12

Intention
and
Reactivity

A thesis submitted to the University
of London for the degree of Doctor of
Philosophy

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2001

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ABSTRACT

The evolution of the human brain, including the ability to make intentional actions, has resulted in our motor system being activated via either our own intentions or external stimuli. It is important that a balance is maintained between these internal and external drives. This thesis investigates the relationship between these two systems. Evidence supporting a distinction between them is considered and hypotheses are examined, specifically: are they independent, unitary, facilitatory, inhibitory, or is there a switching mechanism?

Intentional action is studied using (i) objective paradigms: the generation of intentional actions and how this interacts with stimulus-driven actions, and (ii) subjective paradigms: the perceived time of stimuli and actions. A novel experimental paradigm investigated the relationship between the putative internally-generated and externally-triggered motor systems. The "truncation" paradigm involves subjects preparing an intentional action, which is interrupted by a randomly occurring stimulus requiring a response. Truncation, therefore, involves a balance between *intention and reactivity.*

Seven experiments produced a reliable difference (averaging 51 ms) in reaction time between simple RT and truncated reaction time (TRT). This difference was termed the *RT cost of intention.* The neural basis of the process responsible for this RT cost was investigated using two physiological techniques (pupil dilation and electroencephalography) in two separate experiments. Alternative causes of the RT cost, such as delayed stimulus processing in truncation, were examined and rejected.

The conclusions are that (i) the RT cost of intention is due to switch costs between the hypothetical internally-generated and externally-triggered motor systems; (ii) these two systems are not normally simultaneously active; and (iii) at a subjective level, people are aware of the response delay incurred by the switch process.

ACKNOWLEDGEMENTS

I would like to thank my supervisor Patrick Haggard for inspiring me to continue at UCL, where I did my BSc, and pursue a PhD as his first PhD student. His ceaseless support, commitment, and recognition of my strengths and weaknesses meant that even when I thought I could not do something, I found that I was able to. The hours we spent discussing ideas were always enjoyable, thanks to his willingness to let me vent my latest thoughts about life and the PhD!

Godolphin and Latymer, my secondary school, where I spent 7 years taught me to enjoy intellectual pursuits and gave me the freedom and support to pursue them, particularly in my final years. I would like to thank my parents for having the foresight to send me there. My parents have always believed in me and I want to thank them for their unfailing love and support throughout my life, particularly during the last three years during which I moved out of home, met and married my husband and bought a house, whilst doing this PhD. Their presence, along with that of my grandparents, brother Toby, cousins Mark and Gemma, and aunt Pam and uncle Diccon, has always been a big part of my life and I hope will always be.

My friends, including those that I have met through my husband, but particularly Anna, Ant, Clare and Harri who have put up with my moaning, allowed me to rant about my experiments, theories and computer troubles and have even been subjects for me, during the last three years – thank you so much.

I would like to thank my research group, particularly Sukh for being an awesome office-mate and friend during the last three years, and Rob for his help with MATLAB and Excel. Thank you Hugo for being a good friend and lunch partner at the ICN, and Mark for computer help when I was at the end of my tether!

And lastly I would like to thank my husband. We met just after he submitted his PhD thesis, when I was just beginning my PhD. During the last three years whilst I have been doing this thesis, and he has been pursuing post-doctoral research, we have fallen in love, bought a flat, moved in together, got married and then bought a house! His devotion throughout this time has meant that I have felt able to strive, knowing that he loved me and supported me. Dearest Tony, this PhD is dedicated to you – thank you so much for putting up with me during the difficult times, never failing to love me, make me feel loved and supported, believing in me and my capabilities and most importantly always being there when I needed you most.

TABLE OF CONTENTS

TABLE OF FIGURES

CHAPTER 1

CHAPTER 2

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

TABLE OF TABLES

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

Chapter 1

INTRODUCTION TO THESIS

1.1 OUTLINE

The introductory chapter is divided into four main divisions. Division one (section 1.2) presents the idea of intention: what it is, the importance of agency, and observation of the current lack of scientific studies. Behaviourism is also discussed due to its influence on psychological research in the early part of the twentieth century.

The second division (1.3) discusses the work of philosophers who were the first to tackle the problem of intention, mainly in the contexts of (i) free will (1.3.1), and (ii) the mind-brain problem (1.3.2). Descartes, Locke and James are examined in detail (sections 1.3.2.1, 1.3.2.2, and 1.3.2.3 respectively).

