, and this is an important consideration for intermodal aspects of the spotlight (Skinner & Yingling 1977; Yingling & Skinner 1977).

McCormick & von Krosigk (1992) found that in guinea pigs, electrical stimulation of the corticothalamic fibres anterior to the dorsal LGN resulted in typical monosynaptic excitatory post-synaptic potentials in the dLGN. These slow potentials were associated with a drop in potassium conductance via glutamate metabotropic receptors, and the slow depolarisation could switch thalamic neurons from burst mode, such as in sleep, to single spike mode, such as when awake. Such changes in operating mode could possibly be related to the area of the spotlight.

Another brainstem nucleus, the SC, was examined in a spatial selective attention study in monkeys by Wurtz & Mohler (1976a). They found that the response of cells in the SC is influenced by visuospatial selective attention; specifically that the response of cells in the superficial layer of SC responded more vigorously to a spot of light in their visual fields when the monkey used that spot of light as a target for a saccadic eye movement. However, the authors did not show a clear separation between movement, or the saccade, and attention, and hence it remains unclear whether the enhanced response results from selective attention or solely because of the imminent saccade. Goldberg & Wurtz (1972a) showed that the response of SC cells was modulated by either making a saccade to point, or using a point as an attentional cue without moving eyes, and hence spatial selective attention is evident in the SC. Some cells were active immediately before any movement (Goldberg & Wurtz 1972b). In the same series of studies, the presence of lesions in the SC did not interfere with the accuracy of responses, but delayed any saccadic eye movements (Wurtz & Goldberg 1972). The authors argued that this suggests the role of the SC is to limit the area of visual field in which finer control systems act, and therefore increase the time necessary to specify the search parameters.
Lesion studies also provide clues to the understanding of the action of spatial attention. In an experiment in which targets were repeatedly presented in the periphery of vision while human subjects were fixating a central point, Singer et al. (1977), found that the intensity threshold for detection of the peripheral stimulus with non brain-injured subjects increased by 0.5–1.0 log units and thus caused an adaptation in threshold. This intensity adaptation occurred over a wide area (20 degrees) when the stimulus was in the periphery; but close to the fovea, this area was about 5 degrees. If the subject made a saccade to the peripheral target, then the intensity threshold returned to its original level. A target presented in the mirror symmetric visual field also reset the threshold. In two patients with hemianopia, due to striate or prestriate lesions, the same observations were seen for the adapting stimulus including the mirror symmetric resetting in the blind hemisphere—even though this target could not be detected by the subject. This was interpreted to indicate an involvement of the retinotectal system in guiding attention to parts of the visual field.

LaBerge and Buchsbaum (1990), with Positron Emission Tomography, found that the uptake of glucose in the pulvinar nucleus was greater during a selective attention task than during a non-attention task, and the pulvinar nucleus contralateral to the stimulated visual field showed these changes. This was supported by the findings of Zihl & von Cramon (1979), with one patient with left pulvinar nucleus injury who showed neglect for the contralateral hemifield, even when cued toward this hemifield with light. With minimal injury to other structures, the lesion in the pulvinar nucleus had reduced the ability to selectively attend to one hemifield. The apparent neglect could also have been caused by descending oculomotor fibres, which pass through the pulvinar nucleus, and the ‘neglect’ may have been partly as a result of being unable to attend to this visual location. On the other hand, it is not necessary to foveate an object to attend to that object (Jonides 1980; Posner & Rafal 1985; Posner et al. 1987; Rafal et al. 1988), and the previous case study points to a possible contribution of the pulvinar to visuospatial selective attention (Zihl et al. 1983). Rafal et al. (1988)
studied the effects of lesions in another area examining eight patients with Progressive supranuclear palsy, which typically affects the subcortical nuclei of the basal ganglia and brainstem, including the superior colliculus. Consistently these patients lacked appropriate responses such as: not turning towards people who were approaching them; not maintaining eye contact with others during conversation; and not looking at their plates while eating. These failures did not result from a loss of ocular mobility, for the patients could perform these directed movements on command. The involvement of thalamic nuclei is implied by these observations, however, because the patients were able to voluntarily attend to regions of the visual field, then the responses may have been due to a failure of the orienting reaction. From these examples, there appears to be some evidence for gating of visual-spatial information at the level of the thalamus. In the medial region of the monkey pulvinar nucleus, modulation of cell responses was seen when a point in the receptive field was used as a target for a saccade, and also when a point was used as an attentional cue—without eye movement (Petersen et al. 1985; Petersen et al. 1987). This corresponds with the same effect observed in the SC region (Goldberg & Wurtz 1972a). Rafal et al. (1991) demonstrated that stimuli placed within the temporal visual field were more effective in attentional tasks than those in the nasal visual field. These results were found in humans, and when coupled with the known bias of the geniculostriate pathway to the temporal visual field, yields strong evidence for visual-spatial selective attention taking place within this system.

A step further in locating the spotlight mechanism requires examination of the latency of the pathways from the retina to cortical structures. With depth electrodes in the occipital cortex, Wilson et al. (1983) found the earliest responses to visual stimulation in humans to be in the range 31–110 ms. From scalp recordings of visual evoked potentials, the latency at which the afferent volley of action potentials reaches the occipital cortex in humans was estimated to be 28.6 ms, with the first peak that can be clearly recorded occurring at 39 ms (Cigánek 1961). This is consistent with Spekreijse et al.’s (1977) theoretical estimation that myelinated fibres 1 µm in diameter
with a conduction velocity of 6 m/s, and a distance of 20 cm from the eye to the
cortex, the latency of the action potentials should be around 35 ms. These data are
also supported by studies in monkeys that show the earliest response recorded on the
surface of the occipital cortex to be 50 ms after a visual stimulus (Schroeder et al.
cortex, consistent with the destination of the geniculostriate radiations (Lennie 1980;
Kaas 1989). The contribution of the occipital cortex to visual spatial selective
attention is an important factor that demands more detailed investigation.

2.3.3. The occipital cortex.

The striate cortex is part of the occipital cortex and corresponds to area 17 (see Figure
2.8). It is the first destination of the geniculostriate pathway in the cortex. The
prestriate cortex includes areas 18 and 19 and has direct connections with the striate
cortex.

Most of the pioneering work in the visual system was carried out on anaesthetised
animals and made attentional effects impossible to measure (see Poggio 1980). One
experiment that used conscious monkeys was carried out by Moran & Desimone
(1985). After isolating individual cells in the monkey striate cortex (area V1 in the
monkey), they found the receptive field of each cortical cell, and then in turn for each
cortical cell found the most effective driving stimulus and found a stimulus ineffective
at driving it. An effective stimulus was presented at one location in the receptive field
concurrently with an ineffective stimulus at a second location within the receptive
field. The monkey was trained to attend to one of the locations, but ignore stimuli at
the other. The paradigm was a match-to-sample where a target was compared with a
cue and if the target and cue were identical the monkey was rewarded if it responded
by releasing a bar immediately. If the target and cue differed, a reward could only
occur if the bar release was delayed by 700 ms. When the monkey attended to the
effective stimulus the cell responded well, but when the monkey attended to the
ineffective stimulus there was no response, showing no effects of attention in the
striate cortex. In another study with monkeys fixating on a point, and making a saccade to a stimulus, Wurtz & Mohler (1976b) investigated the response of individual cells in the cortex. The monkey either had to make a saccade to the stimulus from the fixation point (2–20 degrees), or press a bar in response to the stimulus. No enhancement, that is an increased discharge, was seen for the majority of cells studied in the striate cortex. Some of the cells did show an enhancement, but it occurred for both the bar press and the saccade. This contrasted strongly with the response seen in the SC where there was a marked difference between saccades and bar pressing in the enhanced response of the SC cells using the same paradigm (Wurtz & Mohler 1976a).

In contrast to this finding, Motter, in 1993, found that in a study recording responses from visual areas V1, V2 & V4 in the macaque, focal attention resulted in a change of firing rate in cells to what were otherwise identical stimuli at specific spatial locations. The author claimed that this experiment did not confuse findings with the orienting response as any orienting was finished before presentation of the target. This factor could not be guaranteed in previous studies where no involvement of the primary visual cortex was observed (Wurtz & Mohler 1976a; 1976b, Wurtz et al. 1979). The finding of primary occipital involvement in Motter's (1993) study could be downstream effects of preceding structures in the midbrain, and these results are consistent with this explanation.

Bowman et al. (1993) demonstrated that macaques could be trained to perform an attentional task where attention is shifted covertly (often called a Posner task; Posner et al. 1980). Bowman et al.’s results showed that, although the reaction time for valid cues was shorter than invalid cues, the monkeys did not have a validity effect as did humans. In humans as the ratio of valid to invalid cues decreases, a paradigm shift occurs so that targets are eventually considered as non-targets. The lack of this finding in macaques indicates that the response to the cues is overlearned.

Mangun & Hillyard (1987) & Heinze et al. (1990), in a study with humans, recorded event related potentials to an attentional task, which involved selectively attending to one of three locations while fixating on a central location. Attention was maintained
at a location by requiring the subject to find randomly occurring target stimuli, at that location, which differed from the ordinary stimuli. When examining the response in the occipital scalp (at recording sites O₁ & O₂), there was an increased amplitude of the evoked potential components P135 and N185. In a similar paradigm, the evoked responses N1 and P2 showed independence from each other when recorded at the vertex, indicating separate generators for the N1 and P2 responses (van Voorhis & Hillyard 1977). Using letters, Mangun & Hillyard (1990) showed that while the topography of the P110 evoked component did not change, the magnitude of the response did change—indicating that any selective attentional effects had occurred before reaching the striate cortex. When subjects were attending to a stimulus in one visual field, and ignoring a stimulus in the opposite field, Oakley & Eason (1990) found that there was an enhanced N55 evoked response in the attended visual field, which was similar for all regions of the scalp. A different finding was reported by Luber et al. (1990), who recorded the magnetic evoked response† from 3 individuals, and reported that differences were not seen until 250 ms.

Figure 2.9 Magnetic Evoked Response to attention. The time courses of averaged evoked responses to stimuli in the right visual field in attended (solid line) and unattended (dashed line) conditions, obtained over the occipital area on the scalp. Stimulus onset is at 0 seconds. (Reproduced from Luber et al. 1990). A difference is reported by the authors at 250 ms, yet a clearly visible difference, at 50 ms, is ignored!

† Magnetic Evoked Response (or MER) is the recorded magnetic field response to an external stimulus. It is analogous to the Evoked Potential.
However, their data clearly showed that a striking difference in the waveforms for attended and unattended locations existed as early as 50 ms! Even though there are changes in evoked potentials recorded over the occipital cortex, the data support an enhancement, or selective attention at an earlier stage of visual processing than the occipital cortex.

The interpretation given by Näätänen (1975) and Näätänen & Michie (1979) of the style of experiments above, is that a general negativity begins somewhere between 50 and 200 ms after the stimulus and artificially enhances the size of N1, especially if the inter-stimulus interval is short. This interpretation is also consistent with an early selection of visual-spatial information in the attentional process.

While selective attention has been observed, the spotlight properties have not been fully considered. An interpretation of the spotlight model suggests an attentional gradient as the enhancement is strongest when attending to the location where the target occurs, and graded according to distance from the target. Eason (1981) found that for an attentional event related potential (ERP) recording, with human subjects, responses in the 70–120 ms range were enhanced when attending to the relevant position in the visual field. Harter et al. (1982) in a similar study found that there was enhancement of ERPs of latency 125–222 ms, and this was greater in the hemisphere contralateral to the attended location. These experiments support the existence of a graded, spatial spotlight.

In a different experiment, with fixed spatial location, Wastell & Kleinman (1980) saw no change in the evoked potential N1, when the subject attended to the shape or intensity of the stimulus. This result suggests that the subcortical structures may not contribute to selective attention for shape and intensity. Rugg et al. (1987) compared spatial and non-spatial visual selective attention and found that the spatial selection showed earlier changes in evoked potentials than for non-spatial selection. Selective attention to spatial location was shown by Harter et al. (1982), to produce changes in evoked potentials of latency 125–222 ms, while selective attention to form, such as shape or colour, produced changes in evoked potentials of latency 222–275 ms.
Harter & Aine (1984) also found a difference between the right and left hemisphere responses. The right hemisphere showed greater changes when attention was linked to location, whereas the left hemisphere responded to the type of stimulus. It appears from these experiments that selective attention is a specific mechanism and not a general phenomenon. In another study, using a cross-modal attention paradigm, no changes occurred in the visual evoked response before 100 ms, when attending to the auditory modality (Hackley et al. 1990).

Harter & Previc in 1978 demonstrated a physiological mechanism that supports the zoom lens concept, finding that the evoked response (N160) from a checkerboard reversal was greatest when the subject attended to checks of a similar size; and decreased when the subject attended to checks of a different size. This supports the notion of size-specific sensory processing, and the variable size of the attentional spotlight.

In summary, the occipital cortex shows little if any cellular response to changes in selective attention in monkeys. Any observed selective attention changes of ERPs in humans may be downstream effects from cortical and sub-cortical regions. There are no reports of selective attentional effects that are specific to the occipital cortex. The review examines other regions of the visual cortex for evidence of involvement in visual spatial selective attention.

2.3.4. The posterior parietal cortex.

The posterior parietal region comprises area 7 of the cortex, with inputs from a wide range of cortical and subcortical structures. Inputs come from area 19—prestriate cortex, areas 20 & 21—temporal cortex, and the somatosensory and auditory regions (Cavada 1984), and have been found experimentally by fluorescent tracer techniques in macaque monkeys (see Morel & Bullier 1990). The region integrates visual, somatosensory, and auditory sensation, and subserves the roles of spatial and motion analysis, especially in the peripheral visual field (see Walsh 1978; Kolb & Whishaw 1990; Baizer et al. 1991; Goodale and Milner 1992). Regarding connectivity of the
posterior parietal cortex, tracer studies have found that M-cells from the dLGN project to the posterior parietal cortex, together with fibres from the pulvinar and posterior-lateral nucleus of the thalamus (Baizer et al. 1991). Projections from the posterior parietal region connect to the temporal and prefrontal regions probably to access memory processing functions related to these areas, including the visuospatial working memory of the frontal region (see Cavada & Goldman-Rakic 1993).

Within the posterior parietal cortex exist cells mapped in a similar fashion to the frontal eye fields (Andersen 1988), that are responsive to saccades (Lynch et al. 1977), independent of foveal and retinal position (Robinson & Petersen 1984). These parietal cells connect with, and have a similar organisation to the lateral pulvinar nucleus (Robinson & Petersen 1984). One suggested role of these parietal cells is the maintenance of the attentional spotlight, independent of saccadic movement, and independent of the retinal location (Lynch et al. 1977; Bushnell et al. 1981). A second role is to re-map the cortical image during the preparation for a saccade (Duhamel et al. 1992). Some single cell recording in the posterior parietal lobe in macaques found a response to the expectation of sensory stimulation (Mackay & Crammond 1987), illustrating a computational role in the allocation of attention for this region of the cortex. Reports of specialisation of cells within the posterior parietal region complicate the function of this region. Yin & Mountcastle (1978) found four separate types of visual cells in area 7: one type was responsive to visual stimuli, and the others were active in visual fixation, visual tracking or saccadic eye movements. The first type were not active in spontaneous movement, only when attention was drawn to the appropriate area of the visual field (Yin & Mountcastle 1978). This is consistent with input to these cells from the pulvinar-lateral posterior group of the thalamus via the mesencephalic system (Robinson & Petersen 1984).

Other aspects of parietal function come from a variety of human clinical, and animal studies of parietal injury. Disorders of spatial orientation and location; and topographical disorientation have been seen in persons with parietal lobe injury (Walsh 1978), and Villa et al. (1986) found right parietal injured patients impaired on non-
verbal constructive tasks when compared to left parietal injured patients. The posterior parietal lobe also has a role in the integration of visual and other sensory information (Kolb & Whishaw 1990 p. 418ff.). The nature of the representation in body space has been illustrated in studies with unilateral parietally injured patients.

If the posterior parietal cortex suffers injury, a deficit in attention to stimuli in the contralateral hemispace occurs—unilateral spatial neglect or hemi-inattention syndrome (Walsh 1978 pp. 213–217). Similar findings have been reported for the reduction in amplitude of the P300 event-related potential to contralateral stimuli (Lhermitte et al. 1985), and contralateral neglect has also been seen after posterior parietal injury in rhesus monkeys (Lynch & McLaren 1989). In particular, Valler & Perani (1986) found that injury to the inferior regions of the posterior parietal cortex was more associated with spatial neglect. This is more pronounced with right parietal injury, and gives rise to a neglect of both ipsilateral and contralateral hemispace (Weintraub & Mesulam 1987; Ladavas et al. 1989; Rapcsak et al. 1989), indicating that the parietal cortex is an important locus of visual selective attention, particularly the right parietal cortex. These results suggested a representation, related to contralateral visual hemispace. To further examine this relationship, Gazzaniga & Ladavas (1987) replicated the findings of a deficit in the left hemispace for right parietally injured patients, with the deficit persisting, even with left and right tilting of the head. This suggested a dependence upon a gravitational frame of reference, rather than purely a visual field frame of reference.

Posner et al.’s (1984) work with the brain-injured further supports the existence of cells in the parietal cortex involved with disengaging attention from one focus before moving to another, and has been replicated by other groups (Morrow & Ratcliff 1988; Petersen et al. 1989; Farah et al. 1989). The movement of attention is implicated, and further work by Posner et al. (1987) reported that unilateral parietally injured patients when cued in either visual field, followed by a target either toward or away from the lesion side, always performed worse when moving away from the lesion, further supporting a directional view of the visual space.
In summary, these findings suggest that the right parietal cortex hemisphere has a greater involvement in spatial selective attention than the left, particularly those regions more inferior in the right parietal cortex (Vallar & Perani 1986). These findings are consistent with the importance of the right hemisphere in processing of visual spatial information (see Harter & Aine 1984; Neville & Lawson 1987).

2.3.5. The inferior temporal cortex.

The inferior parietal and inferotemporal cortices receive information through largely separate prestriate cortical pathways; although there exist common inputs from the superior sulcus.

The inferior temporal region is made up of areas 20 and 21 of the cortex. It is found at the borders of the occipital, parietal and temporal lobes, so has a role in cross-sensory integration. It is important for auditory selective attention in space, and important for divided field, visual selective attention (Kolb & Whishaw 1990).

The visual input to the inferior temporal region in primates, as delineated by nerve tracer studies, comes largely from the occipital lobe or primary visual cortex, originating in the P-cell region of dLGN, without direct input from the pulvinar nucleus of the thalamus (Baizer et al. 1991). Some properties of the cells of the inferior temporal region in primates have relevance to visual selective attention. Each cell in this region has a large receptive field, which always includes the centre of gaze, and the cells are selectively activated by shape, colour, or texture (Gross et al. 1984). Within the inferior temporal cortex are cells that are responsive to complex spatial patterns (Richmond et al. 1987), faces (see Desimone 1991; Kendrick & Baldwin 1987; Lu et al. 1991), and specific objects (see Corbetta et al. 1991; Baizer et al. 1991). In humans, lesions of the right temporal lobe reduce the ability to recognise objects from incomplete representations (Walsh 1978), and in some cases cause a loss of the ability to recognise faces (Kolb & Whishaw 1990).
Similar findings are reported for other regions of the temporal lobes. Within the mesial temporal lobe in macaques, populations of neurons exist that respond to one of the classes of stimuli: motion, auditory-visual (bimodal), identity (faces), eye contact, and other aspects of social behaviour (Brothers & Ring 1993). In the superior temporal sulcus of the right hemisphere, evoked fields to omitted stimuli in an oddball paradigm were found (Rogers et al. 1993). This response occurred at 210 ms, earlier than the usual P300, in 10 human subjects, and was reported to reflect the shape-matching role of the temporal lobes.

Recordings in human subjects of stimuli varying in shape have pointed to the right inferior temporal cortex, when ERP studies have been analysed with Laplacian techniques to improve localisation (Begleiter et al. 1993). The dependence of this region on both memory and analytical features of the objects indicates an area important for pattern and object recognition, but playing no role in spatial selective attention.

2.3.6. The frontal cortex.

The frontal cortex is the anterior most portion of the cortex, and contains several functionally separate regions: the premotor (areas 6 & 8); the prefrontal (areas 9, 10, 45, 46); and the basomedial (areas 9–13, 24, 32). The basomedial and prefrontal are sometimes collectively known as the prefrontal cortex (Walsh 1978), or granular frontal (Freund & Hummelsheim 1985). Part of the premotor region, the frontal eye fields (FEF) areas 8 & 9, are important for control of eye position and eye movements; as impairments of voluntary gaze and reverse-saccade tasks are seen with lesions to the FEF. The FEF project to the SC and oculomotor nuclei to carry out eye movements. The prefrontal cortex is important for overall planning with connections to the prefrontal cortex from the posterior parietal cortex and inferior temporal cortex (Milner & Petrides 1984).
It is not surprising then, that Goldman-Rakic reports that the prefrontal region has rich interconnections with the parietal region of the cortex, “. . . providing communication relevant to the visual map of space.” (Goldman-Rakic 1985, p. 406).

Lesions of the prefrontal cortex often produce deficit is in task planning and attention related to the tendency to persevere on task performance when the sorting criteria have been changed, such as in the Wisconsin Card Sort Task, or the CANTAB task (Owen et al. 1993). This deficit is distinct from that seen with Parkinsonian patients who exhibit some of the frontal lobe deficits, and can be separated on the results of the CANTAB task. However, aside from a loss of speed, brain-injured patients do not appear to perform any worse in accuracy to a task involving planning and execution, known as the ‘Tower of London’ (Ponsford & Kinsella 1992). They also performed no worse than age-matched-controls on a variety of attentional tasks, apart from speed of performance (Ponsford & Kinsella 1992).

When performance is measured with response to chimeric faces (ambiguous faces with both happy and sad characteristics), there is a left hemiface bias observed in control subjects (David 1993).

The function of the frontal lobes is diverse, and not completely known (Stuss 1986; Stuss & Benson 1983), and Mesulam (1986) lists many behavioural changes taken from a century of study. Lesions of the frontal lobes produce deficits in divergent thinking (Milner 1992). Divergent thinking involves creativity and produces a variety of responses. For example, left frontal lobe lesions often produce an inability to create a list of words beginning with a nominated letter, known as a verbal fluency deficit. Right frontal lesions impair the production of different nonsense drawings (doodles), and this is known as a design fluency deficit (Milner 1992). Other deficits that are seen with frontal lobe injury involve attention and planning (Milner & Petrides 1984). Performance on word fluency tests were found by Crockett et al. (1986) to be the most discriminating between brain-injured and other patient groups. Attentional deficits have been divided into three types by Stuss et al. (1989), and these are: drifting attention—where the individual can attend for brief periods; wandering
attention—where the individual is easily distracted and returns to less alert state; and reduced directed attention—where any degree of planning, monitoring, or selection is involved. These three classes of deficits appear to be respectively linked to the reticular activating system, the thalamic projection system, and the prefrontal regions (Stuss et al. 1989).

Wilson et al. (1993) provide evidence that one population of cells is responsive to object information and not spatial information, and another population of cells is responsive to spatial information, and not object information. This information ties in with the dorsal and lateral pathways of the extrastriate visual system, and provides evidence that the two representations of what and where are present within the region that could control the locus of the spatial attention.

General lesions in the right hemisphere cause deficits in visual-spatial tasks, and cause a slowing in simple reaction times (Coslett et al. 1987). These lesion studies correspond to regional blood flow studies where right frontal regions are more active than the left frontal regions for visuo-spatial attention tasks, and the regional cerebral blood flow increases with task demand (Deutsch et al. 1987). In a Stroop task while measuring blood flow with PET, Bench et al. (1993) found that the anterior and mid-prefrontal structures in the right hemisphere were activated, as well as the right anterior cingulate region. When examined with techniques that require longer periods, and possess greater spatial resolution than rCBF measurements, the mid-frontal division of the frontal lobe increases the most during spatial tasks (Roland 1984).

Frontal lesions do interfere with basic visual function as measured by contrast sensitivity gratings, and the disorder is related to higher order visual processing (Spinelli & Zoccolotti 1992).

Some frontal-thalamic pathways project to the brainstem and synapse in the LGN, the SC and pulvinar nucleus, possibly with a visual role. These efferent pathways would allow for the control of the afferent visual system at the brainstem level.
Yingling & Skinner (1977), showed that gating of sensory information does take place at the level of the thalamus, and postulated that the medial thalamic fronto-cortical system (MTFCS) is the agent of this selection. Stimulation of the MTFCS had an inhibitory effect on the reticularis thalamus nuclei, and gated the thalamic nuclei (including the LGN). Another frontal-thalamic system (the medial reticular formation or MRF) is important in arousal responses, but not specifically involved in visual selective attention (Yingling & Skinner 1977). Kinghorn et al. (1987) studied the albino rat with a lesioned frontal cortex, and found that this suppressed photically-evoked-after-discharge, suggesting that the frontal cortex can inhibit brainstem mechanisms of cortical bursting, possibly with a non-specific modulatory function. In humans with lesions of the prefrontal cortex, had impaired responses to somatosensory evoked potentials (Yamaguchi & Knight 1990). While the findings in this study clearly indicate an impairment in the somatosensory evoked response, they support the role of the prefrontal region in the control of the overall gating of sensory information.

The prefrontal regions are also modulated by affective stimuli (Lhermitte et al. 1986; Lhermitte 1986), and part of the overall system that inhibits overall interaction with the environment. This can lead to so-called ‘imitation’ behaviour. Lhermitte proposes a mechanism whereby the normal inhibition of the reliance of information from the parietal region is dysfunctional due to frontal lobe injury, and the patient therefore places too much weight on this information and emulates the environment. The frontal-parietal interaction has been reported, and in fact is inverse in slow wave recordings of event-related potentials (Loveless et al. 1987).