The third division (1.4) briefly reviews mental chronometry (1.4.1), task switching (1.4.2) and the psychological refractory period (PRP) [1.4.3]. The fourth division (1.5) begins by introducing the bereitschatspotential (BP) [1.5.1] and includes a chronological review of the relevant neurophysiological studies of intention. The BP as a neural correlate of intention is also examined (1.5.2). The anatomical substrate of intention is discussed (1.5.3) and possible hierarchies in the motor system are postulated (1.5.3.1).

Most of the movements that we make in every day life are a composite of intentions, and external stimuli. For example, getting up to close an open window (intentional action), when a cold gust of wind blows in (stimulus). To study intention in comparison to reaction to a stimulus, evidence is needed that a reactive and an intentional motor system exist; that is, that there are truly two concepts that can be compared. Division four reviews anatomical (1.6), neurophysiological (1.7) and clinical disorders of intentional action (1.8) evidence in support of the dimorphism between intention and reaction.

1.2 INTENTIONAL ACTION

One philosophical definition of an intentional action is those actions to which a particular kind of the question ‘why?’ is appropriate (Anscombe, 1963). Translating this into psychological terms, an intentional action is one that is goal-directed. There must be an agent and a goal, and the goal must be the reason why the agent performed the action. Intentions are characteristics of volitional actions and are pre-cursors of internally-driven movements. A voluntary action may be conceived of as consisting of a volition or desire to do something, in this case perform an action. This volition then becomes an intention, which in turn results in preparation for the desired action and physical movement of the body itself. Voluntary actions, therefore, may be thought of as being preceded by an internal mental event, an intention. The ability to intend to do something and then act on that intention is a fundamental part of human existence.

Jahanshahi and Frith (1998) postulate three criteria for defining willed actions in the absence of any convincing physiological data. These criteria are: (i) attention and conscious awareness, (ii) choice and control, and (iii) intentionality. Willed action is a psychologist’s synonym for intentional action. They define willed action as the “formulation of a goal and an intention to act, ... response selection, programming, and initiation that precede the production and execution of an action.” This thesis largely focuses on intentionality, although some of the experiments also invoke the related concepts of attention and conscious awareness.

In this thesis, the operational concept of intention is an action that is internally-generated rather than being a direct response to a stimulus. This is intended as an operational definition and does not imply any commitment to a philosophical standpoint. Historically the concept of ‘intentionality’ has been problematic and has been associated with particular metaphysical commitments, such as whether the mind and the brain consist of the same substance. This can be predominantly traced back to the Cartesian notion of ‘free will’. Descartes saw freely-willed actions as distinct from actions that are caused by physical events. Cartesian dualism still influences the way we think and talk about the mind, and thus there is a natural tendency to assume that any similar distinction also implies a commitment to dualism.

Behaviourism took this tendency to an extreme. Behaviourists basically argued that there are no internal states, only behaviour, and all behaviour is reactive, that is, a conditional response to stimuli. In effect, the behaviourists accepted Descartes distinction between the physical and the mental, and simply ruled that the mental lay beyond the limits of science. Behaviourists, therefore refused to consider internal mental states, such as intentions. Despite the demise of behaviourism, there remains a strong tendency for researchers to dismiss discussions of consciousness and intentionality as non-scientific (Bisiach, 1988).

The concept of intention used here is not, and should not, be confused with the Cartesian notion of free will. The concepts of intention and free will both arise from the experience of performing actions 'intentionally' or 'of our own free will'. These concepts are familiar to all of us and do not require an understanding of philosophy or science. The difference between the two concepts arises when one considers what it is like to do an action 'from the inside'. That is, the initial experience of intention is subjective. This is the standpoint from which Descartes remained, thus his philosophical concept of free will is not scientifically useful.

However, just because out initial comprehension of intention is subjective, does not preclude the examination of intention objectively. Basically, actions that are internally-generated *feel* different to actions that result directly from a stimulus. Only the former are called intentional actions. The scientists' job is to examine and qualitatively distinguish between them. As will be presented in sections 1.5-1.7, there is mounting evidence to suggest that two different systems are involved in these two types of action. For instance, there is evidence that different areas of the brain are involved in intentional actions (the supplementary motor area) as opposed to reactive actions (the pre-motor cortex). For example, Tanji and Shima (1994) demonstrated that the SMA is involved in the planning of memory-driven (rather than stimulus-driven) actions in monkeys.

The main focus of this thesis is to examine the relationship between the two hypothesised motor systems, which underlie intentional and stimulus-driven actions. This task neither presupposes an exact understanding of 'intentionality', nor the workings of the system supposed to underlie intentional action. Considering that within the philosophical conceptual framework, intentionality appears to lie wholly beyond the reach of scientific understanding, it is problematical to adopt another framework, in which intentionality can be fully explained in scientific terms from the start. Moreover, for the purposes of this thesis a full explanation is not necessary – a clear and operational definition is all that is required. It is hoped that a better scientific understanding of intentionality will gradually emerge from investigations of this sort.

The paragraphs above aim to clarify to some extent long-standing confusions regarding intention and provide a theoretical background to the thesis. However, some doubt may remain. Two further questions will be briefly addressed. First, is it necessary to talk about 'intention' at all? Second, is it valid to assume a simple dichotomy between 'intentional' and 'stimulus-driven' actions?

Well-established topics of research, such as 'planning' and 'prospective memory', appear to depend on some notion of intentionality. Planning would be a meaningless pursuit if it did not result in the formation of an intention to act. Prospective memory involves the formation of an intention that will be executed at some point in the future – a point at which the subject must recall their previously formed intention to act. For instance, I might form the intention to tell my friend Clare about my conversation with a mutual friend, the next time I see her. It would seem that intentions are an important part of human mental life and need to be examined to fully comprehend the interesting complexities of human behaviour.

Some support for the two-way classification between 'stimulus-driven' and 'intentional' comes from its use in other fields of study, such as long-term or 'episodic' memory. Rugg, Fletcher, Frith, Frackowiak and Dolan (1997) distinguish between recall that is 'incidental' – where the stimulus alone causes the subject to recall an episode, and recall that is 'intentional' – where the subject makes a deliberate effort to remember information relevant to the stimulus.

It is important to note that, like most simple dichotomies, the distinction between intentional and stimulus-driven actions can be too simplistic. There are two points relating to this issue that are important: first, there are frequently aspects of intentional actions that are stimulus-driven and; second, there are frequently aspects of stimulus-driven actions that are intentional.

The first of these points is illustrated by work on affordances (Ellis and Tucker, 2000). These are discussed in more detail in chapter 8. In brief, this work shows that intentional actions may have stimulus-driven components. For instance, your action to reach for your cup of coffee may be intentional, however the manner in which you move your arm and alter your grasp in order to complete this action is likely to be stimulus-driven.

In this thesis, the actions involved are physically simple keypresses. The principal measures used examine the times at which the action and the physiological concomitants of that action take place. Thus, for the purposes of this thesis, the critical feature of the action that determines whether it is classified as intentional or not is its INITIATION. If an action is initiated at a time of the subject's choosing, then it is classified as intentional, and if it is initiated in direct response to a stimulus, then it is classified as stimulus-driven. Consideration of other components of action, including whether those aspects are intentional or stimulus-driven, lies beyond the scope of this thesis.

Second, there are aspects of stimulus-driven actions that are intentional. Intentional action can be defined as any action that the subject can stop himself or herself from making. It is unusual for us to find that we are incapable of preventing an action. However, there is a more important sense in which the 'stimulus-driven' actions examined in this thesis have an intentional component. This relates to the concept of 'prospective memory' discussed above. In an experimental context, the subject must first be instructed to respond to a stimulus in a particular way. The subject must form an intention to comply with these instructions, before any action is likely to be 'driven' by the stimulus. Thus it appears that even stimulus-driven actions involve an intentional component. One could also claim that the intentional actions performed by an experimental subject are stimulus-driven, since they are ultimately driven by the presentation of the experimental instructions. Again, it is clear that we must be careful to specify the aspect of the action that is important. As was stated above, for the purposes of this thesis, the critical aspect of the action is its INITIATION.

Stimulus-driven actions are therefore defined for current purposes as actions whose exact time of performance is determined by a stimulus. Intentional actions are actions whose exact time of performance is determined by the subject. There are clearly important processes that take place at the moment that experimental instructions are given to the subject, and these processes are responsible for putting the subject in a particular 'task set'. However, as the task switching literature demonstrates, these processes become irrelevant once the first few trial have been performed (Rogers & Monsell, 1995). Understanding what happens when subjects listen to and attempt to follow experimental instructions is clearly important for psychology, yet it is a complex problem and lies outside the scope of this thesis.