2.4. Summary of selective attention.

One model that has been extremely successful in describing the complex processes of visual-spatial selective attention is the spotlight model. (It is also known as the zoom lens or the searchlight model.) The success of the spotlight model has been due to
those features which describe selective attention, such as: the variable size and circular shape of the attentional focus, as well as the manner in which objects are attended inside and outside the beam.

Posner & Driver (1992) reviewed some of the key articles on attention, and propose a model for attention in space comprising a network of nodes including parietal cortex—establishes expectation of the target location, midbrain—the SC provides the locus for overt and covert movement of attention, and the thalamus—the pulvinar nucleus that performs a filtering operation to exclude irrelevant information. This networked model is supplemented by the anterior cingulate gyrus, that plays a role in the detection of multiple targets or in removal of dominant responses. Mesulam (1981) related the role of the cingulate gyrus to integrating limbic and other input, and hence suggested that cingulate gyrus provides the motivational link in the attentional system, due to its close interaction with the limbic system.

The spotlight model is itself sufficient to describe the behavioural experiments; but from the point of view of physiological attention, the physical location of the spotlight is important. Studies of the attentional mechanism have been carried out with simple and elaborate experiments. These experiments have pin-pointed certain regions of the central visual system, both brainstem and cortical. Brainstem structures such as the superior colliculus, the pulvinar nucleus, and the lateral geniculate nucleus, have been implicated; while cortical structures such as the posterior parietal lobe (in particular the right parietal lobe), and the frontal lobes, are also involved in the control of visual-spatial selective attention. Evidence is found for action to be either initiated by the posterior parietal cortex acting via the pulvinar nucleus; or the frontal cortex acting via the MTFCS in the vicinity of the LGN.

The spotlight has been able to explain all the data regarding visual spatial selective attention that is available to date, and its control acts at the level of the brainstem, with control from the frontal and parietal regions of the cortex.
3. The steady-state visually evoked potential.

This chapter provides an overview of selected properties of steady-state visually evoked potentials. The review of selected properties of the SSVEP provides a basis for the type of stimulus used in the experimental work, and underpins the subsequent studies that use this stimulus to elicit Probe-ERPs. It begins with a comparison with the transient evoked response, and is followed by a consideration of the stimulus properties that affect the steady-state response. These changes in stimulus properties are examined with respect to the known function of the visual pathways. A final consideration is the effect of cognition on the steady-state response, leading to the Probe-ERP paradigm and its suitability as a method for studying attentional changes.

This chapter assumes a familiarity with the basic anatomy and physiology of the visual pathways as outlined in Chapter 2 (section 2.3). It is not a review chapter, but more a framework to examine the steady-state visually evoked potential, as used in the following experimental work in Chapters 5, 6, 7 & 8.

3.1. Visually evoked potentials.

Hillyard & Kutas (1983) defined Event-related Potentials (ERPs) as “small phasic potentials elicited in conjunction with sensory, cognitive and motor events”, thus drawing a distinction between these and Evoked Potentials (EPs) which encompass a broader scope. EPs include, in addition to ERPs, those potentials “emitted” in the absence of any stimulus (Regan 1989 p. 195). Using these definitions, visually evoked potentials are examined with their great diversity and variability of responses to different stimulus types.

Most evoked potentials contain components related to the physical characteristics of the stimulus, and also to the cognitive aspects of the signal (Regan 1989). Those components related to the physical characteristics of the stimulus are named exogenous components, while those determined by a cognitive event, rather than the
physical stimulus, are named endogenous (Donchin et al. 1978; Hillyard & Kutas 1983). Donchin et al. (1978) state three criteria that need to be met for identification as endogenous components.

1. The same physical stimulus presented to the same subjects won't necessarily evoke the same response—the so called non-obligatory response.
2. Amplitude and latency of the response are often invariant to changes in the physical stimulus parameters—including different stimulus modalities.
3. The variance in components is accounted for by the variation in tasks assigned to the subject.

Some evoked potentials only contain exogenous components, for example early potentials; while others contain only endogenous components, for example the emitted potentials.

A section on the responses to transient stimuli proceeds, as an appropriate overview of the responses to steady-state stimuli.

3.1.1. Transient evoked potentials.

Evoked potentials produced by transient stimuli are generally short-lived, or transient in nature, characterised by a series of peaks and troughs specific to the type of stimulus used. A flash of light from a stroboscope provides one of the most commonly used (and perhaps the simplest) stimuli producing a response in the cortex, that can be recorded on the scalp a short time later. The flash stimulus by its nature is diffuse and preferentially activates the Y-cell system as it presents a large-field stimulus with transient onset; properties favoured by the Y-cells (Rodieck 1979; Lennie 1980). A representative scalp-recorded response, illustrated in Figure 3.1, shows several distinct peaks and troughs. The occipital region yields the largest potentials, consistent with overlying the visual area of the cerebral cortex. A temporal (that is, time) relationship exists between the peaks and troughs of the response and the stimulus.
Several methods of labelling evoked response exist. Cigánek (1961) produce one of the earliest schemes where roman numerals denoted various peaks and troughs in the response. Halliday (1982) used a more intuitive scheme, where the polarity and approximate latency formed the label for that component, for example P100 corresponds to a positive component the occurs approximately 100 ms after the stimulus. Table 3.1 shows Cigánek's scheme, in 60 individuals along with the equivalent nomenclature given by Halliday (1982), recorded from 17 healthy subjects.

<table>
<thead>
<tr>
<th>Polarity</th>
<th>Cigánek</th>
<th>Latency (ms)</th>
<th>Halliday</th>
<th>Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>I</td>
<td>39 ± 4</td>
<td>onset</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>II</td>
<td>53 ± 4</td>
<td>P60</td>
<td>61 ± 10</td>
</tr>
<tr>
<td>N</td>
<td>III</td>
<td>73 ± 6</td>
<td>N70</td>
<td>73 ± 14</td>
</tr>
<tr>
<td>P</td>
<td>IV</td>
<td>94 ± 7</td>
<td>P100</td>
<td>102 ± 14</td>
</tr>
<tr>
<td>N</td>
<td>V</td>
<td>114 ± 7</td>
<td>N125</td>
<td>127 ± 20</td>
</tr>
<tr>
<td>P</td>
<td>VI</td>
<td>135 ± 10</td>
<td>P160</td>
<td>161 ± 36</td>
</tr>
</tbody>
</table>

Table 3.1 Components of the flash evoked potential.
This table lists the latency, polarity, and labelling schemes used by Cigánek (1961), and Halliday (1982).

The latencies of the strobe response vary by about 15–20% within a population of healthy individuals (Halliday 1982). For an individual, the differences between the response latencies from right and left eyes are within about 2%, however, the amplitudes may differ by as much as 30% (Halliday 1982). Considerable variability in latencies and amplitudes of flash evoked potentials occurs, and Regan (1988) warns...
that because of the variability in latency—each laboratory must obtain and establish its own data on controls. For practical purposes, this means the existence of different descriptions for the same peaks, particularly when described by the latency. Table 3.1 illustrates this point with data from only two laboratories.

Structured stimuli (that is, those containing patterned material), also evoke transient responses. Due to the amount of detail present, the structured stimuli preferentially activate the high acuity, foveal or X-cells, with their receptivity to higher spatial frequencies (Rodieck 1979; Lennie 1980). Different classes of structured responses include those evoked by the appearance, disappearance, or alternation of visual patterns (Skrandies et al. 1980). The response to the presentation of a display of checks, known as check onset or patterned flash EP, is similar to that seen with the flash stimulus, but the polarities of some of the peaks may be inverted with different latencies, reflecting the mixed response of both X-cells and Y-cells (Regan 1972a). The latencies of these peaks depend upon the reversal rate, or speed of movement of the pattern, and latencies decrease as the reversal rate increases, for example from 118 ms to 104 ms when reversal time reduced from 35 ms to 10 ms (Halliday 1982).

If the checks remain displayed, an evoked response to the removal of the pattern eventuates, known as the pattern offset EP (Regan 1972a). Alternation of the checked pattern between light and dark, and referred to as counterphase or reversal stimulation, yields a different evoked response, with characteristic peaks at latencies of N70, P100, and N125 (Bodis-Wollner et al. 1986). As the reversal rate, or frequency of stimulation increases, a point is reached at about 5 Hz where the individual responses begin to overlap, and at sufficiently high reversal rates—no individual response cycle can be associated with a particular stimulus cycle, and the steady-state has been reached (Regan 1972a).
3.2. Steady-state visually evoked potential.

The steady-state response results from a repetition rate above approximately 5 Hz, where the individual responses overlap and merge. Responses alternate at the stimulus frequency or its harmonics, and are small in magnitude when compared to the background EEG. Because of the small amplitude of the SSVEP, some form of signal processing is necessary to enhance the signal to noise. One such method is analogous to averaging of the transient response (van der Tweel & Lunel 1965). Simple averaging improves the signal to noise ratio enabling the response to the stimulus to be preserved at the expense of the non-correlated background EEG. Such improvement in signal to noise ratio increases as the square root of the number of averages (McGillem & Aunon, 1987, pp. 143–145).

To illustrate this averaging technique, I recorded two hundred epochs of data from location OZ (with respect to linked earlobes) in one subject who was watching a 13 Hz diffuse visual stimulus with sinusoidally varying luminance.†

† This is not a true sinusoid as luminance has only positive values. It may also be described as a sinusoid around a mean level of luminance (Regan 1972a, p. 48.).
Figure 3.2 **Average steady-state response.**
The upper panel illustrates the sinusoidal stimulus, while the lower panel shows the average of 200 recorded responses from location OZ.

The computer averaged the epochs with respect to a fixed point in the stimulus waveform. The resultant Figure 3.2 illustrates the sinusoidal nature of the averaged response at the stimulus frequency. This recording also shows other components besides the fundamental frequency, probably some second harmonic, previously reported by several studies, including Regan (1972a), and Donker (1975). The linear response, at the frequency of stimulation, results predominantly from the X- & W-cells, and the non-linear responses, with harmonics, result from the Y-cell (Shapley & Perry 1986; Regan 1989).

The average waveform may be approximately sinusoidal, in which case measurement of the amplitude and phase (with respect to the stimulus) quantifies the response. Alternatively, the Fourier technique provides amplitude and phase measurements for the fundamental and harmonic components, making interpretation straightforward.
Further detailed discussion of the Fourier techniques takes place in Chapter 4.

Although the steady-state responses measure small changes about a mean level, transient effects are still present when the stimulus initially appears, and allowing a period of time (up to about 20 seconds) ensures that these turn-on effects disappear along with adaptation effects (Ho & Berkley 1988).

### 3.2.1. Stimulus frequency.

The amplitude of the SSVEP varies in a complex manner with the frequency of stimulation. The amplitude response has several peaks, over the frequency range 3–60 Hz, with three regions of interest: low frequency: 6–12 Hz; medium frequency: 15–25 Hz; and high frequency: 30–60 Hz (Regan 1972a; Spekreijse et al. 1977; Silberstein & Puce 1985). These three regions, often referred to as subsystems, possess different properties relating to apparent latency, linearity, colour response, pathways, and topology (Regan 1972a, 1989; Spekreijse et al 1977), and are illustrated in Figure 3.3.

![Steady-state response versus frequency](image)

**Figure 3.3** Steady-state response versus frequency. The three frequency regions are shown in this diagram. They are centred around 10 Hz—low frequency, 19 Hz—medium frequency, and 45 Hz—high frequency. [Also included is the frequency response to small checks—approximately 15 minutes of arc.] Reproduced from Regan 1975.
Associated with the amplitude versus frequency response, is the phase versus frequency response—not illustrated in Figure 3.3. Phase lag increases with frequency in three distinct regions, which correspond to the low, medium and high frequency regions of the amplitude versus frequency plot (Regan 1989). These distinct regions have different phase gradients, and hence different delays or apparent latencies. Apparent latency can be estimated by taking several measurements over the frequency range of interest to obtain the phase gradient. A faster method uses simultaneous stimulation with several different frequencies to estimate the apparent latency, with the added advantage of lowered susceptibility to noise (Regan 1976). The three frequency regions exhibit separate phase gradients corresponding to separate latencies: 120–220 ms (low frequency region); 100–120 ms (medium frequency region); and 48–62 ms (high frequency region). The evidence from psychophysical studies also indicates that three separate frequency regions exist (Mandler & Makous 1984; Hess & Plant 1985). These regions do not have exactly the same frequency bounds as the evoked responses, but point toward the existence of separate flicker channels (Plant & Hess 1987; Regan 1989).

3.2.1.1. High frequency subsystem.

The high frequency subsystem is also referred to as the short latency subsystem. It consists of responses occurring between 30 and 60 Hz, with apparent latencies of 48 to 62 ms, is also referred to as the short latency subsystem (Regan 1972a; Spekreijse et al. 1977). The responses can be generated by a stimulus at the same frequency (fundamental response), or a stimulus at half the frequency (second harmonic response). Both these responses possess similar properties (Regan 1989). The latency of the response is largely unaffected by luminance: For a one thousand-fold

† In a system with a fixed time delay, phase ($\phi$) increases linearly with frequency ($f$). The gradient of the phase-frequency plot is therefore proportional to time delay or apparent latency: $L = \frac{-1}{2\pi} \frac{\partial \phi}{\partial f}$. 

\[ L = \frac{-1}{2\pi} \frac{\partial \phi}{\partial f} \]
increase in luminance, the latency decreased by about 15 ms (Spekreijse et al. 1977). The projections to the cortex are fairly diffuse, and responses are recorded most strongly over the occipital, and visual association areas (Spekreijse et al. 1977; Regan 1989). The response is unaffected by the colour of the stimulus (Spekreijse et al. 1977; Regan 1989), and the demyelination caused by multiple sclerosis does alter this response (Regan 1968; Milner et al. 1974). The size of the stimulus is important with a larger response occurring for 60 degree compared to 15 degree stimulus field (Regan 1968). When stimulating within the frequency range 30–60 Hz, the response shows non-linear behaviour, with both responses at the stimulus frequency and at its second harmonic (van der Tweel & Lunel 1965). Taking stock of this sketch of the high frequency subsystem would lead to the conclusion that the most probable projection is from the magnocellular region of the LGN, as it provides a good match to these properties (Regan 1989).

3.2.1.2. Medium frequency subsystem.

The medium frequency subsystem consists of responses occurring between 12 Hz and 25 Hz, with apparent latencies of 100 to 140 ms, and is also named the intermediate latency subsystem (Spekreijse et al. 1977; Regan 1989). The responses can be generated by a stimulus of the same frequency—fundamental response, or a stimulus at half the frequency—second harmonic response (Regan 1989). Both the fundamental and second harmonic responses are affected by multiple sclerosis, which delays the information, or increases the phase gradient (Milner et al. 1974), and lesions of the occipital cortex reduce or remove the response (Regan 1979). The response is recorded most strongly over the midline (Regan 1968), and predominantly to contralateral areas 18 and 19, (Spekreijse et al. 1977). The response is colour sensitive—different phase shifts occur for different colours (Regan 1989), chromatic adaptation occurs: red flicker on a red background has a similar response to white light, but red flicker on a blue background has almost no response (Milner et al. 1974; Regan 1989). The effects of colour on the response depend upon whether the
response is the fundamental or second harmonic response. For example, a steady yellow adapting light enhances the 16 Hz response to 16 Hz flicker, that is the fundamental response. It reduces the 16 Hz response to 8 Hz flicker, that is the second harmonic response (Regan 1989). When stimulating within the frequency range 12–25 Hz, the resultant response is very linear, with responses at twice the stimulus frequency being less than about 13% (Spekreijse et al. 1977). Given these data on the medium frequency subsystem, the best match is provided by projections from the parvocellular region of the LGN (Regan 1989).

3.2.1.3. Low frequency subsystem.

The low frequency subsystem consists of responses in the 5–10 Hz range, with latencies 120–220 ms, and is referred to as long latency subsystem (Spekreijse et al. 1977; Regan 1989). The responses are diffuse and can be recorded over a wide region of the scalp (Spekreijse et al. 1977; Regan 1989). The responses to stimulation in this frequency range usually have considerable harmonic content, and second harmonic may be greater than fundamental response (van der Tweel & Lunel 1965). The response can be preserved with occipital damage and partial cortical blindness (Regan 1989; Regan 1979; Milner et al. 1972; Regan 1979), but is reported reduced or lost in patients with more anterior lesions (Milner et al. 1972; Regan 1972b; Regan 1979). Little is known of the cell types involved in the low frequency subsystem (Regan 1989).

3.2.1.4. Summary of unstructured stimuli.

The three frequency subsystems possess different properties regarding their sensitivity to colour, luminance, and pathways. The high frequency system is aligned with the Magnocellular cells of the LGN, while the medium frequency subsystem is aligned with the P cells of the LGN, and the low frequency subsystem does not possess properties unique to either of these system, and may even be related to the system involved with the superior colliculus (Regan 1972a; Spekreijse et al. 1977).
3.2.2. Structured stimuli.

The type of stimulus used elicits a distinctive response. A comparison of the amplitude versus frequency response of small checks, large checks and diffuse flicker for a similar sized stimulus field, showed that small check response peaked at around 6–7 Hz, while the blank field peaked at around 10 Hz. The response to small checks as a function of frequency is illustrated in Figure 3.3. The large checks showed an intermediate nature, giving a response both at 3–7 Hz and 10 Hz (Regan 1989 pp. 398–399), supporting the concept that evoked potentials to large checks are a mixture of pattern-specific, or X-cell response, and flicker potentials, or Y-cell response. Structured stimuli, smaller in size, provide a method of selectively activating the X-cells and associated pathways. The structured stimuli commonly used are checkerboards and sinusoidal gratings. The responses to spatial sinusoidal gratings are similar, but not identical, to those seen with checkerboards. One significant difference between the responses to the grating and the checkerboard is the degraded check evoked response to a partially defocussed display, as illustrated in Figure 3.4.

Response degradation occurs because the checkerboard distorts considerably when defocussed, whereas the grating shows little distortion (Bodis-Wollner et al. 1986, p. 25.).

![Figure 3.4](image-url)
25.). This is particularly important with subjects requiring corrective lenses†. An explanation of the changes seen in the evoked potentials with blurred or defocussed gratings or checks involves considering the spatial frequency composition for checkerboards and gratings. A sinusoidal grating has a single spatial frequency, described by the number of cycles per centimetre or the number of cycles per degree; whereas a checkerboard contains the fundamental as well as higher spatial frequencies due to its two-dimensional spatial square-wave structure, as it contains odd harmonics in addition to the fundamental spatial frequency. The high frequency components are more influenced by blurring, the equivalent to low pass spatial filtering, and hence the checkerboard is more affected by blurring than the grating, as seen in Figure 3.4.

Despite this shortcoming of the checkerboard, it remains the most commonly used structured stimulus in clinical practice, and has been more widely studied than the grating response (Regan 1989, Halliday 1982).

3.2.3. Size of structured stimulus.

When using a checkerboard as the pattern for the stimulus, the amplitude of the VEP varies with check size. The amplitude of the steady-state evoked response as a function of check size follows the shape of an inverted ‘U’, with a maximum at approximately 11–18 minutes of arc (Regan 1972a). Rebai et al. (1989) found that for a sinusoidal grating stimulus, the maximum amplitude occurred for a spatial frequency of 2–6 cycles per degree. Similar results emerge for the responses evoked from transient stimuli: 12 minutes of arc for checkerboard evoked P100, and 6 cycles per degree for grating evoked response (Regan 1972a, 1989). Transient evoked responses show an increased latency with higher spatial frequencies, consistent with X-cell involvement and slower conduction velocity. This element of spatial tuning contributes to the amplitude and latency of evoked responses. The spatial frequency

† Regan exploited this degradation of the evoked response to measure the required correction in refractive power (including axis of astigmatism) in individuals, and reported on this in 1968, and 1973.
of the grating at 5 cycles per degree corresponds with a check width of approximately 6 minutes of arc, demonstrating a different spatial tuning for the checkerboard and grating stimuli. This finding indicates a difference in the responses for the low and high spatial frequency pathways.

3.2.4. Retinal location and size.

Studies of small stimuli in different positions along the horizontal and vertical axes of the eye show that as the stimulus is moved away from the fovea, the amplitude of the evoked response reduces (Perry & Childers 1969), and is illustrated in Figure 3.5.

The stimulus was a 2.5 degree white spot presented at 3.8 Hz, which would probably preferentially activate the X-cell population, and the reduction in amplitude is accounted for by fewer X-cells in the peripheral retina (Regan 1972a). The amplitude of the VEP as a function of the size of the stimulus within the visual field, indicated a maximum value at 2.5 degrees for pattern-onset stimuli, and a maximum of 3.5 degrees for pattern-reversal stimuli (Regan 1972a; Kurita-Tashima et al. 1991). These findings have implications for the size of the stimulus—if the stimulus covers an area of the visual field greater than four degrees, there will be little effect on the size of the evoked response as a function of field size. As the stimulus proposed to be used in the subsequent studies covers the whole visual field, there should be no effect on the size of the response caused by this parameter.
3.2.5. Monocular and binocular stimulation.

The responses discussed in the previous sections have been binocular responses. Full field monocular stimulation yields similar responses to binocular stimulation (Perry & Childers 1969), particularly with stimuli that presented to the foveal region (X-cells). With the X-cell afferents, only the nasal, or medial, portion of the fibres crosses at the optic chiasm, while the temporal fibres remain ipsilateral, and a complete image from the fovea of the structured stimulus is presented to both hemispheres.

The responses to non-foveal stimuli predicted by the cortical projections yield the largest amplitude in the contralateral occipital cortex. The actual responses for transient stimuli are larger in the ipsilateral cortex! Barrett et al. (1976) explain this paradoxical lateralisation with the known infolding of the occipital poles in the central sulcus, and assuming that the cortical generators are dipoles, and perpendicular to the surface of the cortex (Nunez 1981). The contralateral projection area is facing the ipsilateral region, as illustrated in Figure 3.6, and this explanation is consistent with the cortical projections (Barrett et al. 1976; Blumhardt & Halliday 1979). The geniculostriate, predominantly X-cell, visual system decussates, while the mesencephalic system, devoid of X-cells, has little decussation, supporting the concept that structured evoked potentials are the domain of the X-cells, and in particular those of the geniculate pathway (Rafal et al. 1991).
Figure 3.6 The paradox.
This diagram offers an explanation of the paradoxical relationship between visual evoked potentials and hemifield stimuli. As area 17 exists on the infolding of the occipital poles, the evoked potential is larger on the scalp ipsilateral to the hemifield containing the stimulus. In this example, the left occipital area 17 faces toward the right occipital scalp (From Regan 1989 p. 405.)

Victor et al. (1991) recorded VEPs in a similar fashion, using a bipolar montage of horizontal electrodes spaced 2.5 cm apart at the level of OZ (L_{10–L7.5}, L_{7.5–L5} ... R_{7.5–R10}), and showed that the largest potentials appeared on the contralateral side to stimulation. This inconsistency with Barrett et al.'s results could be due to different check sizes, different overall stimulus size, or a higher frequency of stimulation (8.45 Hz c.f. 2 Hz); however, the rationale for Victor's group making a judgement using the bipolar data without examining the monopolar data remains questionable.

Barrett et al. (1976), who used monopolar recording techniques, and subsequently derived the bipolar data, stated: “The bipolar recording shows a comparatively flat response on the ipsilateral side, not because there is little or no activity, but because there is equally high amplitude activity at all electrodes on this side of the scalp.”. The size of the checks used in these separate experiments could have had an effect, as the X- & Y-cell systems project to different occipital areas, but Victor et al. (1991) did not directly compare the size of their checks and those used by Barrett's group, so this explanation remains hypothetical.
Skrandies (1993) found different topographic patterns for monocular and binocular stimuli, and also examined the differences for stereoscopic stimuli and found different distributions of responses on the scalp, indicating different generators (Skrandies 1991). Klemm et al. (1980), with a patterned steady-state stimulus, found a lateralised response to monocular presentation for frequencies of 6 and 11 Hz, but saw no lateralised response for a frequency of 16 Hz. These findings concord with the contributions of the X-cells, with more lateralised projections, at lower frequencies, when compared to the Y-cell contribution at higher frequencies.

Binocular, full-field stimulation will remove any of the problems of stimulating only one visual field, and the lateralisation effects should not pose problems for interpretation of the evoked response amplitudes.

### 3.2.6. Effects of luminance and contrast.

The luminance of an object is defined as the luminous intensity, sometimes referred to as brightness, and is measured in SI units of candela per metre squared (cd.m\(^{-2}\)) (Regan 1989, pp. 134–138). The evoked response amplitude increases with an increase in luminance of the stimulus, while the latency of the transient response decreases with increasing luminance (Perry & Childers 1969; Regan 1972a). This effect is more noticeable for relative luminance, with respect to the surround, than absolute luminance; Perry & Childers (1969) report that the logarithm of the ratio of stimulus to surround is proportional to the amplitude of the response. A ratio measure, such as the contrast of the luminance, is therefore more likely to be a useful measure.\(^\dagger\) Several studies have shown that as the stimulus contrast increases from zero, the evoked response amplitude increases, but may become constant, or saturate, at a high contrast level (Regan 1972a; Regan 1989; Celesia 1991).

\[^\dagger\] Spatial (Michaelson) Contrast is defined as the ratio of difference between two luminances divided by the sum of two luminances. i.e. \( \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}} \) Regan 1989 p. 364.
occurs at a contrast of somewhere between 20% and 60%, depending upon the type of stimulus, and the size of the checks or grating and the stimulus reversal rate (Regan 1989). Spinelli & Mecacci (1990) demonstrated that evoked responses to contrast in the occipital region were symmetric in the two hemispheres. There was, however, an asymmetry in the temporal region—the left hemisphere showed the typical response, while in the right hemisphere a flat response to contrast was found. Their interpretation of the results relied upon the different sensitivity responses of the X-cell and Y-cell populations. The X-cells show less sensitivity to contrast than the Y-cells, and their projection is postulated to be greater to the right hemisphere; causing the lateralised response (Spinelli & Mecacci 1990).