Given that intention is so important to human existence, it is surprising that so few scientists have studied it. In addition to the conceptual issues touched on above, there are practical reasons for this neglect. Intention is easily trivialised in experimental settings: in general it is pushed into the background to allow the topic of investigation to take the foreground. Asking people to be prescient about their intentions and to actively have intentions can be problematic. A related experimental problem is the difficulty in controlling the timing of the intervention on the intentional activity within the experimental design. A third reason was the lack of agreed scientific methods and technological capabilities in measuring intentions objectively. The aim here is to identify a particularly pure and isolated aspect of a much larger and more general issue. In this way, it hoped that some concrete progress can be made.

1.3 PHILOSOPHICAL TREATMENTS OF INTENTION

The main role for intention as a philosophical concept has been in the free will debate in which intention is defined as a mental state supposedly causing body movement by a yet-to-be-explained mind-body causation process. Issues relating to free will and intentionality have been a central concern of philosophers for centuries. These ideas continue to shape and influence scientific approaches. Therefore, it will be useful to begin with a brief overview of some of the central philosophical ideas relating to intention and free will.

1.3.1 Free Will

The concept of intention and volition is a vital part of human life. The majority of humans believe that they can do what they want, whenever they want, and however they want. People go to extraordinary lengths to preserve this notion.

Civilisation, particularly the legal aspects of it, is built around the notion of agency: the concept of "I" and ownership of actions. Inherent in the concept of free will, entailing moral responsibility is the proposition that when humans do something, they could have chosen to do something else. Can I be held criminally responsible for an action if "I" didn't cause it? Libet (1999), incorporating his earlier findings on the timing of the awareness of intentions, observes that only the completion of the act itself can be consciously controlled, not the occurrence of the intention. That is, ethically, people should not be blamed for having inappropriate intentions, but should only be held responsible for allowing the resultant act to occur. Thus, if Libet's (1999) observation that we are consciously able to veto our acts before fruition is incorporated with the phenomenological experiences of independent action, it can then be suggested that we are consciously able to "causatively control [by using free will] some brain processes" (Libet, 1994).

1.3.2 Mind-Brain Interaction

The mind-brain 'problem' has been approached in many ways. Dualists consider the mind to be somewhat like the traditional soul, an entity without physical basis, and the brain to be real, tangible matter, thus facing the problem of how mental and physical matter can influence each other. Other philosophers, for example Locke (1690), believed that this question could not be answered; so arguing about the fundamental constituents of mind and brain is a pointless exercise. The following section will review a selection of the dominant approaches to the mind-brain problem.

1.3.1.1 Cartesian dualism

Descartes (1596-1650) was a rationalist, meaning that he believed that the faculty of reason has precedence over other ways of acquiring knowledge, for example the senses. The senses were considered to provide faulty information, which therefore resulted in sensory qualities being mistaken for real qualities of physical matter. A good example of incorrect information from the senses is what we *see* when we put a straight rod into a beaker of water. The rod *looks* bent when it is placed in the beaker, and when it is removed it *looks* straight. The laws of physics provide an explanation of this illusion based on the way in which water refracts light.

Dualism suggests that the mind and body are separate: the mind is immortal and conscious (like the soul in religious parlance) and the body is mortal and physical matter, occupying external space. Descartes' argument for dualism can be summarised as follows:

> That I exist is indubitable
> That I have a body is dubitable
> So, my existence is independent of my body
> So, I can't be certain that I exist when I'm not thinking
> So, my existence depends on my thinking.
>
> Robinson and Garratt (1998).

There are two key problems for dualism: the first is the validity of Descartes' argument. The problem with his reasoning is the use of doubt as a proof: "That I have a body is dubitable" is not really strong enough to be succeeded by the suggestion that we do not exist unless we are thinking. The second problem with dualism is that mind (non-extended matter) and body (extended matter) must be able to influence each other (mind-body problem), but by their very nature they are distinct substances. Non-extended matter cannot have a causal effect on extended matter (and vice versa) because it does not follow the laws of physics and does not exist in time and space. Descartes reconciled his religious and scientific beliefs and suggested that the pineal gland was where the soul or mind was located. The mind was thus considered to be co-extensive (rather than non-extended) and was able to interact with the body via the brain in a two-way direction.

1.3.2.2 John Locke (1632-1704)

Locke, an empiricist, challenged the two-substance ontology of extended and non-extended matter that Descartes used. He explicitly stated at the beginning of Essay Concerning Human Understanding (1690) that he would "...not examine wherein the essence of mind consists" (Locke, 1690). However, he did argue that thinking is not the essence of mind, but is an action of mind. This was because there are different levels of thinking and essence, by its very nature, does not alter.