3.2.7. Modulation depth.

In addition to the contrast and frequency of stimulation, another important factor in the amplitude of the evoked response is the overall luminance changes of the stimulus with respect to time. The term modulation depth, a temporal analogue to spatial contrast, is the ratio of the mean-to-peak amplitude to the mean level of stimulus intensity, often quoted as a percentage, indicated as \( \frac{a}{b} \) in Figure 3.7. The maximum modulation depth cannot exceed 100%.

![Figure 3.7 Modulation depth.](image)

The modulation depth is the fraction \( \frac{a}{b} \) expressed as a percentage.

Modulation depth is independent of contrast, and it is possible to have different contrast and modulation depths simultaneously (Regan 1972a, p. 48.) For a diffuse, flickering stimulus, varying sinusoidally, there is no contrast, but a modulation depth due to the changing luminance of the field. The amplitude of the evoked potential
varies as a function of the modulation depth as plotted in Figure 3.8. The evoked potential amplitude increases as a function of modulation depth, but saturates, or reaches a plateau before modulation depth reaches 100%.

Figure 3.8 Saturation of the SSVEP.  
When the modulation depth is increased, the amplitude of the SSVEP increases linearly to about 30%, then plateaus or saturates. (Modified from Regan 1972a p. 51.)

The saturation phenomenon depends upon stimulus frequency, and also colour, but not stimulus size, and occurs at the same modulation depth for one or two eyes (Regan 1989). To allow for the effects of response saturation, the modulation depth should exceed 30% ensuring that the plateau region of the curve has been reached, as illustrated in Figure 3.8. This is important for comparing evoked responses from individuals. If the plateau region has not been reached, then any changes in evoked potential amplitude may be due to modulation depth factors, rather than differences in other experimental variables.

3.2.8. Cognitive stimuli.

Studies of the effects of cognition upon evoked potentials, particularly with transient, visual stimuli, have been reviewed by Hillyard et al. (1978) & Hillyard (1985). Two separate examples, show that: counting flashes of light in one spatial location enhances the evoked potential at that location (Hillyard & Münte 1984); and when subjects attend and respond to words with similar meaning to target words changes in evoked potential amplitudes occur (Rugg 1985).

By contrast, studies on attention and the steady-state evoked potential, have been sparse. Linden et al. (1987), using steady-state auditory stimulation and recording
from the vertex, failed to find any change in the amplitude or latency of the steady-state response when attention was altered. Their experiment was performed by the subject either counting tones, or reading a book; conditions referred to as attend and ignore respectively. The magnitude and phase were extracted using a Fourier analyser. These were averaged over the period of time for which the stimulus was present. Each pair of magnitude and phase values were then averaged at each intensity level, and further averaged across eight subjects to produce a grand mean, from which magnitude and phase versus intensity plots were derived. The amplitude and phase versus intensity level were plotted for the attend and ignore conditions, and showed little difference from each other. This lack of correlation between features of the steady-state evoked response and cognition was earlier reported by Regan (1968) for the visual modality.

Wilson & O'Donnell (1986) examined the steady-state response to a visual memory scanning task (Sternberg paradigm)—here the subject compared a series of presented items with one, four or eight previously remembered items, and responded by pressing a yes or no button. With the memory scanning task, a linear relationship exists between the number of memory items and the reaction time (Sternberg 1969). A graph of reaction time versus number of items has two distinguishing features: an intercept, related to processing time or the sensory motor portion of the task, and a slope, related to the cognitive aspects of the task (Sternberg 1969). Wilson & O'Donnell used two sets of stimulation frequencies in separate recordings: medium 15–23 Hz, and high 40–59 Hz. Using a Fourier analyser, they extracted the phase information, and computed the apparent latency (as described in section 3.2.1) for all eleven subjects. Their results showed differences between the medium and high frequency responses. For medium frequency stimulation, the slope of the graph of reaction time versus memory set, correlated with apparent latency of the steady-state response. For high frequency stimulation, the intercept of the graph of reaction time versus memory set, correlated with the apparent latency of the steady-state response. Wilson & O'Donnell concluded that different visual pathways, of long and short
latencies, carried different information—the medium frequency pathway was related to
cognitive factors, while the high frequency pathway was related to physical aspects of
visual processing. Neither the SSVEP latencies for medium or high frequency
stimulation showed a relationship to mental workload (Wilson & O'Donnell 1988).

Regan (1989 pp. 41–42) suggested that long trains of monotonous, boring stimuli
would make it difficult to manipulate cognitive state. He suggests that a running
average should capture short events that cannot be seen with averaged transient
responses. Galambos & Makeig (1988) used a 40 Hz stimulus and examined changes
in the running average of the auditory steady-state evoked potential. They recorded
the auditory steady-state response while a subject listened to Beethoven's 3rd
symphony. The music was presented to one ear, and the steady-state probe to the
other. Their results demonstrated a sustained reduction in the amplitude of the probe
stimulus, when the subject attended to the music. This finding is illustrated in Figure
3.9.

![Figure 3.9](image)

**Figure 3.9** Auditory steady-state probe response.
This is reproduced from Galambos & Makeig (1988), and shows the reduction in probe amplitude
when attending to music.

One of the potential mechanisms for this reduction seen in the amplitude of the steady-
state response is auditory masking. Auditory masking occurs when the threshold of
one tone—test tone—rises in the presence of a second tone—masking tone
(Schiffman 1982), but auditory masking only affects test tones of higher frequencies.
In Galambos & Makeig’s experiment, the 500 Hz tone bursts, and also described as
probes, are analogous to the test tone, while the music is analogous to the masking
tone. To remove the possibility of the reduction in amplitude occurring due to masking, Galambos & Makeig extended their experiment to check for any change in the threshold of the probe stimulus, by replacing the music with narrow band noise at the same frequency as the probe tone, both set at 1 kHz, and when both stimuli were presented to the same ear, found no increase in probe threshold when the loudness of the noise was between 5 dB and 40 dB, with the noise at 45 dB, the probe was not heard. This masking experiment was repeated with contralateral ear presentation of the noise, to make it comparable to the Beethoven condition, and they reported that no masking of the probe occurred with noise levels up to 75 dB.

Rohrbaugh et al. (1990) demonstrated similar reductions in the amplitude of the 40 Hz auditory steady-state response with both visual and auditory foreground stimuli. Tones were delivered binaurally to subjects who had to determine whether each tone was a standard or a distracter. About 25 per cent of presented tones were standards; while 50 per cent were distinctly different, 200 Hz from standard, and the remaining 25 per cent were similar to standard, 20 Hz from the standard forming a distraction, and referred to as a distracter. In addition to the amplitude changes, they also found decreases in latency of the tone-pip peaks, or the phase of response during both these recordings, and the latency decreased more when the discrimination was more difficult. Similar findings were noted in the amplitude of the auditory steady-state response for a visual foreground task—the more difficult the task, the greater the changes. The visual task used circles as the standards, and ellipses, either grossly or slightly flattened circles, as the distracters.

On the basis of these studies, changes in steady-state responses result from changes in 
cognitive levels or attention—although not all studies demonstrated these changes. 
The reasons why some studies failed to show any changes could be related to the type of task, or related to the analysis of the steady-state response.

The failure of Linden et al. (1987) to show changes is most probably due to the 
averaging of the steady-state responses, as transient evoked responses, recorded 
simultaneously, showed changes with attention. Linden's group's may have removed
any dynamic changes by averaging responses for the total recording time. Galambos & Makeig (1988), without averaging, saw with dynamic changes in their Beethoven experiment.

Other factors can also influence the steady-state response. Galambos & Makeig (1988) found that the steady-state response had spontaneous variation, which they termed *minute rhythms*, and changes related to sleep and wakefulness, in addition to the stimulus-linked variability. The variations associated with the stimulus provides a link to the probe event-related potential work discussed next.

3.3. **Probe evoked potentials.**

Where pairs of stimuli are separated by an interval less than ten seconds, reductions in the amplitude of the evoked potential to the second stimulus occur when compared to the first (Callaway 1973). Roemer et al. (1984) argued that a recovery cycle resulting from a refractory period, caused the 30–80% decrement in evoked potential amplitude. If the stimulus used to evoke the potential bore a relationship to the task, a smaller decrement resulted (Callaway 1973); indicating that amplitude of evoked potentials is sensitive to cognitive factors.

Shucard et al. (1977) used these findings in an experiment with subjects performing different tasks—one musical, one other verbal, and one control—while pairs of irrelevant tone pips (600 Hz, 100 ms, separated by 6 seconds) were presented. The tasks consisted of subjects finding specific words in the verbal task, specific melodies in the musical task, or clicks in white noise for the control task. Bipolar recordings were made from T₄-C₂ the right hemisphere (RH), and T₃-C₂ the left hemisphere (LH), and the resultant evoked potential amplitude are listed.

- **verbal:** LH>RH, tone 2 < tone 1 for RH
- **music:** LH<RH, tone 2 < tone 1 for LH
- **control:** LH≈RH, tone 2 < tone 1 for LH, RH
The major drawback with this experiment involved the use of bipolar recordings. Shucard et al. (1977) argued that higher bipolar amplitudes for verbal stimuli in the left hemisphere indicated unipolar $T_3$ amplitude is less than $T_4$ amplitude, and similarly higher bipolar amplitudes in the right hemisphere: $T_4$ smaller than $T_3$ for musical stimuli, but this interpretation is based upon the assumption that the potential at $C_Z$ remains constant. Shucard et al. (1977) argued that the tone evoked potentials were a probe of available neurons, or resources, because the findings were consistent with the premise of right hemisphere processing music, and the left processing verbal information. The probe evoked potential decreased when the region of the brain was engaged in the processing task. These results concord with Callaway’s (1973) finding of reduced evoked potential amplitude to the second of two tones, across the whole brain.

This study of Shucard et al. (1977) illustrated some important points regarding the use of evoked potentials as a probe of available neurons or resources, and Papanicolaou (1980) compared the effectiveness of probe-evoked potentials with ordinary evoked potentials for investigating cognitive function.

### 3.3.1. Probe-ERP.

Several problems exist with ordinary evoked potentials including the need to repeat the stimulus and average the response. Although this improves the signal to noise ratio, it also produces habituation (Callaway 1973). The subject needs to repeat the same stimulus—forcing the subject to perform the same set of operations repeatedly; a highly artificial situation, unlike normal processing of language, for example (Papanicolaou 1980). With these types of experiments, many variables are controlled, and only one varied, creating an artificial situation, lacking in “ecological validity” (Papanicolaou & Johnstone 1984). Evoked potentials contain both exogenous, relating to the physical stimulus, and endogenous, relating to higher order perceptual processing components. Separation of these two components is difficult when using standard EP techniques, as the stimulus contains both cognitive and physical values,
and requires elaborate preparation of the stimulus to give it the required cognitive or perceptual value (Papanicolaou and Johnstone 1984).

Papanicolaou developed a system for recording probe evoked potentials that circumvented these problems, and referred to it as the *photic probe paradigm* (Papanicolaou 1980), or *Probe-ERP paradigm* (Papanicolaou & Johnstone 1984).

Several important assumptions are made in interpreting the probe paradigm.

1. The stimulus causes a neuroelectric disturbance in the brain tissue. The magnitude of this disturbance is related to the physical parameters of the stimulus, and current state of the tissue—including ongoing information processes, and basic automatic processes, that influence the state of the tissue.

2. Brain regions can act independently, or together in a co-ordinated fashion.

3. The relative contribution of the regions depends upon the subject's intent as prescribed by the nature of the tasks.

4. Cognitive operations can be controlled by instruction in co-operative subjects.

5. When a region is involved in processing a cognitive task, the evoked response to an environmental signal, irrelevant to the cognitive task, will be smaller than if this region is not processing the cognitive task. That is, the efficiency of processing the additional task-irrelevant signal varies inversely with the computational demands of the task.

(Papanicolaou 1980; Papanicolaou & Johnstone 1984).

The simplified model, shown in Figure 3.10, illustrates a system comprising three compartments, that together yield the total available processing capacity.† The three compartments shown are labelled as spare, task, and overheads. Overheads refer to capacity used by basic neural processing, carried on regardless of any other task or activity being processed. Task refers to the cognitive or other activity being undertaken by the subject. How much of the overall capacity the task requires, depends upon such factors as signal to noise ratio, size of stimulus set, or its load (Navon & Gopher 1980). Spare refers to the balance of available capacity not involved in any task, and hence available for use by the probe.

† The overall capacity is dictated by factors such as alertness, arousal, and feedback of performance. See Chapter 2 of this thesis, and refer to Kahneman (1973).
To test these proposals, Papanicolaou (1980) designed an experiment where different cognitive tasks were carried out by subjects. These tasks included finding words belonging to the same semantic category, the semantic task, tokens of stop-consonants, the phonetic task, and items differing in pitch, the acoustic task. They found that these tasks showed different distributions of the visually evoked probe, supporting their hypothesis, that these tasks which involved different types of processing, should be processed in different regions of the brain. Further support for the reduction in potentials comes from observations: where the amplitude of the event-related potential was reduced when subjects were involved in some other experimental task with an auditory probe using tone pips (Papanicolaou et al. 1985), or a visual probe using transient flashes (Papanicolaou et al. 1987).

Robinson & Sabat (1975) investigated the processes occurring during auditory shadowing, where words were presented to the left or right ear, and subjects repeated these words aloud. They recorded from locations C3 and C4, that is, left and right hemispheres respectively. Their shadowing task was difficult, and subjects achieved only a 60–75% success rate. The results showed that an evoked response to irrelevant auditory stimuli, delivered to the opposite ear to the words, showed a complete reduction in amplitude, regardless of ear of presentation, or hemisphere of recording. They also recorded during a listening, a speaking, and a control task and found no differences in evoked potential amplitude among these three conditions. The hemispheric comparisons were not rigorously studied—and in the easier task,
hemispheric differences can actually be seen in the traces. Robinson & Sabat (1975) explained these results by a mechanism of pre-cortical filtering. They could also be explained by a model of two separate hemispheres, where the hemisphere contralateral to the ear of presentation processes the shadowing task, and if the task demands exceed its capacity, recruits the other hemisphere. For a difficult task, both hemispheres show a reduction in the probe activity.

Papanicolaou et al. (1985) in a separate study, found a difference for hemispheres during shadowing. Their experiment examined the effect of a shadowing task on amplitude of auditory N1 and P2 evoked potentials, and found that there was a right ear attenuation for a probe evoked potential during the shadowing task, compared to a control task. As both ears showed different responses to the probe stimulus, this indicated that pre-cortical filtering was not the mechanism of attenuation, as subcortical filtering should not favour one ear over the other. The preferred explanation was that of resource allocation, as in Figure 3.10. Papanicolaou group's (1985) interpretation is not the only possible explanation of this phenomenon; an alternative explanation is that the two ears possess independent pre-cortical filtering. This proposal is feasible with the known structure of two thalami, and two nuclei reticularis, capable of independent operation (Yingling & Skinner 1977).

To further explain the mechanism of the probe attenuation, Johnstone et al. (1984) studied a group of 12-year old boys with two experiments. The first involved irrelevant flashes while subjects were reading silently, while the second used irrelevant tone-pips while the subjects were listening to text. The visual N100 was reduced in the reading task, while the auditory P100 was reduced during the listening task. They concluded that the limited capacity model explained the results, as the pre-cortical filtering was deficient. The results, however, are consistent with a model of pre-cortical filtering that allows for separate filtering of auditory and visual channels, Yingling & Skinner (1977) demonstrate that such filtering can, and does take place at the level of the thalamus.
3.3.2. Probe-ERP and blood flow.

Studies of regional cerebral blood flow and cognitive tasks have indicated a relationship between right hemisphere increases in blood flow during attention demanding tasks, particularly in the frontal regions for tasks such as: mental rotation and line-orientation tasks (Papanicolaou et al. 1987, Deutsch et al. 1988). Papanicolaou et al. (1987) examined the relationship between Probe-ERP amplitude and rCBF for visual probes with a mental rotation task, and found that a strong negative correlation existed between these measurements. This supports the processing capacity model.

To demonstrate the practical applications of the Probe-ERP technique, studies have included an investigation of reading disorders in children (Papanicolaou & Johnstone 1984), and a preliminary study of recovery from aphasia in brain-injured individuals (Papanicolaou et al. 1985). The results of these studies show changes in the Probe-ERP measure, correlated with the functional differences. As a separate verification of the validity of the Probe-ERP technique, simultaneous measurement of regional cerebral blood flow (rCBF) and Probe-ERP was made in a study examining the response when subjects rotated shapes in a visual-spatial task (Papanicolaou et al. 1987). This study showed a strong negative correlation of rCBF with Probe-ERP (particularly in the right parietal region); and supported the model of low probe voltage correlating with high activation, as indicated by the increased rCBF.

When this technique is coupled with a transient stimulus, for example, the probe is a flash of light or a tone pip, the inherent properties of this stimulus determine the properties of the expected response. The transient response is usually averaged to form a composite evoked response. A period of up to 1000 ms has a resolution of fractions of a millisecond, and provides little information about cognitive processes that occur over longer time periods. The process of averaging confines the resolution to stationary signals, and loses the dynamics of longer processes. The steady-state evoked potential, on the other hand, when used as a running average (Regan 1989), clearly provides information about processes that take place over a period of minutes.
as illustrated in Figure 3.9—when listening to Beethoven's 3rd symphony (Galambos & Makeig 1988).

3.4. Summary of the steady-state probe evoked potential.

The steady-state evoked potential possesses properties that make it suitable for the study of processes occurring over a period of seconds or minutes (Galambos & Makeig 1988; Makeig & Galambos 1989), with quick computation and an integration time of about ten seconds (Regan 1972a).

The recorded sensitivity of the Probe-ERP to cognitive factors (for example Papanicolaou & Johnstone 1984), coupled with the properties of the visual response to steady-state stimuli make the visual steady-state probe evoked potential ideally suited to the study of cognitive factors.

A wide variety of stimulus parameters affect the VEP, including those which need careful control, such as modulation depth, and size of visual stimulus. Other parameters depend upon the visual pathway, and these include colour, structure and fine detail, and project to different parts of the visual cortex. The most promising pathway for the study of attentional effects is the steady-state unstructured, or flicker stimulus, as this activates the Y-cells, some of which travel via the mesencephalic system to the areas of the cortex implicated in the mediation of spatial selective attention, such as the parietal region (Lynch et al. 1977; Posner & Rafal 1985).

The stimulus proposed for use in the subsequent experiments possesses the following qualities:

- binocular flicker, to remove problems of stimulating only one visual field (Barrett et al. 1976);
- a modulation depth of 30% or greater, with size at least four degrees of the visual field, to minimise SSVEP amplitude variations due to physical stimulus parameters (Regan 1972a);
- the stimulus switched on for a period of about twenty seconds to minimise turn-on effects (Ho & Berkley 1988);
- stimulus frequency within the medium frequency subsystem, to provide a linear response without large amounts of second harmonic generated (Spekreijse et al. 1977).
The temporal resolution of the steady-state response, combined with the versatility of the Probe-ERP, should allow an insight into the available capacity of cortical regions during the processing of visual attentional information. A preliminary examination of the utility of the visual steady-state Probe-ERP during an attentional task showed sensitivity to visual vigilance (Silberstein et al. 1988; Silberstein et al. 1990; Chapter 5).
4. Practical implementation of the topographic SSVEP.

This section examines the methods used for recording and analysing the SSVEP, particularly those used during development and refinement of the techniques. The sixty-four channel recording equipment and instrumentation are described, including the automated impedance measuring system. After this, the techniques for processing the recorded data are detailed, paying particular attention to the development of the automated artifact checking process. The final sections of the chapter concentrate on the development of the interpolation and topographic display algorithms.

4.1. The sixty-four channel recording system.

The study of the SSVEP begins with the collection of the data—the EEG—and requires electrodes, amplifiers, filters, and computer for data collection. The system for recording, and analysing data was developed and constructed at the Swinburne Centre for Applied Neurosciences (SCAN), due to a lack of suitable systems available to record sixty-four channels simultaneously. This design and construction began in 1986, and was completed in 1990 to the final stage presented in this section. The designing and building of the recording system proceeded in parallel with the development of the Centre for Applied Neurosciences, and considerable effort was expended in reaching the joint goals of reliable, operating equipment, and a functional research centre. The complete system includes helmet and electrodes, pre-amplifiers, amplifiers, filters, Analogue to Digital Converter (ADC), stimulus driver, and computer software for data acquisition, analysis and display. The block diagram in Figure 4.1 shows a schematic illustration of the overall layout of the system hardware for data acquisition, and a description of the system requirements has been presented at a conference in 1988 (Schier et al. 1988).
In data collection mode, the computer controls the main clock, which in turn drives both the sinewave generator (for the stimulus), and the data acquisition. Data recording involves the scalp electrodes, amplifiers, and data are digitised to 12 bit accuracy and stored on the computer. The computer analyses the data at a later stage.

The computer is the hub of this system, and controls all the functions: the presentation of the steady-state stimulus, amplification, filtering, and the data collection. Some specific aspects of the recording system are described in the following sections, including: helmet and electrodes, amplifiers, automated impedance measurement, and stimulus drivers.

### 4.1.1. Helmet and electrodes.

The helmet and electrodes were created to meet a specific need—that of correctly positioning electrodes upon the scalp. The procedure for positioning sixty-four electrodes accurately upon the scalp poses some technical problems: particularly how to minimise the time required to locate and secure electrodes at sixty-four sites, and how to allow for different sized heads. One of the most common methods of attaching EEG recording electrodes is to glue them onto the scalp with collodion after careful preparation of the scalp (American Electroencephalographic Society 1986).

An estimate of the time required to glue 64 electrodes onto the scalp is 60–80 minutes: lengthy for co-operative subjects, but much too long for most patients. To record from patients, possibly with short concentration spans, or an inability to remain
still, the shortest possible preparation time is vital to maximise the useful recording
time and allow the patient to co-operate and attend during the recording.

At SCAN, we addressed the problems of the preparation time and head sizes by using
a helmet to locate and hold electrodes securely on the scalp in the correct positions.
The second problem, that of different head sizes, was addressed by using electrodes
mounted in a radial fashion, and tensioned to adjust to head size. The final solution
consisted of two helmets, one small and one large, to allow easy and accurate
placement of electrodes on heads ranging in circumference from 48 cm to 65 cm. The
helmets are specially built, thermo-plastic shells, drilled to provide anchorage for
electrode locaters. The design and development of the electrode and location system
originated at SCAN; the hollow electrode barrels are manufactured from polystyrene
by injection moulding, with silver wires spot-welded to silver electrode disks, which in
turn are glued to the barrels. A locking device fixes the electrodes to the helmet and
contains a spring loaded mechanism which maintains the electrode in contact with the
scalp. The contact impedance is reduced by injecting conductive paste down the
hollow electrode barrel until it forms a layer between the end of the electrode and the
scalp immediately below. The sixty-four electrodes mounted in the helmet occupy all
the International 10–20 system sites and intermediate sites, as shown in Figure 4.2, to
provide a coverage of the scalp with average electrode spacing of 3.2 cm (Ciorciari et
al. 1987).

![Figure 4.2 Electrode sites.](image)

A schematic view from above the helmet, with the nose at the top, and ears at the left and right of this
diagram. The solid squares represent the 10–20 sites, while the open squares represent the
intermediate sites. The average electrode spacing is 3.2 cm.
An electrical shield, made of conductive mesh and built into the shell of the helmet, is connected to ground to provide improved noise immunity for the recording. The helmet is positioned on the head using the major landmarks—the nasion, inion, and mastoid processes. The actual location of the helmet is quantified by measuring the distance between the central anterior electrode (electrode 2) and the nasion; as well as between the central posterior electrode (electrode 62) and the inion.

The helmet, including electrodes, wiring and conductive paste, weighs about 3 kg when placed upon the head, and is counterbalanced by a weight and pulley system to ease the load upon the neck and shoulders of the subject. A picture of the helmet is shown in Figure 4.3.

![Helmet](image)

**Figure 4.3 Helmet.** This photograph shows the helmet, in position on a subject's head, with 64 recording electrodes (the electrodes are in the raised position).

### 4.1.2. Amplifiers.

To raise the EEG signal to the level required by the computer input device, a two stage amplification system is used, consisting of sixty-four pre-amplifiers and filter amplifiers providing the necessary gain, or amplification for recording purposes. The pre-amplifiers utilise a differential input instrumentation amplifier with a fixed gain of 4000 and common mode rejection ratio greater than 100 dB, while the filter-amplifiers feature adjustable gain to allow for compensation of inter-subject variation in size of the scalp electrical potential. The filters on these amplifiers pass only the frequency band of interest. A programmable active-filter circuit determines the high frequency
cut-off, normally set to 26 Hz, while the low frequency cut-off is preset to 0.5 Hz. The output of the filter-amplifiers connects to the buffered sample-and-hold section, ensuring that simultaneous data collection occurs from sixty-four channels, before digitising by the analogue to digital converter (ADC). The ADC consists of a sixty-four channel plug-in card manufactured by Data Translation Corporation, for the IBM compatible computer. The data acquisition was carried out under software control, using macros written in the DAOS† language. The sampling rate was set to 208 Hz by an external clock, with high cut filters set to 26 Hz to minimise interference and prevent temporal aliasing. The pre-amplifier, filter-amplifier, and sample and hold circuitry were custom designed by David Simpson, and constructed at SCAN.

4.1.3. Automated impedance measurement.

To monitor the contact between electrodes and the scalp, electrical impedance is measured—the lower the impedance, the better the scalp-electrode contact. To determine the impedance of each electrode-scalp interface, a resistive network couples a 40 Hz waveform to the electrode. The 40 Hz waveform is the filtered output of a clock from the ADC card—controlled by software; with each of the 64 channels isolated to prevent cross-talk. The schematic circuit of the input pre-amplifier is shown in the left of Figure 4.4, including the equivalent impedance from the electrode on the scalp.

† DAOS is a trademark of Laboratory Software Associates Pty. Ltd., Melbourne. It is an acronym for Data Analysis Operating System.
Figure 4.4 Voltage divider
The left panel illustrate the voltage division which takes place, the right panel is a simplification, showing that the voltage sampled by the ADC is proportional to the impedance of the electrode (R).

This circuit can be simplified for the purpose of analysis. At 40 Hz, the capacitance 1.5 \( \mu \text{F} \) has an impedance of 2.5 k\( \Omega \). This forms a series impedance with the 1 M\( \Omega \) resistor and reduces to a negligible value, leaving an input impedance of 1 M\( \Omega \). The contribution of the varistor at usual operating voltages (10\(^8\) \( \Omega \) below 3 volts, and 0.1 \( \Omega \) above 3 volts) as a parallel component with the input impedance is neglected. The 100 pF capacitor has an impedance of 4 M\( \Omega \) (at 40 Hz), or an equivalent value for the input impedance of the circuit of 0.8 M\( \Omega \). The circuit has now reduced to a 100 M\( \Omega \) resistor feeding the 0.8 M\( \Omega \) impedance in parallel with the electrode impedance, with a negligible series 10 \( \Omega \). If the electrode impedance is less than 100 k\( \Omega \), then the parallel 0.8 M\( \Omega \) contributes less than one per cent, and vanishes, leaving the equivalent circuit as seen in the right panel of Figure 4.4.

Using data from Geddes, with the electrode impedance modelled as parallel resistance and capacitance terms (Geddes 1972 p. 26); at 13 Hz, the impedance equals 200 \( \Omega \), while at 40 Hz the impedance equals 190 \( \Omega \), showing only a small (5\%) difference between impedances at these frequencies, and vindicating the choice of 40 Hz to
realistically represent the scalp-electrode impedance\textsuperscript{†}. The 40 Hz signal, fed into the 100 \( M\Omega \) scalp electrode, voltage divider network, is sampled at a rate of 200 Hz\textsuperscript{‡} on the high potential side of the electrode, \( V_{\text{out}} \) in the right panel of Figure 4.4, and stored on the computer. For each electrode, the recorded data are Fourier transformed to compute an amplitude spectrum. Several transforms are averaged together to improve noise immunity, and the component corresponding to 40 Hz measured and stored. The procedure for measuring electrode impedances is controlled by computer software and limited to periods when ordinary data acquisition is not taking place. Typically the impedance ranges between 2 k\( \Omega \) and 35 k\( \Omega \) for each electrode, and a table of impedance values is stored for later use. As a visual aid to check electrode impedance, a bar-graph display appears on the computer screen each time the impedance software runs. Those electrodes with values less than 50 k\( \Omega \) are indicated by a blue bar, with the height proportional to resistance, while those above 50 k\( \Omega \), by a red bar. Any electrodes which have a high impedance can be physically examined for adequate pressure against the scalp by the person performing the recording, and moved appropriately to reduce their impedance. The system records accurate and linear values of resistance within the range 1 k\( \Omega \) to 100 k\( \Omega \). The value of 35 k\( \Omega \), considered a large impedance, and is partly due to the small size of the electrode, and partly due to the lack of abrasion in skin preparation (Geddes 1972). This high impedance posed a problem; but was overcome by using high quality amplifiers with common mode rejection ratio more than 100 dB, and a completely shielded recording arrangement, so that the noise immunity was not compromised. Figure 4.5 illustrates the shielding arrangement of the recording system.

\textsuperscript{†} Impedance meters of commercial EEG and topographic mapping machines operate at frequencies of about 20 Hz, but these systems were unavailable at the time of construction of the sixty-four channel system.

\textsuperscript{‡} The filters are set to 80 Hz during this period, and reset to 26 Hz immediately after impedance checking.
4.1.4. **Stimulus drivers.**

To evoke the steady-state response, a sinusoidally flickering stimulus is presented to both eyes. This is achieved with a visual stimulator consisting of a light emitting diode (LED) array, connected to a sine wave generator and a clock (linked to data acquisition). The steady-state sinusoidal stimulus is presented by the LED arrays mounted on half-silvered glasses, to superimpose the flicker on the visual field: so in addition to their normal view, the subject sees the flickering steady-state stimulus. The sine-wave generator sinusoidally modulates the linear brightness of the LED arrays via a high voltage power supply to provide the flicker. The control of the steady-state stimulus is critical; it needs to be stable in amplitude and frequency for adequate extraction of the evoked response. The high quality stimulus generator, LED arrays and power supply were custom designed and built by David Simpson at SCAN.
4.2. Computer software for analysis.

The analysis takes place after the collection and storage of data by the computer, and has several distinct, sequential steps as indicated in Figure 4.6, including: artifact detection, and Fourier analysis. After the Fourier analysis, windowing, interpolation, and topographic display occur.

![Diagram](image)

**Figure 4.6 Software processing steps.**
The data pass through stages to check for artifact, and to extract the Fourier coefficients, before further analysis and topographic mapping. This flowchart illustrates the data processing chain.

During a recording session up to 30 megabytes of data are collected from each subject. Because of the large volume of information, visual examination of all recorded epochs for artifacts would take too much time, so the processing of artifact occurs automatically before further analysis takes place. Artifact detection routines were developed specifically for the steady-state evoked potential system. After this artifact detection, evaluation of the single-frequency Fourier components over a suitable time scale, takes place before the results are displayed. Each of these processes is described in more detail.
4.2.1. First stage of artifact detection.

The scalp electrodes that record EEG and EP signals can also record potentials from other generators, such as the muscles of the face, scalp, and jaw; as well as from the eyes. These contribute to the general level of background activity to be removed by data processing. Trials which are particularly contaminated should be eliminated or compensated for in some way, so that they do not interfere with the results. The trials which contain artifacts are sometimes caused by electrodes making poor contact, or large excessive eye-blinks. With sixty-four spring-loaded electrodes, the possibility of an electrode making poor contact is increased, hence artifact detection plays an important part in analysis. The single cycle Fourier technique, although extremely tolerant of electromyographic activity, eye movements, and 50 Hz mains supply interference, erroneously responds to large artifacts, affecting the resultant SSVEP (Silberstein et al. 1991). The first stage of artifact detection primarily identifies those scalp locations which have excessive overloading of the amplifiers, producing a phenomenon generally known as "clipping." To achieve this end, an examination of the variability of the recorded EEG takes place. Several authors (McEwan & Anderson 1975; Ktonas et al. 1979) have demonstrated that the spontaneous EEG possesses a Gaussian or normal distribution. This feature of the recorded data is used in the following process.

To confirm the Gaussian distribution of the raw EEG signal recorded in this laboratory, in response to the visual flicker, many epochs of data were examined from several individuals—some epochs heavily contaminated with artifact (clipped), and some with minimal or no artifact. These data were processed to form an amplitude histogram; and subsequently Z-transformed (Freund 1972 p. 316) to ensure a mean of zero, and the standard deviation of unity. An illustration of the amplitude histograms for artifact-free and contaminated data appears in Figure 4.7, showing the Gaussian-like shape, and the characteristic peaks respectively.

† Clipping usually results from transient overloading of the amplifier with large signals, such as the EOG.
Figure 4.7 Amplitude histograms. Panel A shows the histogram of acceptable EEG with its Gaussian like distribution; while Panel B shows the histogram of contaminated EEG with the typical shape for a clipped recording.

Amplitude histograms of the recorded EEG, were found to be Gaussian in nature (as in Figure 4.7A), and consistent with the findings of McEwan & Anderson (1975). The shape of the contaminated data (Figure 4.7B) was far from Gaussian, and in an attempt to compare and quantify the divergence from the Gaussian shape two measures were made: the chi-squared goodness-of-fit, or $\chi^2$-GOF (traditionally applied to determine normality; Leaver & Thomas 1974 p. 98); and the correlation coefficient (Freund 1972 p. 380).

Data from ten subjects were visually examined and classified either as acceptable or clipped, then processed by the artifact detection routines. First they were Z-transformed (that is, mean subtracted and divided by standard deviation), then converted to a histogram and compared with an idealised Gaussian function. I found that the $\chi^2$-GOF did not separate the clipped and the acceptable data. For this type of artifact, the $\chi^2$-GOF did not show sufficient sensitivity, and this measurement was not examined further.

The correlation coefficient (equation 4.2.0) showed a clear separation between the acceptable and clipped data.

$$r = \frac{n \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{n \sum_{i=1}^{n} x_i^2 - \left( \sum_{i=1}^{n} x_i \right)^2} \sqrt{n \sum_{i=1}^{n} y_i^2 - \left( \sum_{i=1}^{n} y_i \right)^2}}$$  \hspace{1cm} (4.2.0)

4.2.0 Correlation coefficient.
The separation occurred at a correlation value ($r_1$) of 0.75, (with the contaminated EEG often having $r_1 < 0.4$). The correlation coefficient has been successfully used by one group to examine EEG for artifact during sleep recordings (Hufschmidt & Lücking 1989). They discussed a general method and calculated the correlation between each trial, and all other trials, and determined if the correlation exceeded a critical value, then that trial was uncontaminated with artifact: the actual critical value depended upon the type of recording and the distribution of the correlation histogram.

The artifact detection routine implemented in this work produced Z-transformed frequency histograms which were correlated with a Gaussian function. A decision was made: epochs of data with $r_1 > 0.75$ were accepted, those with $r_1 < 0.4$ were rejected. (Those data with $0.4 < r_1 < 0.6$ were accepted, but noted for the second stage of artifact detection, section 4.2.2).

Not all artifacts cause a distortion, or affect the shape of the amplitude distribution; some contaminants, such as EMG, also possess a Gaussian-like properties. To detect these, a second stage uses other properties of the underlying EEG.

### 4.2.2. Second stage of artifact detection.

Recorded signals, such as band-passed filtered random noise or EMG, have similar properties to EEG. Each signal was scaled to fill the range of the 12-bit ADC, that is, integer values within the range 0–4095. They have separate gains, respectively: spontaneous EEG 75,000; electrode-amplifier noise 90,000; and EMG 5000. The raw data, and their histograms are displayed in Figure 4.8.
Figure 4.8 Band-limited signals. The three signals are EEG filtered 0.5–26 Hz, electrode-amplifier noise filtered 0.5–26 Hz, and EMG filtered 0.5–26 Hz. The scales are for the raw data only, with the horizontal—time, and the vertical—the input range of the 12-bit ADC. The histograms are scaled 0–4095 along the horizontal, and are relative units on the vertical.

This type of interference cannot be removed by comparing the amplitude distribution, but instead is removed by exploitation of the similarity of data from adjacent electrode
sites. When data from neighbouring sites are examined, a similarity can readily be seen with the unaided eye, as seen in Figure 4.9.

![Figure 4.9 Nearest neighbour electrode data.](image)

The 5 plots represented on this graph are for channel 31 and its four nearest neighbours (30, 31, 24 & 40). Note the similarity between the electrodes and its neighbours. The correlation of the upper signal with the average of the four lower traces, yielded a correlation coefficient of 0.83.

Data from ten subjects were examined, including some recorded from electrodes not contacting the scalp. Each time-series was visually inspected to determine whether it appeared similar in shape to the average time-series of its nearest neighbours. The correlation coefficient was calculated between each time-series and the average time-series of its four closest-neighbours, denoted $r_2$. Any electrodes in stage 1 detection which had $r_1 < 0.6$ were not used as neighbours in this stage. There appeared to be a clear separation, with artifact-free data having $r_2 > 0.6$ (and typically above 0.85), and data affected by artifact having $r_2 < 0.6$ (and typically $r_2 < 0.3$). The acceptance point was set at $r_2 > 0.6$.

For each electrode, a table of the nine nearest neighbouring electrodes was computed from the distance between electrodes along the surface of the scalp. From this table, the four nearest neighbouring electrodes, which had passed the stage 1 test, were derived, and the average time-series was formed for the correlation. If the program failed to find four nearest neighbours, that is, more than five neighbouring electrodes were contaminated, then the process was stopped. The program did not fail when
When other data, not from the test data set, were processed by this algorithm, all visibly affected data were rejected, with minimal, if any, unaffected data rejected.

Combining the results from this artifact stage with the previous, a table of contaminated electrodes was formed. Any electrode which failed stage 2 was entered into the table. In addition, any electrode which failed in the first stage was also entered into the table. All electrodes in this table were stored for later replacement as described in section 4.2.4.

4.2.3. Single frequency Fourier analysis.

For an accurate evoked response, the removal or reduction of signals not associated with the stimulus—noise—is of paramount importance. Several analysis methods exist which remove the steady-state stimulus from the noise. We used one mathematical technique, known as single frequency Fourier analysis, to extract the stimulus-related components and remove all other signals (Regan 1972a). This method assumes that the steady-state evoked potential is present in the raw EEG at the fundamental frequency of the stimulus, and also at harmonics of the fundamental, and the mathematical discussion of the technique follows.

Suppose that a signal exists within a noisy recording, which is related to a reference signal by virtue of having the same frequency, and a constant but unknown phase difference.

† In a series of recordings, without electrode impedance monitoring, some contaminated data passed through without detection. It is postulated that the electrode impedance increased during the recording, and decreased the proportion of EEG signal to 50 Hz. The EEG signal remained correlated with its neighbours, even though the 50 Hz increased and the EEG decreased. A more elaborate testing procedure was designed to deal with this, but won't be discussed in this work.
The signal \( y \) is assumed to be of the form:
\[
y = S \sin(x - \phi)
\]

Making use of standard trigonometric relations, allows \( y \) to be expressed as:
\[
y = C \sin(x) - D \cos(x) \quad \text{(4.2.2)}
\]
where
\[
S = \sqrt{C^2 + D^2} \quad \text{(4.2.3)}
\]
and
\[
\tan(\phi) = \frac{C}{D} \quad \text{(4.2.4)}
\]

If we multiply the signal separately by \( \sin(x) \) and \( \cos(x) \), and utilise standard trigonometric identities.

First multiplying by \( \sin(x) \):
\[
y \sin(x) = C \sin(x) \sin(x) - D \cos(x) \sin(x) \quad \text{(4.2.5)}
\]
\[
y \sin(x) = \frac{C}{2} \cdot \cos(2x) - \frac{D}{2} \cdot \sin(2x) \cdot g \quad \text{(4.2.6)}
\]

Then multiplying by \( \cos(x) \):
\[
y \cos(x) = C \sin(x) \cos(x) - D \cos(x) \cos(x) \quad \text{(4.2.7)}
\]
\[
y \cos(x) = \frac{C}{2} \cdot \sin(2x) + \frac{D}{2} \cdot \cos(2x) + g \quad \text{(4.2.8)}
\]

Let \( A \) be the integrated product of the signal and sine reference waveform, and integrating over an integral number of cycles \( (2n\pi) \).
\[
A = \int \sin(x) \cdot dx \quad \text{(4.2.9)}
\]
\[
A = \frac{C}{2} \cdot \int - \cos(2x) \cdot dx - \frac{D}{2} \cdot \int \sin(2x) \cdot dx \quad \text{(4.2.10)}
\]
\[
A = \frac{C}{2} \quad \text{(4.2.11)}
\]

Let \( B \) be the integrated product of the signal and cosine reference waveform, and integrating over an integral number of cycles \( (2n\pi) \).
\[
B = \int \cos(x) \cdot dx
\]
\[ B = \int_{0}^{2\pi} y \cos(x) \, dx \]  
(4.2.12)

\[ B = \frac{C}{2} \int_{0}^{\pi} \sin(2x) \, dx - \frac{D}{2} \int_{0}^{2\pi} (\cos(2x) + 1) \, dx \]  
(4.2.13)

\[ B = -\frac{D}{2} \]  
(4.2.14)

4.2.1–4.2.14 Single frequency Fourier analysis.

For each cycle of the stimulus, one pair of the Cartesian form of Fourier components (A & B) are stored. The complete set of these components—one pair for each cycle—is referred to as the Fourier time-series and may be either Cartesian or polar in form. The magnitude and phase of the response are essentially the polar representation of the Fourier series, and can be readily found by using equations 4.2.3 & 4.2.4. Later, these are evaluated over a time interval referred to as the integration time or window. The width of the window, or integration time can be varied, and a compromise exists between temporal resolution and noisiness of the windowed data. The length of the Fourier time-series is found by subtracting the integration time from the recording time. For example, a time-series of 180 seconds integrated over a 10 second period, yields a windowed, Fourier time-series of length 170 seconds. Fluctuations in magnitude and phase can be examined over the duration of this time-series, with a minimum resolution equal to the width of the integration window. The software which performs the single frequency Fourier analysis was written by Dr Silberstein at SCAN.

4.2.4. Data replacement.

A natural degree of correlation exists between the data from each scalp electrode and its neighbours. This relationship has been exploited in the artifact section—stage 2. Any electrode with detected artifact requires replacement of its time-series to enable the data to be displayed topographically. The replacement approximation uses an averaged time-series of its nearest neighbours. This is a weighted sum based upon a two dimensional polynomial interpolation using the closest neighbours. Dr Silberstein
provided the quadratic interpolation for the electrode replacement. Replacement approximates the time-series of that electrode, but introduces an error, in the spatial information, analogous to under-sampling. The maximum number of electrodes which can be replaced has been limited arbitrarily in this application to seven. The probability of all seven electrodes occurring in the same area is small, because stage 2 detection routines would have already terminated the analysis if this had occurred. Intuitively, this means that only a small error exists, if any, in the overall data before further processing.

![Graph](image)

Figure 4.10 **Effect of data replacement.** Two time-series are represented on this graph—The original channel 31, and the replaced channel 31. The coefficient of correlation was found to be $r=0.74$.

After the data pass through the analysis and processing regimes to assess presence of artifact, and to extract the SSVEP, sixty-four channels of time-series data are available for further processing. With so many sites, the time-series data cannot be readily visualised, so topographic display techniques assist in the examination of the recorded data. The following sections deal with the modes of interpolation and their algorithms which have been studied.

### 4.3. Topographic representation.

The examination of electrical activity from different regions of the cortex, depends upon the ability to record from the scalp with sufficient resolution. To adequately
sample the scalp spatially, the Nyquist criterion must be met, that is the spatial sampling frequency must be twice that of the highest frequency present, to prevent distortion of the signal\(^\dagger\). Several authors have reported the spatial sampling necessary to adequately represent the EEG (Gevins 1987; Spitzer et al. 1989). The spatial frequency of the EEG (either spontaneous or evoked) depends upon the type of waveform, and the depth of the generator, making generalisation difficult. Localised activity close to the surface of the brain gives rise to the high spatial frequencies, while diffuse activity from midbrain sources, yields low spatial frequencies due to volume conduction (Rush & Driscoll 1969). To examine data on the scalp, the sampling requirements are less critical than recording from the cortical surface, as the skull acts to smear the cortical response, and filters out some of the high (spatial) frequency information (Nunez 1981). Spitzer et al. in 1989 recorded the somatosensory evoked potential and found the highest spatial frequency was 0.14 cycles/cm, implying that a minimum sampling frequency of 0.28 cycles/cm would be sufficient to record the data without distortion (that is, 3.5 cm minimum distance between electrodes). The system used at SCAN has an average electrode spacing of 3.2 cm (a spatial frequency of 0.31 cycles/cm), and is within this limit suggested above\(^\dagger\), and our system can sample adequately, up to a maximum frequency of 0.16 cycles/cm. With the sampled EEG information, a surface representing the scalp potentials my be formed in several ways—these are presented and discussed now.

\(^\dagger\) Generally, this is understood in the time domain. The highest frequency which can be adequately recorded is half of the sampling frequency. For example, a 20 Hz waveform must be sampled at a minimum of 40 Hz to prevent aliasing of the signal.

\(^\dagger\) The experimental determination of the spatial bandwidth of the EEG has not been rigorously studied in this work, but forms a separate study occurring at SCAN.

Mapping in this context means the topographic representation of potentials on the scalp—on a two-dimensional outline of the head. I consider the routines which generate and display this information. In the past, several interpolation and display algorithms have been used to create the maps (for example, Buchsbaum et al. 1982, Duffy et al. 1979). I have investigated some of these and will discuss their usefulness as a mode of presenting the sixty-four channel data. It should be noted that any interpolation used does not add new information to the sixty-four locations, rather it aids in the understanding of the topographic distribution of activity. Invariably it can at best be considered an approximation of the intervening points, and thus the choice of interpolation function must rest with the ability to produce a clear, easy to read map, and should faithfully reproduce the original data at the recording sites.

The interpolation methods that I have investigated and implemented all utilised the weighted sum of nearest neighbours to calculate the intermediate points. Using the weighted sum of neighbours, or EEG-independent measures allows for pre-calculation of the weighting functions, and interpolation is carried out simply, by a process of matrix multiplication of the EEG data with the weights. The interpolation methods are discussed below and follow a progression of simple to complex in terms of the weighting factors. The simplest technique uses linear interpolation, with planes constructed between neighbouring electrodes and the intermediate values calculated from the equation of that plane. The other methods use an inverse-squared distance weight, with different parameters, such as number of neighbours used, amount of spatial smoothing, and normalisation of weights. One important aspect in the presentation of data regards the use of colours: with few colours, contouring of the interpolated data results at the boundaries of dissimilar colours, while the use of as many colours as possible, in a graded fashion, enhances the presentation. Using 256 colours generated on an IBM VGA display system produces non-contoured maps; each containing up to 57000 interpolated points or pixels.
4.4.1. Linear interpolation.

The first method considered is the linear approach as used by Duffy et al (1979). It uses the 3 nearest electrodes to each pixel, and assumes that the data lie on a three-dimensional plane (x & y are spatial co-ordinates; z the pixel voltage or value). The electrode locations have fixed values of z, and the intervening points are derived from the equation of the plane. The calculation of the weights is complicated by the existence of several planes for some pixels, and the existence of planes with too much error in their equations—particularly those with small areas like flattened triangles. The calculation of weights then includes checking for the best plane for each pixel without moving too far away from the pixel. This method produces accurate interpolation, but suffers from alignment problems with the edges of planes, giving rise to a triangular effect of the interpolated data. The value or voltage at each electrode is faithfully reproduced but the intervening points may appear somewhat disjointed. This can be alleviated by some spatial smoothing of the interpolated data to improve the continuity. An example of the unsmoothed linear interpolation is seen in the map of Figure 4.11. For comparison between this and subsequent maps, all voltages at the electrodes remain the same, and hence each interpolation function acts upon the same sixty-four data points. The map is a view from above the head, with the nose located, but not shown, at the top of the map for consistency with Figure 4.2.

Figure 4.11 Linear interpolation. This map illustrates the interpolation technique based upon planes bounded by the three closest data points (electrodes) to each pixel.
4.4.2. Inverse mapping.

The inverse mapping technique is similar to that used by Buchsbaum et al. (1982), where the interpolated, intermediate points are calculated by assuming that the effect each electrode has on any pixel decreases with the inverse of the distance from each electrode. The number of electrodes chosen can be as few as three, or as many as the total number of recording sites. The calculations are straightforward and easily stored in a matrix. However, this does not yield a very satisfactory interpolation of the data unless some modifications are made because: the value becomes large when the pixel is in the vicinity of an electrode; and the value of each electrode is not preserved as it is a non-linear sum of the value of the nearby electrodes. This has the unmistakable effect of producing discontinuities on the interpolated output. One solution to the discontinuities is to replace the interpolated value at each electrode site and adjacent points with the recorded value. An example map is shown in Figure 4.12 using 4 nearest neighbours, and shows this effect of the discontinuities.

A related technique uses the inverse-squared distance, instead of the inverse distance, to interpolate between electrodes. This function possesses a degree of physiological realism in that it approximates a potential distribution due to a dipole source (Nunez 1981). It generally suffers from the same problems as the inverse distance, with the added problem of having a steeper fall-off, which accentuates the discontinuities.
4.4.3. Smoothed inverse-squared interpolation.

A modification of the inverse mapping technique is to use another interpolation algorithm, based on the convolution of the interpolation function $\frac{k^2}{k^2 + r^2}$ with the recorded potentials. This adds a degree of spatial smoothing to the previous method and overcomes the discontinuity effect—the larger the $k$, the smoother the surface. A straightforward application of this approach, however, suffers from two deficiencies.

Firstly, the interpolated values calculated at the recording sites differ from the recorded values. Secondly, these deviations in the interpolated values are a function of the surface density of the recording sites. For example, applying a constant value to all the recording sites yields non-constant interpolated values with larger deviations from the true potential in the regions of high density of recording sites. The smoothness of the interpolated data is seen in the map of fig 4.13, which utilises the same data as the previous maps. Note however, that it produces different result in some areas (particularly noticeable in the lower part of the map) when compared to the previous two maps.

Figure 4.13 Smoothed inverse-squared interpolation. This smooth-looking map does not accurately reproduce the recorded values, partly due to summation effects, and partly because the electrode density is not uniform.

In an attempt to minimise the error of the previous inverse-squared interpolation method, normalisation of the weighting factors took place in the following manner. Assuming that a constant value, of unity applied at each electrode produces a uniform, equal valued map, that is, unity at every pixel. Re-calculation of the weights to meet this criterion took place, showing good results where small or gradual changes exist in the recorded values at electrodes, but poor results occurred in the regions with larger recorded values. When examined closely, the divergence from the desired appears largest in regions with the highest electrode density. The non-linearity of the weights and a variable electrode density causes this effect, and would be alleviated with equidistant electrode spacing.

4.4.5. Lawrencian-like interpolation function.

To circumvent the problems seen in the previous sections, a Lawrencian-like function was used as the basis of the interpolation function. In this approach the sites for interpolation form a subset of all the recording sites, using the ten nearest neighbours of sixty-four. This represents about 15% of the total recorded area, which compares favourably with the 4 nearest neighbours applied with the 10–20 system of recording sites (as used by Buchsbaum et al. 1982) and the 3 nearest neighbours (as used by Duffy et al. 1979).