Locke later went on to suggest that he did not think it was possible to discover the unchanging essences of either extended or non-extended substances. Combining this suggestion and the following quotation, it seems that Locke limited his opinion about the mind-brain interaction.

> *Volition* or *willing* is an act of the mind directing its thought to the production of any action, and thereby exerting its power to produce it... He that shall turn his thoughts inwards upon what passes in his mind when he will, shall see that the will or power of volition is conversant about nothing but our own *actions*; terminates there and reaches no further; and that volition is nothing but that particular determination of the mind, whereby, barely by a thought the mind endeavours to give rise, continuation, or stop, to any action which it takes to be in its power.
>
> Locke (1690).

Locke places the key component in the action (the effect) rather than the intention (the cause). This allows him to sidestep the mind-body causation issue. He clearly identifies volition as something, which is "conversant about nothing but our own *actions*". It is understood that Locke was implying that when one introspects or "turn[s] his thoughts inwards"; it is only possible to tell that one is affecting one's actions. When one wills an action, the will only has direct effect on the action itself. That is, the will "is conversant about nothing but our own *actions*" implies that the will can effect actions alone. This process cannot inform us about whether 'willing' is concerned with extended or non-extended matter. This highlights the need to study will or willed actions using scientific methodologies, in addition to introspective measures. Locke recognised that humans possess volition, but limited it to actions, and did not consider it to be complex introspective thought.

1.3.2.3 William James (1842-1910)

William James suggested an alternative way of conceiving of volitional actions. James (1890) made a distinction between "ideo-motor" and "willed" acts: ideo-motor acts are those that "... wherever movement follows unhesitatingly and immediately from the notion of it in the mind... we are then aware of nothing between the conception and the execution." Willed acts are those where "an additional conscious element in the shape of a fiat, mandate, or expressed consent" is involved (James, 1890). Willed actions, therefore, are those movements that are preceded by the idea (or representation) of the movement. He also observed that conscious attention is a key component of willed actions.

James considered volitional movements to be a learned consequence of reactive movements; that is, willed acts can only occur once a mental representation of the movement has been formed. He conceived of reaction as being the basic mode, which results in representations of the movements being formed and stored in the brain. Through associative learning these internal representations are accessed to make voluntary movements. James therefore extended the ideas of Hume who postulated that we observe and experience reactive and reflex movements and, based on these observations/experiences, we can initiate volitional movement.

> ... it follows that no creature not endowed with divinatory power can perform an act voluntarily for the first time... so we must wait for the movements to be performed involuntarily, before we can frame ideas of what either of these things are.
>
> James (1890).

James discusses the problem of how the idea of a movement can arouse the movement itself in terms of the education of the will. The 'narrow sense' of the education of the will is defined as the acquisition of the abilities to inhibit irrelevant impulses and to initiate the movements that are required to complete the desired goal. Alternatively, he suggests that the involuntary act may occur instinctively, by reflex or by random execution. In an involuntary movement, the motor discharge occurs first and the sensory process second; in a voluntary movement, he considers that the sensory process occurs first, which results in the motor discharge. How the sensory process causes the motor discharge is, James proposes, a physiological problem, which as yet has not been answered. James, therefore, believed that we are capable of intentional action, but that it can only occur when there is a representation for that action in our brain. Moreover, this representation is basically sensory. This view removes humans' ability to be creative and therefore limits the definition of intentional action.

Experimental psychologists had not previously studied will and intention, primarily because the main type of evidence was subjective introspection, which was not wholly reliable; and as previously mentioned, behaviourism was the dominant force in psychology in the early twentieth century. Stout (1906) observed that:

> …[the] view among experimental psychologists is distinctly adverse to the existence of any peculiar kind of immediate experience distinctively characteristic of conation. What we have called 'felt tendency' seems to elude introspection as carried out under the test conditions of the laboratory. The experimental psychologist when he looks for this finds only motor sensations and the qualities of affective consciousness – pleasure and pain.

He then went on to suggest that the experimental psychologists viewed the "real mind" as just a "sensation-complex", where sensations are considered to be modifications of the individuals' immediate experience and exist only at the given moment of experience. Their methodology and idea of the mind are designed to ignore conation, which "… by its intrinsic nature involves a mental reference to something which is not part of the actual experience of the individual at the moment when he actually experiences the conation."