This section (4.4.5) forms the basis of work I undertook with Dr P Cadusch, and Dr RB Silberstein for presentation at the 1st International Congress on Brain Electromagnetic Topography, held in Osaka, Japan 1990 and subsequently published as Schier et al. 1990. The justification, and method for generating the weights follow.

\[ V(\vec{r}) = \sum_n \frac{a_n k^2}{k^2 + (\vec{r} - \vec{r}_n)^2} \]

Where
\( \vec{r}_n \) is the position vector of the nth recording site.
\( \vec{r} \) is the position vector of the interpolated site.
\( k \) is a constant.
The values of \( a_n \) are then determined by requiring \( V(\vec{r}) \) to take on the recorded value at each of the recording sites \( \vec{r}_n \), i.e.

\[
V(\vec{r}_m) = \sum_n a_n k^2 \frac{k^2 + (\vec{r}_m - \vec{r}_n)^2}{n} \quad (4.4.2)
\]

If

\[
M_{mn} = \frac{k^2}{k^2 + (\vec{r}_m - \vec{r}_n)^2} \quad (4.5.3)
\]

then (4.4.2) becomes

\[
V(\vec{r}_m) = \sum_n a_n M_{mn} \quad (4.5.4)
\]

the values of \( a_n \) are determined by inverting the matrix \( M_{mn} \)

\[
a_n = \sum M^{-1}_{mn} V(\vec{r}_m) \quad (4.4.5)
\]

Note that \( M_{mn} \) is a function only of the inter-electrode distances for the ten nearest neighbours of the interpolated point.

Substituting (4.4.5) into (4.4.1) we obtain:

\[
V(\vec{r}) = \sum_n W_m V(\vec{r}_m) \quad (4.4.6)
\]

\[
W_m = \sum M^{-1}_{mn} k^2 \frac{k^2 + (\vec{r} - \vec{r}_n)^2}{n} \quad (4.4.7)
\]

Note that \( W_m \) is independent of the recorded potentials \( V(\vec{r}_m) \) and can be used as weighting factors for the interpolation.

4.4.1–4.4.7 Lawrencian-like interpolation function.

The implementation of the interpolation procedure is based upon the weighting factors derived for the interpolation function \( \frac{k^2}{k^2 + r^2} \). This accurately reproduces the recorded values at the recording sites, independently of the surface density of recording sites. The results seen in Figure 4.14 compare favourably with the linear and inverse schemes, but present an easier map to read, and because of its smoothness aids in assimilation of the topographic data.
As a postscript, subsequent developments by Dr P Cadusch, at SCAN, have provided an interpolation function routine, based upon the mathematical theory of spherical splines*, superior to the one above. As a basis, it uses three dimensional locations of electrodes and pixels, and not just the projected two dimensional equivalent, and utilises all 64 electrodes—not just the ten nearest neighbours. The topographic projection is different also, yielding a more circular map. As an adjunct, manipulation of the spline functions, the interpolation weights can be substituted for weights which allow projection and interpolation onto a spherical and smooth cortex. This type of deconvolution has also been described by Nunez (1987). In this thesis, only the map of the scalp potentials is included. The reader is referred to Cadusch et al. (1992) for more information. Figure 4.15 gives an illustration of the map and its properties, at the level of the scalp.

---

* The theory is beyond the scope of this thesis, and the reader is referred to Cadusch et al. 1992 for detailed information.

The detailed examination of the interpolation methods indicates that those which make use of an interpolation function provide the best possible representation of the data, independent of electrode density or position. The initial aim with the mapping technique to passing through all data points, producing an aesthetic and functional map has been met.

These techniques make use of pre-calculated, tabulated weights, with fast computation of the maps from sixty-four data points. The ease of use of the interpolation function routine (Cadusch et al. 1992), coupled with its refinements, makes it the choice for all subsequent data interpolation and mapping in this thesis.
4.5. Summary.

The techniques and methods developed and discussed in this chapter represent considerable work in setting-up the recording, analysis, and display system. The laboratory at SCAN was formed as I undertook this work, and the description of the design and implementation follows in parallel with the building up of the Centre for Applied Neurosciences. All the methods, and techniques described within this chapter form a key part of the work in the following chapters regarding recording and analysis of the visual steady-state evoked potential.
5. **Relationship between alpha and the SSVEP.**

The previous chapters have described the setting up of the system for recording, analysing, and displaying the steady-state visually evoked potential topography. This and subsequent chapters evaluate the methods relevant to the technique. In particular, this chapter examines the relationship between the SSVEP and EEG activity within the alpha band.

5.1. **Introduction.**

An inverse relationship has been reported between SSVEP magnitude and cognitive or activation tasks, with dynamic and phasic properties (Galambos & Makeig 1988). This dynamic, inverse relationship has also been reported between alpha activity and activation tasks—particularly with a phasic nature around specific cognitive events, the Event Related Desynchronization or ERD (Pfurtscheller et al. 1989). In this chapter, I will summarise some of the properties of alpha activity and review a study that examines both spontaneous EEG alpha activity, and driven or steady-state evoked activity. This study examined links between spontaneous and driven activity and found a correlation existed between these measures. The remainder of the chapter describes an experiment to study further, relationships between spontaneous and driven activity. Some of the experimental work forms part of a presentation given with Dr Silberstein at the Pan Pacific Workshop on Brain Electrical and Magnetic Topography in Melbourne, in February 1992.

5.1.1. **Alpha activity.**

Alpha activity was noted by Berger in 1929 as visibly different from other EEG. When later measured it was found to be around 10 Hz with some variability, and distinctive inter-individual variation in frequency (Wieneke et al. 1980). Subsequent use of Fourier and frequency domain techniques have made the detection of alpha
activity more automated and precise. In 1974, the International Federation of Societies for Electroencephalography and Clinical Neurophysiology defined alpha as: “Rhythm occurring at 8–13 Hz occurring during wakefulness over the posterior region of the head, generally with high voltages occurring over the occipital areas.” (Chartrian et al. 1974).

Activity within the 8–13 Hz range occurs in other regions of the brain, and may include the mu-rhythm†, but the topographic distribution of activity in the 8–13 Hz range will be loosely termed alpha activity in this thesis. Alpha activity disappears when the subject opens their eyes, particularly if they look at something with pattern or structure (Markand 1990). For this reason alpha activity has been described as “idling activity”. The distribution of alpha activity is not symmetrical between hemispheres—and generally the left hemisphere alpha has smaller amplitudes than the right (Butler & Glass 1974). Its inherent asymmetry depends upon the gender and handedness of the subject, and also the subject’s state, and type of recording situation—whether relaxed or focussing on some type of task (Butler & Glass 1974). Alpha activity bears an inverse relationship to other frequency bands such as beta (14–25 Hz) (Papanicolaou et al. 1980). When focussing, or performing some task, alpha activity is responsive to factors other than the physical value of the task, and appears to be sensitive to emotion or affective stimuli (Davidson & Schaffer 1983), where a reduction in alpha activity occurs with affective stimuli.

The dependence of alpha activity on cognitive processing is not clear, but may relate to the processing of information external to the subject. Ray & Cole (1985) separated the types of tasks used in an alpha experiment to determine the role of alpha activity in those tasks that used external information—intake task, and those which used only internal information—rejection task. They found that alpha activity clearly increased

† The International Federation of Societies for Electroencephalography and Clinical Neurophysiology describes the mu-rhythm as: activity in the range 7–11 Hz, composed of arch-shaped waves occurring over the central or central parietal regions of the scalp during wakefulness. It is blocked or attenuated by contralateral movement, or readiness to move (Chartrian et al. 1974)
during the rejection task when compared to the intake task, and concluded that alpha attenuation may have been erroneously associated with cognitive processing, as both their intake and rejection tasks were ‘cognitive’ in type.

These prior studies have utilised averaged EEG activity over long periods of time, and give good indications of the tonic behaviour of alpha activity. Phasic or short-lived changes in alpha activity (like those seen when opening the eyes) may also exist for cognitive stimuli, and a group of studies has explored this aspect and found that phasic reductions in alpha power occur around cognitive events. Such reductions have been termed Event Related Desynchronization or ERD (Pfurtscheller 1977; Pfurtscheller et al. 1989; Pfurtscheller & Klimesch 1990). ERD measures the drop in alpha power as a ratio of the initial alpha power (for example, complete blocking of alpha yields a value of 100%, and negative ERD indicates an increase in alpha power). One example of a specific experiment to measure ERD: a subject was presented with two stimuli—a warning light followed some seconds later by a tone, and the subject was required to press a button when the tone occurred (Pfurtscheller 1977). As an extension to this type of experiment, a larger and more distinct ERD occurred if the second stimulus had meaning. Pfurtscheller & Klimesch (1990) recorded spontaneous EEG from several scalp sites and presented cognitive stimulus on a display in front of the subject. The subject had to categorise a word or number that was presented, and respond verbally. From the subject's viewpoint, a warning tone alerted them to the imminent presentation 1–3 seconds after the tone. The subject's response depended upon the character displayed: the subject had to say, ‘yes’ if the stimulus was the name of an animal or an odd number, or ‘no’ if the stimulus was the name of a tool or an even number. The subject's response occurred about one second after the stimulus. The period of time from 4 seconds pre-stimulus to 3 seconds post-stimulus was recorded and the pooled responses from 10 subjects are shown in Figure 5.1. The greatest reduction was seen at approximately 4.5 seconds. This reduction between the stimulus and response was interpreted by Pfurtscheller & Klimesch as the preparation for the verbal response.
In Figure 5.1, two frequency ranges are illustrated. ERD in the 8–10 Hz range is widespread in its topographic distribution, and long-lasting, and has been more associated with attentional or expectancy states, whereas, within the 10–12 Hz range, is more localised and more phasic in nature, and possibly associated with memory matching or other shorter cognitive events (Pfurtscheller et al. 1989; Pfurtscheller & Klimesch 1990). In an examination of general properties of alpha activity, Boiten et al. (1992) compared ERD with pre-stimulus alpha activity, and found that ERD has phasic properties, while resting alpha indicates more of the person's tonic state, and can be used as an indicator of tonic arousal. This difference between alpha activity and ERD illustrates, that while alpha activity at rest may shed light on the subject's state, the ERD is potentially more useful for monitoring short-latency changes associated with cognitive and other events.

The potential for ERD to monitor changes during cognitive processing parallels the findings with reduction in amplitude of the steady-state evoked potential. The next section reports an experimental study that investigates the interrelationship between...
alpha activity and steady-state evoked activity, or spontaneous and driven activity. This will assist in understanding how the steady-state evoked potential relates to spontaneous alpha activity, and provide valuable information about the mechanisms that control the steady-state evoked potential. The study utilised driven and spontaneous brain electrical activity.

5.1.2. Spontaneous and driven activity.

Pollock et al. (1986) examined spontaneous and driven activity at several frequencies. They recorded spontaneous EEG and separated it into bands of delta (1.0–4.0 Hz), theta (4.0–7.0 Hz), alpha-1 (7.0–9.0 Hz), alpha-2 (9.0–11.0 Hz), alpha-3 (11.0–14.0 Hz), beta-1 (14.0–22.0 Hz), and beta-2 (22.0–29.6 Hz). They separately recorded responses to visual stimulation at frequencies of 5, 10, 15, 18 & 24 Hz. Both spontaneous and driven EEG recordings used the same eleven healthy subjects, over four recording sessions, (two for spontaneous, and two for driven activity), with an interval of between one month and one year for the tests.

To compare the spontaneous and driven activity, all responses to driven frequencies were correlated with all distinct frequency bands of the spontaneous activity (35 correlations in all). Spontaneous activity was taken from four-minute epochs, while driven activity was taken from two-minute epochs. The most striking feature was the strong positive correlation between spontaneous alpha activity and 10 Hz driven activity. Regression coefficients were found:

- 0.679 for \( \text{alpha-1} \) (10 Hz driven with 7–9 Hz spontaneous).
- 0.736 for \( \text{alpha-2} \) (10 Hz driven with 9–11 Hz spontaneous).
- 0.745 for \( \text{alpha-3} \) (10 Hz driven with 11–14 Hz spontaneous).

The other frequencies, both driven and spontaneous, showed low correlations.

The findings of Pollock et al. (1986) yield information regarding the nature of spontaneous and driven activity. Several extensions of their basic experiment are possible. Vijn et al. (1991; 1992) found that visual stimulation reduced the EEG amplitude over the broad EEG spectrum. The first questions that could be answered
from an extended experiment concerns the correlation of spontaneous and driven activity when they are extracted simultaneously from the same record. With a recording of driven activity, alpha activity can be extracted, and this allows further examination of the relationships for different time periods, in light of the phasic and tonic differences between alpha and steady-state evoked potentials.

The previous research indicated two factors requiring further study. Firstly whether this correlation held when the driven and the spontaneous responses were extracted simultaneously. Secondly, whether the correlations held for individuals over much shorter time intervals—to determine how closely alpha attenuation and activity was associated with changes in driven activity, or SSVEP.

The recordings of spontaneous and driven activity were not recorded simultaneously in Pollock et al.’s 1986 study. The practicality of extracting these simultaneously is unknown, as another group found that visual stimulation reduced the EEG amplitude over the whole range of EEG frequencies (Vijn et al. 1991; 1992). Two experiments are posed by the studies above:

1. Does the overall reduction of EEG, and particularly alpha, affect the relationship between spontaneous and driven activity if they are extracted from the same recording?

2. Does the observed correlation between EEG and SSVEP of 0.75 for a population also occur for individuals?

An experiment was designed and carried out to investigate these two questions.


5.2.1. Subjects.

Twenty right handed males served as subjects, each in a single recording session, where activity was recorded and analysed from electrode site OZ. They were involved in another recording session carried out at SCAN.
5.2.2. Recording.

For the recording session, a steady-state 13 Hz visual flicker stimulus was presented through half-silvered glasses, as described in Chapter 4. EEG was recorded, for a period of approximately three minutes, from an electrode located at site OZ on the International 10–20 System. From the recorded data, both alpha activity and steady-state 13 Hz activity were extracted. Before the driven and spontaneous activity were extracted, the raw data were windowed with a tapered cosine window to minimise the sidebands in the frequency domain caused by truncation of the time-series data (Dumermuth & Molinari 1987 p. 94.). Data were then transformed by a Fast Fourier Transform, or FFT algorithm. Alpha activity was quantified by calculating 90 power spectra, and summing them to form an average power spectrum for the full three minutes of recorded EEG. This time of 180 seconds yielded approximately the same time and facilitated a comparison of the recording with that of Pollock et al. (1986). The area beneath the spectrum bounded by 8.1 Hz and 12.2 Hz† was calculated and termed the average alpha power. The square root of the value of integrated power was calculated to yield the RMS, or Root Mean Squared value of alpha for each individual. Figure 5.2. illustrates the power spectrum for one individual, subject CY.

† The alpha activity had an upper bound of 12.2 Hz to ensure that the 13 Hz SSVEP was not included in the alpha power. This appears to be a reasonable assumption when Figure 5.2 is examined, because the alpha peak and driven activity show little overlap.
To quantify the amount of driven activity, a variation of this method was utilised for the SSVEP. To calculate the magnitude of the SSVEP activity, 90 Fourier transforms were added together to yield an average Fourier spectrum; Figure 5.3 illustrates one such spectrum from subject CY, the same individual as Figure 5.2. This spectrum clearly shows the 13 Hz peak. The magnitude of the 13 Hz component was measured for each individual. The Fourier spectrum appears different to the power spectrum because of the manner in which it is produced. Adding together Fourier transforms preserves the phase information, so that signals with a non-constant phase are reduced. The Fourier spectrum in Figure 5.3 shows the 13 Hz driven peak because it has consistent phase from one 5-second epoch to the next, whereas the large region of spontaneous activity, with variable phase is absent from Figure 5.3.
The computed RMS alpha power over the complete three minute period, and the computed 13 Hz SSVEP magnitude for the same period, were recorded for each subject. From these twenty subjects, the correlation coefficient was computed between SSVEP magnitude and alpha RMS power.

To investigate the relationship between changes in alpha and SSVEP of shorter duration than 3 minutes, the recorded data were examined over segments of 5 seconds. RMS alpha and SSVEP magnitude from were extracted from 90 epochs of 5 seconds, obtaining for each individual, 90 pairs of RMS alpha and 13 Hz SSVEP magnitude. For these 90 pairs of values (for each subject), the correlation coefficient was computed between SSVEP magnitude and alpha RMS power.

5.3. Results.

5.3.1. General findings for alpha and SSVEP.

For each individual in this study, one value of alpha magnitude and one value of 13 Hz SSVEP were calculated. The scatter diagram in Figure 5.4, illustrates the aggregation of the results from the 20 subjects.
This experiment found that a relationship exists between alpha and SSVEP activity with a linear trend, as illustrated in Figure 5.4. Fitting a regression line by the least-squares method (for example, Leaver & Thomas 1974 pp. 59–60.) yielded a correlation of 0.74. This result when tested with a t-test for dependent correlations (Cohen & Cohen 1983), reached significance at the 1% level. The pairs of points used in this correlation are the average of 3 minutes of recorded activity, and the correlation compares favourably with the r-value of 0.745 found by Pollock et al. (1986).

### 5.3.2. Individual findings.

For the second segment of the analysis, the correlation between SSVEP magnitude and alpha RMS power, over consecutive 5 second epochs, was examined by plotting these data pairs on a scatter plot. This yielded twenty such scatter plots, and one has been included as Figure 5.5.
Unlike the previous scatter plot, there appears to be little correlation between SSVEP magnitude and alpha RMS power for this individual. The same trend was noted for the remaining subjects, and the complete group correlations are included in Table 5.1. Their values ranged from $-0.43$ to $0.41$. The trend of the values of correlation coefficients from the twenty subjects indicates that SSVEP activity and RMS alpha are unrelated over short time periods.
### Table 5.1 Correlation between alpha and 13 Hz SSVEP.

For each subject (initials), the correlation coefficient between SSVEP and RMS alpha is listed. The mean value for the 20 subjects is listed below the individual values.

<table>
<thead>
<tr>
<th>Subject</th>
<th>r</th>
<th>Subject</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>-0.1664</td>
<td>GW</td>
<td>-0.2980</td>
</tr>
<tr>
<td>DD</td>
<td>-0.0911</td>
<td>JB</td>
<td>-0.0274</td>
</tr>
<tr>
<td>HD</td>
<td>-0.0505</td>
<td>GE</td>
<td>0.3107</td>
</tr>
<tr>
<td>MC</td>
<td>0.2520</td>
<td>RC</td>
<td>0.0388</td>
</tr>
<tr>
<td>RB</td>
<td>-0.2456</td>
<td>BT</td>
<td>0.2351</td>
</tr>
<tr>
<td>TB</td>
<td>0.2181</td>
<td>WH</td>
<td>-0.0058</td>
</tr>
<tr>
<td>WG</td>
<td>-0.4303</td>
<td>JP</td>
<td>-0.3101</td>
</tr>
<tr>
<td>BC</td>
<td>0.2569</td>
<td>GS</td>
<td>0.2717</td>
</tr>
<tr>
<td>RS</td>
<td>-0.3096</td>
<td>TW</td>
<td>0.4040</td>
</tr>
<tr>
<td>CY</td>
<td>0.0032</td>
<td>SC</td>
<td>-0.0546</td>
</tr>
</tbody>
</table>

Mean 0.0001

Using the square of the correlation coefficient as a guide to the variance†, the largest value of correlation, subject WG, shows at most 19% of the total variance in the SSVEP accounted for by the RMS alpha activity. In the other individuals this proportion of variance associated with alpha activity is even less than 19%. The average of the group is negligible, being 0.01%. This indicates an absence of any relationship between SSVEP and alpha over short intervals of time.

### 5.4. Discussion.

The high correlation of alpha activity with driven activity found by Pollock et al. was interpreted as a close relationship of alpha activity and driven activity, analogous to SSVEP. The results of the experimental study in this chapter have not supported Pollock's finding, because when the analysis is carried out over a shorter time period for single subjects, the correlation between alpha and SSVEP disappears. This may indicate that the correlation found by Pollock et al. really shows that the subjects with

---

† For the regression equation: \( y = ax + b \), the value \( r^2 \) is the proportion of the variance of \( y \) linearly associated with \( x \) (Cohen & Cohen 1983 pp. 46-47).
larger SSVEPs are the same subjects that possess larger alpha activity, or it may indicate that the presence of the visual stimulus has altered the alpha response.

This experiment has used concurrent measures of alpha activity and SSVEP to determine the correlations coefficient. This may indicate that the driving activity has altered the spontaneous alpha activity, as noted by Vijn et al. (1991; 1992). If this had happened in the current study, then it follows that the relationship between SSVEP and alpha activity would be reduced in both the minute period, and the five second period. The results of this experiment clearly show that the correlation for the three minute period is directly comparable to Pollock's, but the intra-subject, five second segment correlation is low. It therefore seems improbable that the visual stimulation has significantly altered any relationship between SSVEP and alpha activity. To further examine any possible interaction of 13 Hz SSVEP and EEG, the same frequency could be used for driven and spontaneous activity. There are difficulties with making comparisons at identical frequencies, and some factors would require clarification. One method could involve, subtracting the overall envelope of the spontaneous activity from the sharp resonance of the driven activity as illustrated in the hypothetical spectrum of Figure 5.6. This would yield more information regarding any interaction with driven and residual activity at the same frequency.

A more plausible explanation of the non-correlation between SSVEP and alpha involves separate mechanisms for their generation.

![Figure 5.6 Power spectrum of spontaneous plus driven activity.](image)

In this hypothetical power spectrum, both the spontaneous activity (indicated by the smooth envelope), and the driven activity (indicated by the spike above the envelope) are illustrated. To measure both at the same frequency is possible, if the shape of the power spectrum is known. The spontaneous envelope is subtracted from the total spectrum, yielding the measure of driven power at 13 Hz, and spontaneous power at 13 Hz is the balance of the power at this frequency.
The SSVEP and alpha activity possess separate generators. One input to the generator could be some general processing factor, such as arousal. This general arousal level sets the overall or tonic level of the SSVEP in the same way that has been identified for alpha activity and arousal (Boiten et al. 1992). This means for more general time periods of the order of minutes or longer, the amount of alpha activity and SSVEP are related. For shorter time periods, this does not automatically occur.

Activity as measured by regional cerebral blood flow correlates with spontaneous EEG, and a positive correlation exist between blood flow and peak alpha frequency, but a negative correlation exists for blood flow and alpha power (Osaka et al. 1984). A similar finding for visual evoked potentials and regional cerebral blood flow exists, when the visual stimulation is used as an irrelevant or distractor stimulus (Papanicolaou et al. 1987). This showed that the regions where cerebral blood flow increased, the Probe-ERP decreased.

The time length of recording the regional cerebral blood flow is of the order of 8–10 minutes, and cannot be studied in the time frame of seconds (Roland 1984; Jaggi & Obrist 1987). The use of SSVEP in a probe experiment showed that both changes associated with tonic levels of activity, such as arousal, and momentary changes in state, such as directed attention, can be seen from this type of recording (Silberstein et al. 1990).

The examination of alpha activity is made by several spectra averaged together over a period of minutes (Pollock et al. 1986), or several spectra averaged together to form a time-locked event—ERD (Pfurtscheller 1977). In the experiment in this chapter, another measure of alpha activity was made: that of individual spectra and these showed a low correlation with SSVEP. This further supports the proposal that alpha and SSVEP are measuring separate mechanisms when examined over a short time scale.

The results from this study support the concept that alpha activity and SSVEP have separate generators. In some aspects they show similar responses to cognitive tasks—
when used in the ERD paradigm. The only consistent finding seen is that those subjects who show large alpha amplitudes are the same subjects who show large SSVEP responses.

5.5. Summary.

The relationships investigated in this Chapter lead to two conclusions regarding alpha activity and the SSVEP. The first is that, those individuals who produce larger responses to visual stimulation at 13 Hz also produce larger amounts of alpha activity—these values have a correlation coefficient of 0.74. The second, when each individual's responses are examined in more detail over a shorter time period, this correlation disappears (r=0.0001), and has a large inter-subject variability suggesting that alpha activity does not index the same pool of resources as the SSVEP.

The following chapters deal with experiments exploring the sensitivity of the SSVEP-probe to changes in cognitive activation, in particular: sustained attention, and graded attention.
6. Sensitivity of the SSVEP to attention.

Using the known sensitivity of the steady-state evoked potential to cognitive stimuli (for example, Galambos & Makeig 1988), and the techniques described in Chapter 4, an experimental investigation of attentional effects on the steady-state visually evoked potential took place and is described in this chapter. This experiment was part of a large study in collaboration with members of the Centre for Applied Neurosciences, and has been published as Silberstein et al. 1990. The experimental study consisted of an examination of some of the effects of vigilance upon the SSVEP, to test the hypothesis that changes in the attentional state will cause an increase in neural activity leading to a reduction in the magnitude of the SSVEP.

6.1. Exploring SSVEP changes with visual vigilance.

The phenomenon of vigilance is characterised by prolonged observation and focussing upon a situation—for example, long distance driving requires vigilance on the part of the driver. Another way of describing vigilance is sustained attention (Posner & Rafal 1985). Some observed effects of attention upon the steady-state evoked potential were described in Chapter 3.2.10, where a reduction in the evoked potential coincided with a period of attending to a piece of music played to the subject (Galambos & Makeig 1988). This chapter describes an experiment which deals with the steady-state visually evoked potential and changes in sustained attention or vigilance.

When recording the SSVEP, or even the EEG, some extraneous variables exist the experimenter cannot fully control. These include pupil size, light intensity, and contamination of the EEG with artifact. The size of the pupil is known to be related to arousal, light intensity, and attentional level (Janisse 1977). Although b-wave amplitude of the ERG is influenced by pupil size (Karpe & Wulfing 1969), the latency and amplitude of transient EPs are reported to be unaffected by pupil size (Skalka & Holman 1986). It is also reported that VEP latencies are affected by the changes in
the intensity of the visual stimulus, with a decrease in latency with intensity, and an increase in amplitude followed by saturation with intensity (Regan 1972a). No studies have been found for pupil size with the steady-state stimulation. Given the other findings where steady-state and transient responses are similar, it would be reasonable to assume initially that steady-state response won't be affected by pupil size. Pupil size and other factors that influence the steady-state response will be addressed in the experimental section of this chapter. The parameter that is primarily under investigation is attention.

The review of Chapter 2 provides an insight into those regions of the cortex involved with visual spatial selective attention. The region most often indicated is the posterior parietal lobe, particularly in the right hemisphere. The frontal and prefrontal regions are also important in any planning and directing of attention, and also play a role in selective attention. One model of attentional systems involves four separate regions of the brain, encompassing both subcortical and cortical structures. These are the reticular formation and cingulate gyrus and the frontal eye fields and posterior parietal cortex. Evidence comes from both unilateral neglect studies in humans, and normal and lesion studies in monkeys (Mesulam 1981).

The parietal regions have strong reciprocal connections with the subcortical regions that are involved in selective attention, such as the pulvinar nucleus, and other thalamic structures. Further evidence for the involvement of the parietal region comes from lesion studies, where neglect of the body contralateral to the lesion occurs—giving rise to behaviour such as completely ignoring objects, and even food on one side of the body (Walsh 1978). This effect is more apparent with right rather than left hemisphere lesions (Walsh 1978; Weintraub & Mesulam 1987).

The frontal lobes are also implicated in this spatial selective attention, and associated meta-tasks, such as divergent thinking, error correction, and planning (Milner & Petrides 1984; Milner 1992). Directed attention or focussed attention for long periods of time results from injury to the frontal lobes (Mesulam 1981; Weintraub & Mesulam 1987), with the findings of increased distractibility often reported (Milner & Petrides
1984). These findings are supported by studies examining regional blood flow in control subjects. Several groups have reported increased regional cerebral blood flow to the right frontal, and prefrontal regions during a directed attention task (Deutsch et al 1987; Fuster et al. 1982; Fuster 1990). Within the frontal regions, some degree of lateralisation of function exists. Blood flow studies clearly show an increase for sustained attention in the left prefrontal region, when the subject controls the rate of the task. The right hemisphere shows increased blood flow during attention tasks, particularly when the task rate is controlled by the equipment or the tester (Milner 1992). The activation in these frontal regions is different, the right shows a diffuse increase in blood flow, while the left increases in much smaller regions, probably indicating a large involvement of the right frontal region in directed attention, while the left has more localised regions involved in different types of tasks (Milner 1992). Injury to the right hemisphere produce errors in object and design fluency, while those in the left produced errors in verbal and gesture fluency (Milner 1992). Fluency in this context is an indication of ability to produce lists of words, or objects, for example.

Based on these studies of directed sustained attention, the expected outcome of an experiment involving visual vigilance is increased activation in the frontal and parietal regions, particularly in the right hemisphere. The measure used in the experiment in this chapter is the magnitude of the SSVEP in a probe paradigm. With the probe paradigm, reductions in probe magnitude indicate an increased activation, and hence the overall expected result is a reduction in the SSVEP magnitude in the frontal and parietal regions during periods of sustained visual attention. I hypothesise that the cortical regions showing increased neural activity in trial 3 compared to trial 2 will also show a corresponding attenuation of the SSVEP.


The experiment involved subjects watching a monitor over a period of several minutes to detect any changes in the shapes of objects displayed there. A preliminary
experiment examined the effects of eye position upon the SSVEP. An additional study examined the sensitivity of the SSVEP to changes in pupil size.

### 6.2.1. Subjects.

Fifteen right-handed males aged between 18 and 42 years (with a mean age of 24.1 years) served as subjects. All subjects gave their informed consent, and completed a questionnaire recording their state of health and other general information (Appendix 1). None of the subjects reported a history of any neurologic or psychiatric condition. Handedness was assessed with the Edinburgh inventory (Oldfield 1971; Appendix 2). The majority of subjects were undergraduate students at Swinburne Institute of Technology, and were paid about five dollars for their participation.

Four additional individuals satisfying these same criteria served as subjects for the preliminary experiment. A further four individuals satisfying these criteria (postgraduate researchers at SCAN) served as subjects for the additional experiment.

### 6.2.2. Sustained attention task.

Subjects were seated comfortably one metre from a video monitor, and asked to fixate on the centre of the monitor and watch a sequence of geometrical shapes there. The sequence consisted of 60 squares followed by 60 circles followed by another 60 squares displayed at a rate of one per second, with each shape presented for a duration of 500 ms. To ensure that subjects maintained fixation, a fixation cross was displayed in the period when shapes were not present on the screen. Subjects were requested to view the sequence of shapes three times, each presentation constituting a trial, as illustrated in Figure 6.1. During the first and second trials, subjects were instructed to view the shapes, and in the third trial, they were instructed to look for a modification made to one of the circles. The shapes, including the fixation cross, subtended an angle of 1 degree, both horizontally and vertically, and had a luminance of 13.0 cd.m\(^{-2}\) against a background of 1.2 cd.m\(^{-2}\).
Each trial was 180 seconds in duration, and consisted of 60 squares followed by 60 circles and another 60 squares; trials 1 and 2 were identical. Trial three had the last circle modified, which served as a target.

<table>
<thead>
<tr>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ □ □ □ □ □ ○○○○... ○○</td>
<td>□ □ □ □ □ □ ○○○○... ○○</td>
<td>□ □ □ □ □ □ ○○○○... ○○</td>
</tr>
<tr>
<td>60 s</td>
<td>60 s</td>
<td>60 s</td>
</tr>
</tbody>
</table>

Just before the third trial began, the subjects were instructed to attend carefully and find the modified circle, included somewhere in the sequence of circles. They did not know the nature of the modification, or which circle had been modified, and should therefore have increased their attention at the beginning of the circles phase. For ease of data analysis, the modified circle was always the final circle in the trial. The three trials, although similar in the mode of presentation, served different purposes. Trial 1 familiarised the subjects with the task, trial 2 was a passive viewing task, and trial 3 required increased attentiveness to identify the modified circle. To validate their performance, after the third trial we required subjects to choose the modified circle from a set of 9 different modified circles.

### 6.2.3. Probe and EEG recording.

The probe stimulus, a 13 Hz sinusoidal flicker which evoked the SSVEP, was superimposed on each subject's visual field using half silvered mirrors mounted on glasses, and formed the irrelevant or probe stimulus. The maximum luminance associated with the peak of the stimulus waveform was 3.2 cd.m$^{-2}$, when viewed against the background was 1.2 cd.m$^{-2}$. The flicker therefore had a modulation depth of 45% and, when measured, subtended angles vertically 30 degrees, and horizontally 80 degrees.

The EEG recording occurred simultaneously from sixty-four scalp sites using the electrode helmet, and data storage system as described in Chapter 4. These sites
included all the International 10-20 sites and intermediate sites, giving an average inter-electrode spacing of 3.2 cm. Recordings in this experiment were made with respect to linked earlobes. After artifact detection and rejection routines as described in Chapter 4, the magnitude of the SSVEP was determined from the cosine and sine Fourier coefficients. To reduce the noise in the single cycle coefficients, a 10 second, moving-window cosine filter was passed over the data, and yielded for each individual a time-series of 170 seconds, that is, the window period subtracted from the recording time during each trial. This meant that the Fourier coefficients were evaluated over a 10 second integration period, and then shifted one cycle, and the magnitude recalculated for this overlapping period. This procedure yielded an SSVEP magnitude time series 170 seconds in duration. An identical procedure was applied to all 64 recording sites. The SSVEP phase information was also calculated from the Fourier coefficients, and considered separately.

There were large inter-subject differences in the magnitude of the SSVEP, and so normalised Fourier coefficients were calculated for each subject, and used to form a cross subject average. To account for the differences in magnitude of SSVEP between subjects, all data were normalised by dividing the normalisation factor. The normalisation factor was formed by computing the mean value of the magnitude of trial 2, at each electrode site. These sixty-four values were then averaged to yield one normalisation value for each subject. Finally, all data from all subjects were averaged to compute three separate time-series: for trials 1, 2, & 3. The time series were then represented as a multiple of the mean value during trial 2. Failure to carry out this normalisation procedure could lead to skewing of the cross subject average by the larger SSVEPs.

The phase data were normalised by calculating the mean phase angle at all electrodes during trial 2 and arbitrarily making this phase angle zero, yielding a phase constant. All other phases for all electrodes and trials had this phase constant subtracted to form the time series for the phase information.
To examine the effect of attentional states on the SSVEP, the differences between trials 2 and 3, and the differences between trials 1 and 2 were calculated. Maps of the differences between trials were computed at several points in time, that were coupled with events in the trials. The statistical strength of these differences were explored with a 2-dimensional analogue of the Student's t-test known as the Hotelling $T^2$ test (Picton et al. 1987).

### 6.3. Results

#### 6.3.1. Results of vigilance experiment.

For the main experiment, all subjects completed all three trials of the task and correctly identified the modified circle in trial 3. An examination of the results showed that fluctuations existed in the SSVEP magnitude within all trials. This variability in the three trials is illustrated for the cross-subject average in Figure 6.2.

![Figure 6.2 Magnitude time-series (right parietal site).](image)

Normalised magnitude time-series of the group data, from a location in the right parietal region. Trials 1, 2, and 3 are represented on the graph. The phases of presentation, anticipation, and detection are indicated with the symbols P, A and D respectively. The time 0–60 seconds corresponds to the first block of the squares, 60–120 seconds corresponds to the circles, and 120–180 seconds the second block of the squares.

Figure 6.2 illustrates that differences exist between the three trials. Trials 1 and 3 appear similar in their magnitude time-series, especially in the initial and final stages of the task. These correspond with the period that the squares were presented on the
screen, and in the period with the circles, some difference existed. Trial 2 showed considerable difference from both trials 1 and 3.

With sixty-four channels in this experiment, considerable amounts of data were collected, and data reduction became necessary. Rather than deal with the whole time-series, three points were considered for further analyses. These three points in time are indicated as P, A, & D in Figure 6.2.

P. The first circle in trial 3 alerted subjects to the possible appearance of the modified circle. Heightened visual attentiveness occurred at this time, and this point was termed presentation.

D. The time of appearance of the last circle, in trial three, corresponded to the appearance of the modified circle, or target detection. This point in time was called detection.

A. In the intervening time period, the subject was in an anticipatory phase, and a point chosen 15 seconds after presentation, was termed anticipation. In the period from 15 seconds to 60 seconds after presentation, the magnitude varied little, and the topographic distribution of activity varied little, and it was assumed that the anticipation phase lasted for this time period.

Data reduction occurred at the selected three points in time. The evaluation of the steady-state magnitude at all sixty-four scalp locations yielded data sets for presentation, anticipation, and detection for trials 2 and 3. The topographic distribution of the SSVEP in trials 1, 2 and 3 are illustrated in the maps of Figure 6.3 for the point in time of presentation.
The shapes of these three maps appeared similar, with an overall reduction in SSVEP magnitude for trial 3 compared with trial 2, as seen by the scale alongside each map. The maps show the magnitudes and phases of the SSVEP of sixty-four sites in comparison to the single channel of Figure 6.2. The responses show that a complex topographic distribution of the SSVEP exists.

The next point considered was anticipation. Here the circles had been presented to the subject for a period of roughly 15 seconds, and the expectation of the subjects was assumed higher as they awaited the modified circle during trial 3. Figure 6.4 illustrates the magnitude and phase topography for anticipation during trials 1, 2, and 3.
The third point considered was detection. Detection only occurred during trial 3, when the modified circle was presented. Figure 6.5 illustrates the magnitude and phase topography for detection during trials 1, 2 and 3.
6.3.2. Effects of attention.

To clearly highlight the regional variation between the trials, the differences in SSVEP magnitudes between trials 2 and 3 at each scalp site were mapped, yielding information regarding the spatial distribution of the reduction in SSVEP magnitude as illustrated in Figure 6.6. At each recording site, the values of trial 3 have been subtracted from trial 2, so that regions where the magnitude of the SSVEP is lower for trial 3 than trial 2, appear positive or larger, making the interpretation of the maps consistent with the Probe-ERP. A decrease in the SSVEP magnitude, and hence increased activation, occurs during the anticipation detection stages. These changes are interpreted as due to increase attention as indicated by positive or increased values.
on the maps. In Figure 6.6, the greatest increases occurred in the parietal and occipital regions during anticipation; and in the occipital, parietal and right prefrontal regions during detection.

![Figure 6.6 Differences between trials 2 and 3.](image)

The upper map illustrates the difference during presentation, the middle map during anticipation, and the lower map during detection. The arrangement of maps is the same as previous, but with $\Delta$(magnitude) on the left, and $\Delta$(phase) on the right.

For the maps of the three separate points in time in Figure 6.6, different topographic distributions occurred. For presentation, the positive values at all recording sites illustrate that during trial 3 SSVEP magnitude was smaller than during trial 2. The greatest differences were in the occipito-parietal and right temporal regions. For anticipation, or the period of heightened attention, much larger differences were evident especially in the occipito-parietal areas extending into the central regions. Some smaller differences were seen in the frontal regions also. For detection, greater attenuation occurred during trial 3 than trial 2, particularly in the right prefrontal and parieto-temporal regions. At all three points in time, the phase maps revealed little differences for these data.
To examine the statistical strength of the differences that were observed in Figure 6.6, the Hotelling test was carried out, and $T^2$ values were computed from the cross-subject average time series. This test includes both the real and imaginary components of the SSVEP across the 14 members of the population in this study. It gives a measure of the degree of similarity between the 14 subjects at each recording location. For ease of mapping and to reduce the dynamic range of the data, a T-value (rather than a $T^2$ value) is computed at each recording site, then interpolated to form the T-map. Contours on the T-map join regions of constant T-values. They are present at 2.7 and 3.35, and correspond to p-values of 1.0% and 0.1% respectively, and are indicated for exploratory purposes only.

Figure 6.7 **Hotelling T-maps: trial 2 vs 3.** The upper map illustrates the difference during presentation, the middle map during anticipation, and the lower map during detection. The iso-T contours are preset at the T-values of 2.7 and 3.55, giving equivalent p-values of 1% and 0.1% for exploratory statistical analysis.

The statistical test indicates that although differences between trials 2 and 3 for presentation occurred in the occipital and temporo-parietal regions, only the occipital regions reached significance (p<0.01). During anticipation, or the phase of most
attentional demand, the most significant differences were found in the right hemisphere (almost all p<0.01) and specifically the right temporo-parietal or central region (p<0.001). For target detection, the most significant differences were seen in the right temporo-frontal and prefrontal regions. This reached the equivalent p-value (p<0.01). These findings are consistent with the hypothesis of increased attention during trial 3 compared to trial 2. Examination of the time-series of Figure 6.2 also shows that differences exist between trial 1 and trial 2, and these are considered next.

6.3.3. Effects of novelty.

A comparison of trial 1 with trial 2 also shows some strong differences that are not immediately associated with changes in sustained attention. These are illustrated in Figure 6.2, where for a single parietal location, the SSVEP magnitude for these two trials is considerably different. These differences need to be examined more closely for their topographic distribution, and these are illustrated in Figure 6.8.
For the three maps illustrated in Figure 6.8, the most striking effects were observed at the points of presentation and anticipation, with little differences noted for detection. It should be noted that these terms do not really apply when comparing these two trials, as the subject is totally unaware of the requirement in the third trial to find a modified circle, and thus any differences between trials 1 and 2 must be due to overall levels of attention. Novelty is known to alter attention, in that when sensory stimuli become more routine, they fail to capture attention as strongly as new items, and novel stimuli give rise to the an orienting response (Kahneman 1973). None of the subjects had participated in this experiment before, and therefore the task was a novel experience for them all. The first trial was designed to reduce any novelty effects, and by its presence in the task, enabled a study of some of the effects of novelty to be undertaken. The greatest effects seen in both presentation and detection were decreases of the SSVEP during trial 1, when the stimulus was more novel. This effect
extends over a larger area at the point in time of anticipation, to cover the central regions of the scalp as well. By the time detection is reached, some 120 seconds after the beginning of the trial, very little difference appears between the magnitudes of trial 2 and trial 3.

To examine the statistical strength of the differences between trial 1 and trial 2, Hotelling's T-maps were computed from the 14 subjects, and they are illustrated in Figure 6.9.

![Figure 6.9 Hotelling T-maps: trial 1 vs 2.](image)

The upper map illustrates the difference during presentation, the middle map during anticipation, and the lower map during detection. The iso-T contours are preset at the T-values of 2.7 and 3.55, giving equivalent p-values of 1% and 0.1% for exploratory statistical analysis.

For presentation, the strongest effects were seen in the left posterior region, and reached a significance level of p<0.001. This area as surrounded by a larger region with a similar shape where the significance was p<0.01. For anticipation, the subject is not expecting anything different to the first trial, and the regions of significance have moved to include left and right posterior regions (p<0.001), and almost all of the
posterior region of the scalp (p<0.01). For detection, the differences have reduced, leaving only pockets of significant regions in the central part of the scalp (p<0.01). The overall changes in the distribution of the differences between trial 1 and trial 2 perhaps reflect the dynamic nature of the novelty of the stimulus.

6.4. Discussion.

The results of the preliminary and additional experiments regarding the effects of gaze position and pupil size upon the SSVEP provide evidence that these variables do not cause changes in the SSVEP. The changes in the SSVEP that have been recorded for the vigilance section, are not therefore due to eye position or pupil size, and must be caused by other factors, the most likely are visual vigilance, or novelty, and these are now considered.

6.4.1. Vigilance.

In general, trial 3 showed a larger attenuation of the SSVEP than trial 2. The topography of this attenuation varied with different phases of the task, although it was consistent at the occipito-parietal, parieto-central, right temporal, and right frontal sites. To consider the topographic distribution of attenuation, the Probe-ERP technique was used to interpret the attenuation and indicated that higher activity occurred during trial 3 compared to trial 2. The occipito-parietal attenuation was apparent during presentation, anticipation, and target detection. This suggested increased occipito-parietal activity during these components of the task. The increase was also lateralised to the right hemisphere, and this is consistent with the literature, which indicates that visuo-spatial tasks are predominantly processed by the right hemisphere (in right-handed males).

Involvement of the occipital region is not totally unexpected, as this is the primary visual region of the cortex. The increase in occipital activation during anticipation and target detection ties in with studies of blood flow and regional metabolism of the
cerebral cortex with heightened visual attention (Roland 1984; Mazziotta & Phelps 1984). The involvement of the right parietal region confirms that this region is important for sustained visual attention, and perhaps sustained visual attention in general (Walsh 1978; Weintraub & Mesulam 1987). The finding of involvement of the frontal regions is consistent with their hypothesised role for maintaining levels of sustained attention (Milner & Petrides 1984). The right frontal region showed a greater activation than the left in the present study, and is consistent with the blood flow studies (e.g. Roland 1984), lesion studies (e.g. Mesulam 1981). Furthermore, the finding of right frontal region activation coincides with the particular finding of overall right frontal involvement with tasks running at a pace not set by the subject (Milner 1992). The involvement of the temporal lobe could be due to the involvement of shapes. Single cell recordings in monkeys show that cells activated by objects exist in the temporal region, but the removal of features, such as the eyes, from the facial image reduces the firing rate of the cell (Gross 1991; Gross et al. 1984). The ability to recognise the feature of the changed circle, would perhaps suggest the involvement of the inferior temporal region. ERP recordings in humans indicate responses in visual short-term memory for simple and complex shapes at a latency of 170 ms in the temporal region (Begleiter et al. 1993), and the Magnetic Evoked Response to an absent stimuli, oddball-paradigm elicits strong dipole-like response in the superior temporal sulcus (Rogers et al. 1993).

The aim of comparing trial 2 with trial 3 was to examine the effects of sustained attention. After a single familiarisation trial, it was assumed that any novelty effects were minimised. When comparing trial 3 with trial 2, the differences should be strongly related to any differences in sustained attention between the two trials. The comparison of trial 1 with trial 2, on the other hand may be influenced by the effects of novelty, and a discussion follows in the next section.
6.4.2. Novelty.

The subjects took part in a task of watching a series of shapes appear on the screen at a rate of one per second. This was designed to be boring due to its repetitive nature. Even though it was repetitive, it may have interested the subjects on its first presentation. The first trial allowed an investigation of the effects of novelty, when compared to the second trial. The effects of novelty on the activation of the brain are not as well documented as those of sustained attention (see Moray 1969). Novelty, however is a strong modulator of attention, and the experimental changes, that are recorded and found in this study may be due entirely to the modulation of attention. Novel stimuli produce one of the most salient manifestations of the orienting response (Kahneman 1973). Other physiological measures such as heart rate or skin potentials that are used to examine the orienting response have not been recorded in this experiment, but cannot be discounted in terms of their alteration to the state of the subjects. The predominant feature of the trial 1 versus trial 2 comparison is that of the largest changes appearing in the occipital and parietal regions. These are consistent with findings of increased blood flow over these regions during visual processing (Roland 1984; Mazziotta & Phelps 1984). From the current study, it seems plausible that the SSVEP magnitude can follow dynamic changes in novelty.

6.5. Summary.

This experiment is consistent with the view that regions demonstrating reduced SSVEP magnitude, are associated with visual vigilance. The right occipito-parietal and right frontal regions show reduced SSVEP magnitudes. These changes are consistent with the literature, as the right posterior parietal region is important in the control of the attentional spotlight, and the right frontal region is involved with planning, and other forms of directed attention (see Kolb & Whishaw 1990). Novelty of stimuli also caused changes in the dynamic SSVEP with different topography to attention. Overall, this technique is a powerful and consistent indicator of changes in the magnitude of the steady-state visually evoked potential when used as a probe for
measuring attentional effects. In the experiment, a visually-based sustained attentional task showed marked and significant reductions in the right occipto-parietal and frontal regions. These changes are consistent with the literature regarding areas involved in attentional tasks of this type.
7. Modulation of attention.

The results from Chapter 6 showed a relationship between sustained attention and the SSVEP. Further exploration of the SSVEP and attention, to qualify the sensitivity of this relationship, took place experimentally. This experiment was part of a large study undertaken in the Swinburne Centre for Applied Neurosciences, and differed from the sustained attention experiment by including tasks which had periods of high and low attentional demands using alternating simple and complex tasks.

7.1. Introduction.

With the sustained attention or vigilance task described in the previous chapter, the subject's attention was maintained for the period of each of the tasks in the recording. The performance of subjects was verified by their correct identification of the modification applied to the circle after the task had finished. This method of checking on subject compliance is not ideal, and some form of checking during the experiment would be preferable. One such task to monitor subject performance at all stages during the recording is a continuous performance task or CPT (Rosvold et al. 1956). Originally designed to differentiate brain-injured children from controls, this task has letters, words, or objects displayed in a continuous train, and the subject has to respond to certain specified objects—called targets. In 1983, Klee & Garfunkel produced a computerised version of the task, and essentially the CPT used in this current experiment was a computer based task presented in a similar fashion.

In addition to the measures provided by the SSVEP, reaction times to the targets are recorded in the implementation, to provide a check on the performance of each subject. The tasks were planned to incorporate a simple continuous performance task—with a target number appearing in a regular series, and a complex continuous performance task—with a target letter appearing in a random series.
The findings of this experiment were expected to be consistent with the previous experiment. The extra information contained in this task, that is the alternation of high and low attentional periods, should produce a different topographic distribution of activity than the vigilance experiment. The frontal and parietal regions of the cortex are expected to have a major role in this task.


7.2.1. Subjects.

Forty right handed individuals aged between 18 and 28 years, with normal or corrected visual acuity served as subjects. All subjects gave their informed consent in accordance with the ethics committee of Swinburne Institute of Technology. The subjects completed two questionnaires: one of general information, the other of handedness—the Edinburgh inventory. Appendices 1 and 2 contain copies of these questionnaires. In addition, visual acuity was assessed using a Snellen Chart. Nineteen of the subjects were females, and twenty-one were males.

7.2.2. Attention task.

The subjects attended and responded to a Continuous Performance Task or CPT (Rosvold et al. 1956), presented using a computer in the manner of Klee and Garfunkel (1983). In this implementation of the CPT, subjects were asked to respond with a button press, when certain characters appeared on the screen†. The CPT had two distinct sections: a section where numbers were displayed (referred to as N), and a section where letters were displayed, and referred to as L. The task alternated between these two sections, each section lasting approximately 42 seconds, and began and finished with a numbers section as illustrated in Figure 7.1. Another task, referred to as Baseline Task (or BT), was carried out before the CPT. In this task, there was

† The exact instructions, as read to the subjects, are included as Appendix 3.
no alternation between numbers & letters; numbers were presented for the whole
duration of this task. The structure of the CPT and BT, including targets and timing,
are illustrated in Figure 7.1

![Figure 7.1](image)

Figure 7.1 **Attention tasks.** The CPT had numbers (N) or letters (L) components. The BT contained only numbers (N), with timing set the same for ease of comparison.

The numbers and letters sections of the tasks had their own internal structure. In the
numbers section, the digits 1, 2, 3, 4, & 5 were sequentially presented in an ordered
pattern, as illustrated in Figure 7.2. This pattern was repeated throughout the 42
second period, while the digits were presented each second.

![Figure 7.2](image)

Figure 7.2 **Numbers section of the CPT.** The digits 1–5 were presented in an ordered, sequential fashion. The target number was the number 5—as indicated. The target appeared 20% of the time in a predictable fashion. The subject had to respond by pressing a button when the target appeared.

Subjects were instructed to respond with a button press on the appearance of the
number ‘5’. Each digit was presented for a period of 500 ms, then disappeared, before
the next digit appeared. The numbers were presented at a rate of one per second, at
the centre of the screen, subtending a vertical angle of 2 degrees and a horizontal
angle of 2 degrees.

In the letters section, a random sequence of letters drawn from the letters C, D, E, F,
& G, were presented on the screen one at a time at a regular rate, as illustrated in
Figure 7.3. The letters appearing in this section were not predictable, as the numbers were in the previous section.

The subjects were asked to respond with a button press upon the appearance of the letter ‘E’. The letters were the same size, and presented at the same location, and rate as in the numbers section. Subjects responded whenever they believed that a target had been presented on the screen. The interval between presentation of the character on the screen and the subject responding was measured with a computer-based timer (Pipingas & Maruff 1991). Results were stored in a computer file along with other information regarding the presented character.

7.2.3. EEG & Probe recording.

The probe stimulus, a 13 Hz sinusoidal flicker which evoked the SSVEP, was superimposed on the subject's visual field using half silvered mirrors mounted on glasses to form the irrelevant, or probe stimulus. The flicker had a modulation depth of 45% and, when measured, subtended angles vertically 30 degrees, and horizontally 80 degrees, as described in Chapter 4.

The recordings were carried out in a quiet room with the 64 channel electrode helmet, and the Probe-ERP paradigm. The recording in this experiment was made with respect to a balanced non-cephalic reference (Stephenson & Gibbs 1951). After artifact detection and rejection routines, the magnitude of the SSVEP was determined from the cosine and sine Fourier coefficients, as described in Chapter 4.
Before the experiment began, a recording was made of duration 2 minutes. For the first 60 seconds of this time no visual stimulus was presented. The flicker stimulus was turned on at 60 seconds and the final 60 seconds contained a visual stimulus. During this preliminary recording, the subject watched the screen without pressing buttons. For convenience, this section of the recording is referred to as the ‘stimulus off-on’ period. Single frequency Fourier analysis techniques were used to extract the evoked response of the steady-state stimulus, at the stimulus frequency during the stimulus off-on period.

To make comparisons between the tasks, the consistent features within the CPT and BT were extracted. Both the numbers section, and the letters section of the CPT were separately examined, and alternate number sections of the BT. Data were collapsed across each section, yielding separate Numbers, Letters, and Baseline sections as illustrated in Figure 7.4.

![Figure 7.4 Collapsed recorded data.](image)

In the CPT, the mean SSVEP was calculated of all the numbers and letters sections respectively. In the BT, the mean SSVEP was calculated from alternate numbers sections (to allow a direct comparison with CPT).

The Fourier coefficients were separately evaluated to yield a single complex value at each recording location for both N & L. The BT yielded 1 complex value (B). Results from the 40 subjects were averaged to produce a group response. Averaging of the sine and cosine (or Cartesian) Fourier coefficients was computed separately before converting to the magnitude and phase (or polar) form for display. All subsequent analysis was carried out on the complex data, and both magnitude and
phase were interpolated using the spherical spline technique (Cadusch et al. 1992; Chapter 4).

7.3. Results.

Within the CPT, all subjects judged the letters section to be more demanding, requiring a greater degree of attention than the numbers section. The BT, consisting only of numbers, was also reported by the subjects to be less demanding than either section of the CPT.

With the three main sections for comparison: numbers (N, L) in the CPT, and numbers (B) in the BT, the results are included and salient features noted. The baseline task consisted only of numbers and the magnitude and phase of this period is illustrated in Figure 7.6.

Figure 7.5 Comparison of BT and CPT. The upper maps illustrate the mean magnitude and phase for the whole of the BT and CPT tasks. The lower map is the difference in magnitude and phase between the two upper maps.
Figure 7.6 **Baseline (B)**. The map on the left illustrates the magnitude of the SSVEP, while that on the right illustrates the phase of the SSVEP. The maps are a view from above the head, with the nose at the top of the diagram. The central and frontal regions are most active in this BT.

These data displayed on this map are direct SSVEP magnitude and phase. The task was recorded using a probe paradigm, where the regions with the lowest magnitudes have the highest activation or involvement in that task. The largest area of activation covers the occipital, temporal and frontal regions. The phase response illustrates uniformity across the scalp, with small changes in the occipital region.

The numbers section of the CPT is illustrated in Figure 7.7.

Figure 7.7 **Numbers (N)**. The overall appearance of the shape of these maps are similar in appearance to figure 7.6, although reduced in overall magnitude. The orientation and layout of the maps are the same as figure 7.6.

The results for the SSVEP probe response in N is similar to that seen for B. The largest reductions are seen in the occipital, temporal and frontal regions. This result shows consistency with the numbers of the BT, or B map in Figure 7.6.

The results for the CPT letters or L section are illustrated in Figure 7.8.
The letters section of the CPT shows a reduction in overall magnitude when compared to either Baseline or Numbers. The topography appears similar to both the Baseline and Numbers maps.

For the purposes of comparison of three separate sections, maps of the differences between the three previous maps were produced and the regions of greatest differences therefore stand out more clearly than in the previous maps. The relative importance of features on the difference map are measured by using a two dimensional analogue of the Student's t-test known as Hotelling's $T^2$ test (Picton et al. 1987). This is used to take into account both the Real and Imaginary components of the SSVEP, and the consistency of features between subjects. To examine the difference map, Hotelling's $T^2$ value is calculated at each electrode site and then interpolated. The interpolated map illustrates the value for $T$, as this reduces the dynamic range of the map for ease of display. On the T-value map contours join regions of constant T-value. They are present at T-values of 2.7, 2.97, and 3.35; corresponding to significance levels of 1%, 0.5%, and 0.1% respectively and subsequently mapped in each case.

Figure 7.9 illustrates Letters subtracted from Baseline. It shows positive numbers (or warmer colours) in regions where the SSVEP magnitude in the Letters section is lower than the Baseline section. This reduction in magnitude, according to the Probe-ERP interpretation corresponds to an increase in activation. In this section, a reduction in magnitude and increase in activation will be used synonymously. Thus, regions which show warmer colours have more task-related activity. The left centro-
occipital region shows the greatest activation, and the fronto-central region with large activation.

Figure 7.9 Difference and SPM maps Baseline vs Letters. The top left is Δ(magnitude) on the left, and Δ(phase) on the right, and the lower map the Hotelling’s T-value map. The largest differences exist in the central and frontal regions, particularly on the left, but the most significant region is the right central and frontal area.

The Baseline and Letters map shows the major effects in the frontal regions, closely follow the shape of the difference map. The left central frontal region which showed large activation in the difference map, shows a large T-value. The right frontal region also shows a large T-value, indicating that frontal regions are more active during the numbers section of the CPT when compared to the numbers section of the BT.
When Numbers are subtracted from Baseline, greater activation occurs in the left hemisphere, particularly spreading to the frontal regions.

When comparing the Numbers and Letters sections of the CPT, the differences are smaller overall, but concentrated in the frontal and central regions of the scalp. The map of Numbers and Letters within the CPT does not demonstrate changes as large as the other two T-maps, but does show the effects most consistently in the left fronto-temporal region, where the greatest activation was seen in the difference map. The effects here may also be explained by the planning role of the frontal regions, as they shift the processing from the low to high attentional states and back again.
7.4. Discussion.

The results of this study show some consistent trends. The frontal and central regions appear to be active when comparing either of the components of the CPT (that is N, L) to the BT. This finding is consistent with the degree of effort reported by subjects regarding the two tasks. It is also consistent with the literature regarding the increased involvement of the frontal lobes in tasks that require a higher level of sustained attention (Milner 1992).

The right frontal region reaching a T-value above 3.35 is particularly interesting as this indicates that it may be more important than the left frontal for the visual-spatial nature of the task.

The involvement of the parietal regions is consistent with the study in the previous chapter, and agrees with the blood flow studies indicating that these regions have a function in directed attention (Roland 1984). The parietal lobes have long been associated with attention, or injury to this region has been associated with unilateral spatial neglect—particularly right parietal injury (Walsh 1978). The left parietal
region is also involved but in a less severe form of spatial neglect (Kolb & Whishaw 1990).

The active temporal regions were not expected, but may be related to the recognition of objects. Single cell recordings in the monkey inferior temporal region show that cells fire maximally upon the presentation of faces, and their firing rate decreases when features of the face—such as eyes—are removed (Gross et al 1984). Other studies show strong links between the temporal lobes and object recognition in (Desimone & Ungerleider 1989; Desimone 1991; Corbetta et al. 1991; Baizer et al. 1991; Goodale & Milner 1992; Pigott & Milner 1993).

When the comparison is made between the Numbers & Letters of the CPT, fewer and smaller differences are found, but they exist in the precentral motor strip areas of the cortex. This may be related to the planning and execution of movement, as the subjects were instructed to “. . . respond quickly . . .” to the targets in the CPT, whereas in the BT they were only instructed to “. . . respond . . .” to targets in the BT.

The SSVEP probe topography appears to be influenced by changes in attention. The SSVEP probe topography shows differences when comparing a CPT with a BT. Within the CPT, the greatest reduction in the probe amplitude is seen with the letters section of the task (that is, the more difficult section of the CPT). These differences were greatest in the frontal regions of the topographic maps.
The underlying premise of the interpretation has been the limited capacity model. The examination of the experimental data in the light of this model provides findings consistent with the neuropsychological literature regarding the type of attention used here. Interaction with the subcortical regions remains difficult to measure with superficial scalp recordings, and their limitations. No speculation can be offered regarding the nature of subcortical role in these attentional processes beyond those previously reported functions described in Chapter 2.

7.5. Summary.

Using an attentional task and young adults, experimental data were obtained that showed various regions of the cortex strongly involved in visual selective attention. These regions were frontal, parietal, and temporal regions that have significantly different topographies during the high and low attentional phases of the tasks. The findings are consistent with other findings regarding attention and led to a subsequent study to examine the suitability of such tasks for use with brain-injured individuals.
8. **An examination of some brain-injured individuals.**

This chapter details a small pilot experiment with several brain-injured individuals, using the same attentional task as in Chapter 7. The results were examined for correlation with findings in any available neurological, radiological, and neuropsychological data. This study was planned to make comparisons of individual Probe-SSVEP recordings and those of a control group of subjects, but it became apparent that a comparison was not possible due to the small numbers of brain-injured subjects who were both suitable and available at the recording time.

### 8.1. Introduction.

Brain injury is frequently a debilitating experience. Trauma, infection, tumours, strokes and other factors cause brain injury. This in turn causes changes that manifest in a complex variety of behaviours and functions. Due to the unique layout and connections of the cortex, predicting functional changes from localised brain injury remains a difficult task. Although as Walsh points out:

“A century of lesion studies has demonstrated that these abstractions, the ‘lobes’ of the brain, are still more useful at this stage in discussing brain-behaviour relationships than those based on finer subdivisions of the cytoarchitecture.” (Walsh 1978 p. 18.).

Luria (1973) analysed how mental activity is altered by local brain lesions. He did so by dividing mental activity into three principal units: (1) regulating tone or waking; obtaining, (2) processing and storing information; and (3) programming, regulating and verifying mental activity. With these guiding remarks, generalisations about possible loss of function in the frontal, parietal, and subcortical structures are included here.

The frontal lobes take up about one third of the cerebral cortex in humans, and serve a variety of functions, including abstract thinking, planning and problem solving, error evaluation, and some aspects of emotion and personality (Walsh 1978). The left frontal region has been associated with positive affect, and also with verbal fluency;
while the right is more commonly associated with negative affect and constructional
tasks (Walsh 1978; Davidson & Schaffer 1983). The frontal lobes are part of the third
system in Luria's model, and hence the performance on a task requiring planning may
suffer as a result of impairment in this third system.

The parietal lobes of the cortex perform a different function to the frontal lobes. They
are in the posterior portion of the cortex, and have a variety of sensory roles—
including that of somatosensory reception, and intersensory association (Walsh 1978).
Luria (1973) assigns three roles to the parietal regions: (1) that of general sensory
cortex; (2) secondary regions for the visual and auditory function; and (3) tertiary
function which overlaps these regions to integrate sensory input to the spatial domain.
He also emphasises that this tertiary role shows a diminution of specificity and an
increase in functional lateralisation. With unilateral parietal injury, the contralateral
body space suffers a loss of representation, and this is functionally more pronounced in
right rather than left hemisphere injury, and is termed unilateral spatial neglect (Walsh
1978). The mechanisms for reduction in awareness of body space, such as reported
with the parietal lobes, or the reduction in planning and error correction, reported with
the frontal lobes, is unknown. One theoretical framework in which to describe the
changes, is the capacity model.

The brain's capacity for processing is limited, and the resources allocated to processing
any given task depends upon the overall available capacity, difficulty of the task, and
non-controlled variables. The available capacity is determined by factors such as
overall arousal and alertness, and a reduction in either of these, leads to a reduction in
available capacity (Kahneman 1973). To determine the resources allocated for a
particular task, an index of spare-capacity—the Probe-ERP—has been previously used
(Papanicolaou & Johnstone 1984). The available capacity in brain-injured individuals
may be further reduced for other reasons, such as lack of attention, or reduced
function (Shulman et al. 1960). This reduction in capacity may affect the evoked
response recorded in an experiment such as an attentional task. The expected
outcome of a reduction in capacity is an overall decrease in the probe response, as
seen for the controls in Chapter 7. The patients, therefore, would be expected to have lower overall probe responses for the tasks, due to an overall smaller capacity compared to control subjects, as illustrated in Figure 8.1.

![Figure 8.1. Processing model.](image)
The expected change in Probe-ERP is a reduction, brought about by the overall reduction in resources.

The changes in Probe-ERP for brain-injured subjects is one of the factors examined in this additional experiment.

### 8.2. Materials and methods.

The equipment and recording arrangements are described in detail in Chapter 4, and the task protocol in Chapter 7, and only a brief description of these follows. Firstly the recording arrangements. Subjects were seated in a comfortable chair in a quiet room. A monitor was directly in front of them, and the sixty-four channel helmet suspended from the ceiling with a counterbalance. All the instrumentation was situated directly behind the subject to reduce subject anxiety. Briefly, the tasks included a Baseline Task (BT) and a Continuous Performance Task (CPT). Both these tasks comprised a 13 Hz visual flicker superimposed on the visual field of the subject viewing a monitor. The subject viewed letters and numbers on the monitor, and responded by pressing a button whenever a target letter or number appeared. In other words, the tasks involved both a steady-state stimulus, and a cognitive task, forming the Probe-ERP paradigm. Before the subject began these tasks, a short period without flicker followed by a short period after the flicker onset was recorded. During this preliminary recording, the subject watched the screen without pressing
buttons. For convenience, this section of the recording is referred to as the ‘stimulus off-on’ period.

### 8.2.1. Subject preparation and assessment.

Six brain-injured individuals—in-patients at St. Vincent's Hospital Melbourne—formed the patient recording group. This group included individuals with brain lesions involving frontal, parietal, or subcortical structures. Each patient had a unique injury, making the patient group heterogeneous. As a result, they have been treated as individuals and not as a collective *brain-injured* group. Table 8.1 lists the subject identifier and other personal data. All patients gave their informed consent in accordance with St. Vincent's Hospital ethics committee (Protocol Number S.V.H. 33/85, attached in Appendix 4). Patients completed, or were assisted to complete, a handedness questionnaire (Appendix 2), and were interviewed to complete a subject data form (Appendix 1). The patient history was examined for information regarding region of injury and other relevant information. A summary of patient information is recorded in Table 8.1. All patient and subject identities are coded for confidentiality.
<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Education level (yrs)</th>
<th>Age</th>
<th>Lesion</th>
<th>available data</th>
</tr>
</thead>
<tbody>
<tr>
<td>VP</td>
<td>M</td>
<td>10</td>
<td>76.9</td>
<td>Right frontal tumour ≈2 cm.</td>
<td>RT</td>
</tr>
<tr>
<td>AC†</td>
<td>M</td>
<td>11</td>
<td>73.5</td>
<td>Right parietal infarction.</td>
<td>RT</td>
</tr>
<tr>
<td>RB</td>
<td>M</td>
<td>14</td>
<td>65.5</td>
<td>Left frontal tumour ≈2.5 cm.</td>
<td>RT+ERP</td>
</tr>
<tr>
<td>EC</td>
<td>M</td>
<td>8</td>
<td>73.0</td>
<td>Right posterior parietal tumour.</td>
<td>RT+ERP</td>
</tr>
<tr>
<td>TC</td>
<td>M</td>
<td>8</td>
<td>64.8</td>
<td>Right middle cerebral artery infarction affecting right frontal parietal structures.</td>
<td>RT+ERP</td>
</tr>
<tr>
<td>MT</td>
<td>M</td>
<td>11</td>
<td>75.9</td>
<td>Left internal capsule infarction.</td>
<td>RT+ERP</td>
</tr>
</tbody>
</table>

Table 8.1 **Brain-injured subjects.**

A summary of the information regarding the six brain-injured patients. In the available data column, RT—indicates Reaction Times were recorded, and ERP—indicates Event-Related Potentials were recorded.

It is important to note that there was considerable effort involved in locating suitable brain-injured individuals. This was due to uncontrollable factors affecting the availability of brain-injured individuals, who:

- were able to perform the tasks,
- had no symptoms of epilepsy because the visual stimulus may induce a seizure (because epilepsy is often a consequence of brain injury, several subjects were rejected before the recording sessions began),
- gave their informed consent,
- understood the English language,
- were able to see and hear,
- remained in-patients for several days to allow time for scheduling a recording session.

Apart from the difficulties of recruiting suitable subjects, the physical nature of the recording posed limitations upon the subjects. The need for subjects to remain still during a recording is something taken for granted with control subjects, but with brain-injured subjects proved difficult to achieve. In some instances subjects were prone to be restless, while in others they were unable to maintain their balance properly, and leaned to the side contralateral to the lesion. This meant that some

† Subject AC was an outpatient of another hospital, and complete records were unavailable at the time of writing.
recordings did not progress smoothly, but all recordings were satisfactory for the tasks described here\textsuperscript{†}.

The sixty-four channel recording system was available for a limited time only, and needed to be shared among other members of SCAN introducing a further, tighter constraint, independent of those above. Despite these limitations, over a period of about one month, six patients were recruited from Neurology and Neurosurgery wards, and recordings made—four with event-related potentials. Each recording lasted about one hour from beginning to end, including the initial interview and questionnaires.

8.3. Results and analyses.

The experimental recording protocol yielded primarily evoked potentials, in the form of steady-state Probe-ERP for the Preliminary, BT, and CPT. Additional information about reaction times were extracted from each subject’s responses to the BT and CPT, and are also considered. Predictions regarding performance are considered first.

8.3.1. Analysis of injury.

The two frontal patients have similar sized tumours, but in opposite hemispheres (VP—right; AC—left). It is difficult to make any predictions regarding their performance, except that they may have a problem inhibiting incorrect or inappropriate behaviour. During the tasks, this was not evident for patient AC, but patient VP had difficulty distinguishing the ‘E’ in the CPT (which was supported by the overall number of errors in his response).

Patients AC (right infarction), EC (right tumour), and to a lesser extent TC (infarction of right middle cerebral artery) have injury in the parietal region. The expected decline

\textsuperscript{†} Two other tasks were recorded in the same session, after the CPT and BT, but all subjects showed problems with electrode and movement artifact, and these tasks have not been considered.
in function with unilateral spatial neglect, with weakness on the contralateral musculature was observed. The design of the CPT and BT meant that the letters and numbers were presented in the central visual field of the subject, and thus the visibility of the characters should not be influenced by any spatial neglect. This was the case, as none of these patients reported any difficulty in seeing the monitor or the characters displayed upon it.

The middle cerebral artery supplies blood to an extensive area of the cortex. Blockage often tends to be confined to the superior division which supplies the lateral orbitofrontal and dorsolateral prefrontal areas, premotor, somatosensory and anterior parietal cortex (Walsh 1991). The patient with right middle cerebral artery infarction (TC) has been considered with both the frontal and parietal groups, but overlaps both with an extensive range of infarcted tissue, and probably a larger potential disruption of function, and would be predicted to show most impairment, or poorest performance—this was not the case.

The patient with left internal capsule infarction (MT) has not been considered yet. This region of the brain acts mainly as a thoroughfare for afferent and efferent fibres—with the posterior end containing visual and auditory afferents, and the anterior end containing contralateral motor efferents. Not surprisingly, this patient had the most trouble maintaining balance, perhaps indicating an anterior infarction of the internal capsule. This patient performed reasonably well on all tasks.

8.3.2. Reaction times.

With the BT and the computerised CPT, there were about 140 characters presented on the screen. Within the BT, there were twenty-eight presentation of the target ‘5’, and within the CPT, twelve presentations of the target ‘E’. The occurrence of targets, from the subjects' point of view, appeared to be completely regular for the BT, and completely random for the CPT. The detection of targets and response to targets was the prime aim of the subject, and an analysis of the reaction times deals with the time from presentation of the target until the button press.
For the set of targets in each task, the initial examination of the data was to check for any trends, such as a reduction in the reaction times, or a learning effect, the mean CPT reaction times were plotted for the control group—as illustrated in Figure 8.2. The responses for all control subjects are reported in Appendix 5.

Figure 8.2 Reaction times of control group plotted against target number. Mean reaction time (dark shading) and three standard errors (light shading) for all 12 targets. This illustrates that the reaction time is independent of the target position.

Figure 8.2 shows no evidence of any reduction in the reaction times over the CPT—that is, no learning effect. This finding indicates that any target is representative of the reaction times (except perhaps target 11), and two targets were chosen to make a comparison with the brain-injured individuals. The choice of these two targets depended upon the patients. The patients failed to identify more of the targets (errors of omission) than the controls, but all patients responded to both target 6 and target 9. Most of the control subjects also responded to targets 6 and 9, and hence, these targets were selected for comparison with the control group, as illustrated in Figure 8.3, with the complete responses for all patients contained in Appendix 6.
The upper chart shows the reaction times of the patients (VP, AC, RB, TC, MT) for target 6, and the controls—C (dark shading), with added 3-standard errors of the mean (light shading). The lower chart shows the reaction times for target 9.

All patients except RB, have significantly longer reaction times than the control group.

The patient data lie outside the three standard errors of the mean, and are significantly different from the control group. The only exception to this is patient RB, whose reaction times lie just outside the upper limit of the normal range for both targets. The finding of increased reaction time is consistent with the studies of simple reaction times and brain-injured individuals and groups (for example, Benton 1986; Stuss et al. 1989; Deacon & Campbell 1991).

Clearly all the patients (except RB) have demonstrably slower reaction times than the control group for the target presentation within the CPT. These differences are significant, but because of the age differences between the patients and the control group (average age 19.6), are not conclusively different. To address this question, I examined the reaction time literature for the effect of age on reaction times. Gottsdanker (1982) reported that simple reaction time increases by 0.2 milliseconds for every year of age, while choice reaction time increases by 1.5 milliseconds per year (Salthouse 1990). The reaction time protocol is neither simple, nor choice, it is disjunctive†, and Welford (1977), from a substantial review of reaction time and age, surmised that between ages 20 and 60 years, a 19 per cent increase in reaction time

† Disjunctive reaction time is where the subject responds to only one of several signals. It differs from choice reaction time—which has the same number of responses as signals. Disjunctive reaction time is shorter than choice reaction time (Welford 1977).
occurs. For the same age range as in the present study, simple reaction time increases 16 per cent (Welford 1977). These figures correspond to approximately 0.32 milliseconds per year for simple, and 0.37 milliseconds per year for disjunctive reaction time. To account for the age difference between controls and patients, an overestimate of 0.5 milliseconds has been subtracted from each patient, for every year above the mean control age (19.6 years).

A summary of these corrections is found in Table 8.2, and the earlier findings of significant differences between all patients (except RB) and the control group still exist.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Uncorrected RT (ms)</th>
<th>Corrected RT (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>target 6</td>
<td>target 9</td>
</tr>
<tr>
<td>VP</td>
<td>1194</td>
<td>799</td>
</tr>
<tr>
<td>AC</td>
<td>828</td>
<td>586</td>
</tr>
<tr>
<td>RB</td>
<td>478</td>
<td>423</td>
</tr>
<tr>
<td>EC</td>
<td>843</td>
<td>757</td>
</tr>
<tr>
<td>TC</td>
<td>867</td>
<td>694</td>
</tr>
<tr>
<td>MT</td>
<td>561</td>
<td>518</td>
</tr>
<tr>
<td>control</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.2 Reaction times for patients.
The corrected reaction time is computed by subtracting from the reaction time of each patient the value of 0.5 milliseconds for each year older than mean control age (19.6 years).

When the same comparisons, of patients with the control group, are made for the reaction times within the BT, considerably more variation appears than in the CPT; these data can be found in Appendix 7. One possible reason for this variation is the instructions given to the subjects. In the BT, they are instructed to: “. . . press the button whenever you see the ‘5’.”, whereas in the CPT, they are instructed to: “. . . press the button as quickly as you can whenever you see the letter ‘E’.”‡. For this reason, the remainder of the reaction time results and discussion deal with the CPT only.

‡ The exact instructions read to the subjects can be found in Appendix 3.
The findings of increased reaction times in all patients agrees with the studies of Stuss et al. (1989) and Campbell et al. (1990) who found that head-injured patients record longer reaction times than control subjects. Other studies have differentiated between left and right brain injury and shown the greatest slowing of reaction times occurs for patients with injury in the right hemisphere (Heilman & van den Abell 1979; Coslett et al. 1987). This increased reaction time is seen in all the patients in the present study, with the two left hemisphere injury patients showing the smallest increase in reaction times (patients RB & MT), and the right hemisphere injury patients showing the largest increases in reaction time. This finding is consistent with the studies above—as Stuss et al. (1989) found that increases in reaction time occurred in both left and right hemisphere injured patients when the task was a choice (and not just a simple) reaction time paradigm.

The results, however could be influenced by levels of anxiety, and other factors. Patient-reported levels of anxiety for the CPT were indicated on an analogue scale by the patient before and after the cognitive task. These data are recorded in Table 8.3, before and after the CPT. The analogue anxiety scale is a continuum twelve centimetres long; the subject indicates with a stroke of a pencil their level of anxiety on this line. The left end of the line is labelled as *most relaxed*, and the right end as *most anxious*. The number in the table below is the measured anxiety level in centimetres.
When the Table 8.3 is compared with Table 8.2, one noteworthy finding emerges: the patients with the longest reaction times on the CPT had the highest anxiety levels. The regression line had an \( r \) value of 0.75, 0.83 (target 6 vs. pre & post score respectively), or \( r \) value of 0.72, 0.82 (target 9 vs. pre & post scores respectively).

With the available data, a cause or effect is unknown, as the poor performance may have caused an anxiety, or the anxiety may have caused a poor performance. Such questions, although interesting, cannot be answered from this study. The interaction between anxiety and reaction time may be a confounding factor. It is difficult to dissociate selective attention from other neuropsychological tests—that can be influenced by factors including: motivation, verbal comprehension of instructions, memory, and language production (Papanicolaou 1987).

The level of arousal or of attention or vigilance may be measured by the number of errors and their type. The overall level of cortical arousal has been reported lower in right hemisphere injured patients than controls or left hemisphere injured patients (Walsh 1978; Heilman & van den Abell 1979). Other measures such as Galvanic Skin Response have also been found to be lower in right hemisphere injured patients (Heilman & van den Abell 1979).

<table>
<thead>
<tr>
<th>Patient</th>
<th>Anxiety score before:</th>
<th>Anxiety score after:</th>
<th>Subject's comments.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VP</td>
<td>8.0</td>
<td>9.3</td>
<td>difficulty with task</td>
</tr>
<tr>
<td>AC</td>
<td>9.4</td>
<td>9.4</td>
<td>extremely anxious</td>
</tr>
<tr>
<td>RB</td>
<td>0.8</td>
<td>0.8</td>
<td>found task easy</td>
</tr>
<tr>
<td>EC</td>
<td>7.0</td>
<td>8.7</td>
<td>difficulty with task</td>
</tr>
<tr>
<td>TC</td>
<td>10.9</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>MT</td>
<td>0.9</td>
<td>1.6</td>
<td>tired</td>
</tr>
</tbody>
</table>

Table 8.3  Anxiety scores.
This table lists the self-reported level of anxiety immediately before and after the CPT.
### Table 8.4 Error scores.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Errors:</th>
<th>Errors:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>omissions</td>
<td>commissions</td>
</tr>
<tr>
<td>VP</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>AC</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>RB</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EC</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>TC</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>MT</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Control</td>
<td>0.31±0.26</td>
<td>0.02±0.05</td>
</tr>
</tbody>
</table>

This table lists the errors of omission and the errors of commission for the CPT. The control value is the mean ± 3 standard errors.

With the small number of patients in this study, the findings of right hemisphere injury interfering with reaction times more than left hemisphere injury has been supported. The unanswered question from this work is, whether this increase in reaction time is due to the injury, or due to anxiety effects.

Having found that right hemisphere injury produced the longest reaction times, consistent with Heilman & van den Abell (1979) and Coslett et al. (1987), the next step was the examination of the electrophysiological responses for any patterns or trends.

#### 8.3.2.1. Cognitive task analyses.

One of the major aims was to show some differences between the brain-injured individuals and the control group during the cognitive tasks. If the brain-injured individuals have deficits in attention, these may manifest in a higher relative SSVEP level for the CPT (high-load) compared to the BT (low-load). The control group show greater distinction between the high and low-load cognitive tasks, as reported in Chapter 7.

The initial analysis was an examination of the average level for the complete tasks. The magnitude and phase of the SSVEP was evaluated over the complete cognitive
Figure 8.4 displays interpolated, topographic maps for the BT for the control group and the patients.

![Maps of BT](image)

There are no trends, apart from a maximum SSVEP level in the occipital region. This maximum value is not apparent in the control map due to the scale used. For a more indicative, scaled map, refer to Figure 7.6, that uses a more sensitive scale.
Figure 8.5 Maps of CPT.
The upper row illustrates the mean level of the SSVEP during CPT for the control group. Subsequent rows contain the patient data: RB, EC, TC & MT. The left map of each pair is of the magnitude, while the right map is phase.

Figure 8.6 Maps of difference between BT & CPT.
The upper row illustrates the mean difference of the SSVEP during BT and CPT for the control group. Subsequent rows contain the patient data: RB, EC, TC & MT. The left map of each pair is of the $\Delta$(magnitude), while the right map is $\Delta$(phase).
The differences between the tasks, as illustrated in Figures 8.4, 8.5 & 8.6, show that distinctions between individuals and control group were small by comparison. The analysis becomes more involved at this level by considering the separate components of the tasks; that is, the Letters and Numbers sections of both tasks—such as for the controls in Figure 7.13.

For the controls, an examination of the Letters versus Numbers in Chapter 7 showed a difference. Higher potentials occur in the Numbers when compared with the Letters, and also higher potentials in the BT when compared with the CPT, for the Numbers section.

![Maps of numbers](image)

Figure 8.7. **Maps of numbers.** The upper row illustrates the mean level of the SSVEP in the control subjects during the alternate numbers phases of the BT. (Refer to Figures 7.1 & 7.4 for timing information). The subsequent rows contain the patient data RB, EC, TC, & MT respectively. The left map of each pair contains the magnitude information, the right the phase.

The topographic maps illustrated in Figure 8.7 show that the response for the brain-injured subjects is similar to that of the controls for the magnitude, apart from patient RB. The phase information appears different due to discontinuities. Most of the discontinuities in the phase are caused by wrap-around, where $-\pi$ is equivalent to $+\pi$. The phase discontinuities could be reduced by subtracting a constant from the phase.
data before mapping. Little detail appears in the control maps, as all maps have been displayed on the same scale, but detail in the control maps can be observed in figure 7.5.

The topographic maps illustrated in Figure 8.8 show that the response for the brain-injured subjects is similar to that of the controls for the magnitude, apart from patient RB. The phase information appears different due to discontinuities. Most of the discontinuities in the phase are caused by wrap-around, where $-\pi$ is equivalent to $+\pi$. The phase discontinuities could be reduced by subtracting a constant from the phase data before mapping. Little detail appears in the control maps, as all maps have been displayed on the same scale, but detail in the control maps can be observed in figure 7.6.
The topographic maps illustrated in Figure 8.9 show that the response for the brain-injured subjects is similar to that of the controls for the magnitude, apart from patient RB. The phase information appears different due to discontinuities. Most of the discontinuities in the phase are caused by wrap-around, where $-\pi$ is equivalent to $+\pi$. The phase discontinuities could be reduced by subtracting a constant from the phase data before mapping. Little detail appears in the control maps, as all maps have been displayed on the same scale, but detail in the control maps can be observed in figure 7.7.

8.4. Discussion.

There are no trends observable in the brain-injured patient data for the maps of the tasks. Either in the overall averages for the BT and CPT, or in the sections of the tasks containing high and low attentional states. Therefore no real conclusions, can be
made regarding the effects of brain injury on such attentional states as used in the recordings.

Arguments exist for both a decrease or an increase in the probe SSVEP as a result of brain injury. They are as follows.

a. The ability to perform the attentional task is decreased (compared with the controls), and overall resources remain the same. This gives rise to an increase Probe-ERP value, as illustrated in the upper portion of Figure 8.10.

b. The overall resources are smaller (compared with the controls), but the ability to perform the task is the same. This gives rise to a decreased Probe-ERP value, as illustrated in the lower portion of Figure 8.10.

![Figure 8.10. Changes in the Probe-ERP.](image)
The upper panel explains the case of an increase in the Probe-ERP increase by the reduction in the ability to perform the given task. The lower panel explains the decrease in the Probe-ERP by the reduction in the overall resources (capacity).

Either of these explanations could be argued, and accepting that the underlying functional changes may be unique to each individual, then an unpredictable Probe-ERP value may result.
8.5. Summary.

In general, no consistent electrophysiological differences between the brain-injured individuals and the control group were observed. This lack of a positive result for the Probe-ERP could be due to one of several reasons.

a. No differences in the Probe-ERP exist between the brain-injured and the control group. This would indicate that the technique is not sufficiently sensitive to distinguish between the individuals and the control group.

b. Differences occur in the Probe-ERP between the brain-injured and the control group, but the variability of the results from the individuals masks these differences. This would indicate that the technique may possess sufficient sensitivity, but the individual variation in the four brain-injured individuals is too great to draw out any patterns. A large-scale repeat study with a large group of brain-injured individuals with injury in the same region, may allow this proposal to be fully investigated.

c. Differences exist, but the methods used in this study may not elucidate such differences. This explanation is favoured, as the existence of differences between the brain-injured individuals and control subjects is clearly established (both within the literature, and from the reaction time data). The arguments presented for resolving the increase or decrease in different individuals (in a and b above), show an attempt to explain the observed changes.

This study comparing the brain-injured with the controls serves as a useful introduction to their further comparison. Such a study is beyond the scope of this work due to the time-consuming factors of recruiting and recording such a huge amount of data from many brain-injured subjects, and age-matched controls. The suitability of the cognitive tasks may also have to be re-assessed in the light of this work.
9. Conclusion.

This thesis has considered aspects of visual selective attention. It has reviewed the relevant literature, described the practical considerations of implementing the recording system, and reported and interpreted the recorded information and its applications.

The visual field provides more information than can be processed, and the removal of extraneous or irrelevant information forms the process of visual selective attention. The spotlight model provided a framework in which to interpret the process of selective attention. The removal of irrelevant information occurred by focussing attention in the region of the spotlight. The level in the processing where this information reduction takes place was reviewed. Some reports placed the reduction as early as the visual pathways, citing evidence of peripheral gating of sensory information. Other reports implicated the midbrain structures such as the superior colliculus, lateral geniculate nucleus, and pulvinar nucleus as the regional locus of information reduction. More evidence existed for the midbrain regions than the peripheral structures.

The spotlight model does not provide an overall perspective of the process of selective attention; other factors, including conscious, or cortical control of attention need to be considered. Two regions of the cortex have been found to have strong links with visual selective attention—the frontal and parietal lobes.

Two separate pieces of evidence link the parietal lobes with attention. Firstly, the finding that injury or lesions to the posterior parietal region produces a condition known as spatial neglect, with difficulty attending to the visual field contralateral to the lesion. Secondly, interconnections have been reported between the posterior parietal cortex and the pulvinar nucleus, already implicated in selective attention. These findings indicated that the parietal region has an important role in mediating visual spatial selective attention, and may provide a mechanism for ‘fine-tuning’ the midbrain mechanisms.
The other area of the cortex linked with control of attention was the frontal lobe. This region has been associated with action, motor movement and planning stages of action, including overall control of other regions via connections with most regions of the cortex. The frontal lobes possess connections with thalamic reticular nuclei via the medio-thalamo-frontocortical system (MTFCS), and may influence information arising from the superior colliculus, pulvinar nucleus, and lateral geniculate nucleus. The frontal lobes have an important role in providing conscious control over the spotlight of visual spatial selective attention.

The functional connections of the frontal-midbrain, and parietal-midbrain regions in addition to fronto-parietal connections provide a working model of visual spatial selective attention. The spotlight acts to reduce the amount of information outside the region of interest entering the stream of conscious processing. The spotlight successfully described visual spatial selective attention, allowing flexibility with its variable size, somewhat circular-shape and its ability to move in space to envelop other locations. The spotlight possesses a fuzzy edge, so that objects and locations just outside the main beam are attenuated but not completely eliminated from the information processing.

The properties of the spotlight and other aspects of attention have been tested previously with behavioural methods, and also with some event-related potential (ERP) methods. The ERP methods involved the recording of responses to several hundred transient stimuli containing information. These methods answered some questions about attention, but could not provide information about the changes of attention with time, as they were based upon an assumption that during the recording period (of the order of tens of minutes), attention remained static.

Changes in attention occurs over a period of seconds to minutes, and are best investigated by a technique that functions over this range. An innovative procedure was developed to explore aspects of visual selective attention—the Probe-SSVEP. The SSVEP was extracted from the scalp recorded EEG in response to an appropriately modulated visual stimulus. The SSVEP was evaluated using a ‘moving-
window’ function, and the size or width of this ‘moving-window’ can range from ten seconds to several minutes. A variant of the SSVEP technique, with the stimulus presented in a task-irrelevant fashion, allows the SSVEP to be a probe of unused neural processing capacity—this variant is known as the Probe-ERP paradigm. The research group at SCAN used the steady-state stimulus in a probe fashion to index the functional capacity of the system during attentional tasks, and attempted to gain insight into the available capacity of cortical regions during the processing of visual attentional information. To assess the contribution of various cortical regions required adequate coverage of the scalp by recording electrodes. This meant that a multi-channel recording system was needed. The multi-channel recording of the SSVEP included the development of hardware, and associated computer-based data acquisition, testing and analysis packages. Considerable work was required in setting-up the recording, analysis, and display system. The laboratory at SCAN was also formed during this developmental work.

The recording of the Probe-SSVEP began after the experimental procedures were in place. Several experiments were carried out to provide some knowledge of the mechanisms of the SSVEP. The first of these investigated more thoroughly the correlation previously noted between the SSVEP and spontaneous alpha activity. The current experimental work was consistent with the earlier findings, and showed that across the group the largest responses to visual stimulation at 13 Hz also corresponded to the largest amplitude alpha activity. More detailed examination of the recordings of individual subjects showed that alpha activity was not always correlated with SSVEP. The findings of this experiment clearly indicate that 13 Hz SSVEP and spontaneous alpha activity are similar, but may have different populations of neurons responsible for each.

The next experiment examined the effects of sustained attention on the Probe-SSVEP. The experiment recorded the Probe-SSVEP from subjects while they watched a series of shapes displayed on a monitor. Subjects in the first two trials simply looked at the screen, but in the final trial they were instructed to look for a modified shape. The
results were a decreased SSVEP magnitude, indicating increased activation during periods of visual vigilance or sustained attention. In the experiment, three separate phases occurred when subjects were presumed to be in three separate states: that of waiting during presentation of the shapes, anticipation of the modified shape, and detection of the modified shape. The greatest increases of activation occurred in the parietal and occipital regions during anticipation; and in the occipital, parietal and right prefrontal regions during detection. These changes are consistent with currently accepted models of attention. The right posterior parietal region is important in the control of the attentional spotlight, and the right frontal region is involved with planning, and other forms of directed attention.

The attentional task in the previous experiment was simple, and the logical progression was to use a more sophisticated task. To further examine the sensitivity of the Probe-SSVEP to attention, a continuous performance task (CPT) was designed with distinct levels of attention. In addition, a simpler task was used as a control and referred to as the baseline task (BT). The regional distribution of the Probe-SSVEP was recorded from 40 subjects during both the CPT and BT. The distribution of activity showed that the frontal and central regions had reduced Probe-SSVEP amplitudes when comparing the CPT and the BT. This indicated that during the task with high attentional demand (CPT), the frontal and central regions were more active than during the low attentional demand task (BT). This finding is consistent with previous studies reporting increased involvement of the frontal lobes in tasks that require a higher level of sustained attention.

The CPT was used for a pilot study with a small group of brain-injured subjects, and compared to the 40 control subjects. The results from this pilot study showed that reaction times recorded from the brain-injured subjects were significantly longer than for the control subjects. The Probe-SSVEP yielded no consistent results for the brain-injured subjects.

The finding of longer reaction times for all patients was consistent with other studies of brain injury and reaction time. The expected finding of right hemisphere lesions
producing larger deficits than left hemisphere lesions was supported by this study, but
due to small numbers is equivocal.

The numbers of brain-injured subjects in this additional study did not allow any strong
conclusions to be drawn. Future studies would require access to a large ‘bank’ of
brain-injured individuals, with comparable lesions in comparable locations, which the
present study was unable to successfully obtain. It could conceivably take several
years to access sufficient numbers to adequately answer the questions regarding
deficits in attention, that proposed at the outset.

In conclusion, this thesis encompasses the wide range of activities involved in the
setting-up and recording the ‘human steady-state visually evoked potential topography
and attention’. It provides a basis for the place for such systems and experimental
recording techniques as a tool for understanding attention. The preliminary findings of
this work provided, in the first instance, a foundation upon which potential extension
of the work is possible and ultimately attainable. The similarity between alpha and
SSVEP is shown to be superficial, probably with separate mechanisms involved in the
generation of each type of activity. The important findings regarding high and low
attention (in the CPT) indicate that the consistent topographic trends observed with
forty subjects add to our understanding of selective attention under these experimental
conditions, and begs further testing of the Probe-SSVEP technique for other
attentional and cognitive tasks. The small pilot study involving functionally impaired,
brain-injured subjects highlights the promise of application of the technique to this
area on a much larger scale, but at the same time provides a sober reminder of the
difficulty of recording from brain-injured people, and the much more difficult task of
finding groups with homogeneous lesions.

9.1. Future directions.

There are many directions in which future research can travel from this starting point.
They fall roughly into three main areas: further development of the equipment and
techniques; further exploration of attention; and further exploration of the brain-injured population.

1. The equipment used was primarily developed for a series of studies, including those described in this thesis. The equipment could be further improved to offer greater spatial resolution by better coverage of the scalp with recording electrodes. It could also be improved by the use of some of the added features of the ‘interpolation function’ mapping routines, including those currently being developed at SCAN for conversion to source currents both on the scalp and mapped onto a realistic cortical surface. These techniques would yield much higher spatial resolution than that obtained by the recording of scalp potentials alone, once the spatially blurring effects of the skull and scalp were removed from the potentials. These need to be coupled with higher electrode density recording, and these projects have already begun at SCAN. This direction of development will lead to better recording techniques, and perhaps provide a better base for the Probe-SSVEP to examine cognitive function of the human brain.

2. The studies of attention using the Probe-SSVEP indicated various regions of the cortex were involved in visual vigilance, and sustained attention. These regions predominantly included the frontal, parietal regions, but also other regions. However, the selectivity of such findings is poor, and further studies should examine the possibility of refining the attention or activation experiments so that a greater ability to localise those regions of the brain is possible. If this area is developed along with the equipment and techniques, then the understanding of attention and cognitive processes in the human brain may be enhanced to a level where examination, and comparisons of patient groups can occur.

3. The third area for extension of the techniques is in studying the changes that occur with acquired brain-injury. The pilot study showed promise with small numbers of subjects, and if access was available to large numbers of brain-injured patients, such as ‘stroke banks’, then information regarding interconnections of the dysfunctional brain is possible. Another valuable area is that of therapeutic investigation. This
may entail using each person as a control for their own recovery from brain-injury. The possibility of monitoring therapeutic techniques with individuals and groups of patients could provide some insight into different therapies and their usefulness, both for the individual concerned, and yield information on more effective treatment. This would see the techniques discussed in this thesis provide a very worthwhile applied research return to this part of the health sector. Acquired brain-injury is prevalent in the community as a result of strokes, motor vehicle accidents, industrial accidents, and other causes, and the quicker return of the individuals to the best possible lifestyle may be assisted by such research and application.
10. References.


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ADC (4) Analog to Digital Converter.
CAT (1) Computer Axial Tomography.
cd.m^2 (5) Candela per square metre.
CPT (5) (6) Continuous Performance Task.
EEG (3)(4) Electroencephalogram.
ERD (5) Event-Related Desynchronization.
ERG (2) Electoretinogram.
FFT (5) Fast Fourier Transform.
Hotelling's (T) (5) A two dimensional analogue of the Student's t-test.
IBM (4) Trademark of International Business Machines.
Inion (4) A superficial, anatomical landmark found at the back of the skull.
LED (4) Light Emitting Diode.
LGN, (dLGN, vLGN) (2) Lateral Geniculate Nucleus, (dorsal, ventral region).
LVF (2) Left Visual Field.
M (2) Magnocellular geniculate cell (a large cell within the lateral geniculate nucleus).
MRF (2) Mesencephalic Reticular Formation.
MRI (1) Magnetic Resonance Imaging.
MTFCS (2) Medio Thalamic Fronto-Cortical System (a neural pathway which travels between the frontal cortex and the thalamus).
N1, N2 (2) The first and second negative evoked potentials, respectively.
Nasion (4) A landmark found between the eyes at the bridge of the nose.
Nxxx (2) Negative waveform occurring at xxx milliseconds after the stimulus.
O_1, O_2 (2) Location of the 10–20 system—left and right occipital respectively
P (2) Parvocellular geniculate cell (a small cell within the lateral geniculate nucleus).
P1, P2 (2) The first and second positive evoked potentials, respectively.
Pixel (4) Smallest element resolved on a monitor or page.
Probe-ERP(3) Probe Event-Related Potential.
Pxxx (2) Positive evoked potential occurring xxx milliseconds after the stimulus.
rCBF (3) Regional Cerebral Blood Flow.
RMS (5) Root Mean Squared
RT (6) Reaction Time (or response time).
RVF (2) Right Visual Field.
Saccade (2) An abrupt eye movement from one location to another.
SC (2) Superior Colliculus.
SCAN (3)(4) Swinburne Centre for Applied Neurosciences.
SPM (5) Significance Probability Mapping.
SSVEP (3) Steady-state Visually Evoked Potential
Striate (2) Meaning striped—the area of the occipital cortex described as Area 17.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>VEP (3)</td>
<td>Visual Evoked Potential.</td>
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<tr>
<td>VGA (4)</td>
<td>Virtual Graphics Adaptor.</td>
</tr>
</tbody>
</table>
12.1. Appendix 1. Subject data form.

SURNAME........................................ GIVEN NAMES...........................................

DATE OF BIRTH.................. SEX............... UR..........................

OCCUPATION........................................

HIGHEST EDUCATIONAL LEVEL REACHED......................

HAVE YOU EVER SUSTAINED A HEAD INJURY?................

SPECIFY...........................................................................................................

DO YOU PRESENTLY SUFFER OR HAVE EVER SUFFERED FROM ANY
NEUROLOGICAL AND/OR PSYCHIATRIC PROBLEMS?........... SPECIFY......................

ARE YOU A SMOKER?.........

IF YES, INDICATE THE LAST TIME YOU SMOKED......................

HAVE YOU CONSUMED TEA OR COFFEE RECENTLY?............

IF YES, INDICATE TIME OF LAST CONSUMPTION....................

DO YOU CURRENTLY TAKE ANY PRESCRIPTION DRUGS?.........

SPECIFY...........................................................................................................

DO YOU CURRENTLY TAKE ANY NON-PRESCRIPTION DRUGS?....

SPECIFY...........................................................................................................
12.2. Appendix 2. Edinburgh Handedness Inventory.

Please indicate your preference in the use of hands in the following activities by putting a + in the appropriate column. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, put ++. If in any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave blank if you have no experience at all of the object or task.

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<th></th>
<th>LEFT</th>
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<tbody>
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<td>Drawing</td>
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<td>3.</td>
<td>Throwing</td>
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<td>4.</td>
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<td>5.</td>
<td>Toothbrush</td>
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<td>6.</td>
<td>Knife (without fork)</td>
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<td>7.</td>
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<td>8.</td>
<td>Broom (upper hand)</td>
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<td>9.</td>
<td>Striking match (match)</td>
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<tr>
<td>10.</td>
<td>Opening box (lid)</td>
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</tbody>
</table>

i Which foot do you prefer to kick with?

ii Which eye do you use when using only one?
| LQ | Leave these spaces blank. | DECILE |
12.3. Appendix 3. Subject instructions.

Instructions given to subjects for baseline and continuous performance tasks.

Before all tasks:
In the centre of the screen in front of you, a series of coloured numbers and letters will be displayed. These numbers and letters will appear one at a time. There will be a number of tasks. Please don't speak during the tasks. I will tell you what you need to do before we begin each task.

No Stimulus.
In this task there will be a cross on the screen. Follow the cross with you eyes, but don't move your head. Part way through this task, the flicker will be switched on, don't be alarmed, disregard this and attend to the cross.

Baseline task.
In this task, a series of BLUE NUMBERS will be presented in the centre of the screen. These will be the numbers 1 2 3 4 and 5. Do not move your eyes away from the centre of the screen. This pattern will repeat itself over and over again. During the BLUE NUMBERS, I want you to relax as much as you can and casually press the button whenever you see the number 5. It is not necessary to press the button quickly. RELAX. Remember, do not move you eyes away from the centre of the scree.

When pressing the button at any time, press and release, there is no need to keep it held down. (SHOW HOW).

Do you have any questions? (If yes read through instructions again!)

Continuous Performance Task (CPT).
In this task as well as the BLUE NUMBERS, a series of RED LETTERS will also be presented. The letters: C D E F and G will appear. Try to CONCENTRATE as hard as possible and press the button as QUICKLY and as ACCURATELY as you can whenever you see the letter E (show). During the BLUE NUMBERS, RELAX and press the button slowly whenever you see the number 5. During the red letters press the button quickly whenever you see the letter E. The blue numbers and red letters will be repeated a number of times.

Do you have any questions? (If yes read through instructions again!)
12.4. Appendix 4. Subject Consent Form.

PROTOCOL NUMBER S.V.H.  33/85.

NAME OF PATIENT: ............................................................

NAME OF INVESTIGATORS: Professor Ball, Dr. Byrne, Mr. Nye, Dr. Silberstein, Mr. Schier.

STUDY TITLE. The Use of Evoked Potentials in Brain-damage Assessment.

EXPLANATION TO PATIENT OF RESEARCH PROCEDURE; (including possible short & long
term risks).

This investigation is not harmful or painful at all. We are studying brain wave
activity patterns in a new way, taking recordings from the scalp just as in an
ordinary brain wave examination (EEG) whilst you watch and listen to things on a
T.V. and/or by ear phones. This study will help to develop ways of examination of
patients and may prove of benefit in diagnosis and treatment.

The above patient CERTIFIES

a) Dr/Mr .................................. has fully explained to me the above procedure
b) I understand:– i) its purpose and nature
   ii) the methods to be employed
   iii) the risks to my health
   iv) the inconvenience to me
   v) the discomforts which may be caused to me

c) I am willing to take part in this research
d) I also understand that I am free to withdraw from the research at any time

Dated ........................................day of ................................19

SIGNED ........................................................................

Patient/Guardian/Next Friend

WITNESS:.......................................................................

I CERTIFY that I have provided the above patient/the guardian of the patient/the
next friend of the patient, with adequate information on the above research
procedures which, according to my assessment of his level of comprehension, he
seems fully to understand.

...................................................................................

INVESTIGATORS SIGNATURE INCLUDING TITLE.

(Revised May 1981)
12.5. Appendix 5. Reaction time data.

The plot below illustrates the complete reaction time data for all the control subjects, in a compressed form.
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The plot below illustrates the complete reaction time data for all the patients.

![Plot showing reaction times for different targets]  

Tabulated below are the reaction times for the separate targets, the calculated means, and the errors of omission for each of the six subjects.

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