1.4 Mental Chronometry, The Psychological Refractory Period and Task Switching

1.4.1 Mental Chronometry

Mental chronometry involves the study of subject's reaction times (RTs). Conclusions about human information processing are inferred from the differences in reaction times between different tasks (Meyer, Osman, Irwin and Yantis, 1988). Donders (1868, 1969) proposed a model which states that performance is mediated by processes such as perceptual encoding of the stimulus, retrieval of S-R mappings, making decisions and preparing a response, which are sequential and time-consuming.

The mental chronometry approach is based on the discovery by Helmholtz that mental operations take measurable time, (Helmholtz, 1850, 1853). The typical paradigm of mental chronometry is the RT paradigm familiar to all psychologists. The trial starts with a warning stimulus, after which an imperative stimulus is presented. The time between the warning and imperative stimulus is known as the foreperiod and allows the subject time to prepare the appropriate response(s). The reaction time (RT) is the time taken to respond to the imperative stimulus. Subjects are occasionally provided with their data in order to improve performance and are often encouraged to be as fast and as accurate as possible, in order that neither speed nor accuracy are compromised.

Mental chronometry assumes that there are distinct component processes involved in the production of an overt response to a stimulus. Psychologists have striven to qualitatively and quantitatively define these stages, and to examine whether they occur in a serial, parallel or temporally overlapping fashion. However, studying the RT alone may not be able to answer these questions alone, hence RT is frequently used in concert with other measures of the processes involved in producing an overt response. Functional magnetic resonance imaging (fMRI), electroencephalography (EEG) and pupil dilation are a few such measures (these are reviewed in sections 1.7.1 and 1.7.2).

Following the introduction of the SRT paradigm, much research ensued, such as that of Woodworth (1899) who plotted speed-accuracy trade-off curves and Donders (1868, 1969) who introduced the choice reaction time and the subtraction method. The subtraction method involved task A, an SRT, task B, a CRT (where there are multiple stimuli and corresponding multiple responses) and task C, a go/no go procedure with multiple stimuli and only one response. By subtracting the RTs produced in each task, he suggested that the different stages could be quantified. For example, subtracting A from B would result in the time taken to discriminate and select a response.

Although it is now recognised that strong assumptions are required for these processes to be fruitful (Sternberg, 1969), such as the supposition that stimulus discrimination and response selection are strictly serial, the chronometric method and the ensuing methodologies are still in use today by the majority of psychologists.

1.4.2 The Psychological Refractory Period (PRP)

The chronometric method specifically studies seriality of processing. An example in which the seriality of processing is prevalent is PRP, where the effect on response time to two consecutive stimuli of the presentation of two stimuli is tested. The psychological refractory period (PRP) was originally suggested by Telford (1931). Its effect occurs when subjects are instructed to react to one stimulus followed by a second stimulus, as much as two seconds later: the RT to the second stimulus is markedly reduced. Attempts to eliminate the PRP have been made, such as the use of ideo-motor compatible stimuli and responses. That is, if the stimulus is similar to the output of the response, for example, auditory stimulus and vocal response, then the RTs to the second stimulus are reduced (Greenwald, 1970).

Alternative explanations for the delayed response to stimulus two have been proposed, such as lack of preparation (Gottsdanker, 1979). In a paradigm involving responses to S1 and S2, he inserted a number of 'catch' trials in which subjects were instructed not to react to S1, but only to S2. Long RTs were still found, implying that due to their being no involvement in S1, the delayed RT must be due to the lack of preparation.

1.4.3 Task Switching

The experiments in this thesis do not require subjects to respond to two stimuli in quick succession, therefore the relevance of PRP is perhaps only tangential. PRP involves the study of two consecutive stimuli. Task switching involves the study of two consecutive tasks. The concept of seriality is therefore, transferred from two stimuli to two tasks. One might say that the experimental paradigm used in this thesis does require subjects to perform one task followed by another in quick succession (preparation for an intentional action followed by a reaction to a truncating stimulus). The experimental paradigm utilised throughout this thesis (and explained in detail in the first experimental chapter, section 2.1.3) is similar to a probe task, in which subjects prepare to make an action, which on approximately 50% of the trials is made.

However, a stimulus is presented at random which requires the subjects to make a response. Thus, subjects either make the first action or the second action, never both. Hence, although there are surface similarities with task-switching, there are also important differences.

As the study of human information processing progressed throughout the last century, and certain characteristics of the stages involved in producing overt responses were discovered, the study of task switching became prevalent. Task switching involves subjects performing one task, followed by another. The temporal, perceptual and executive features of the tasks are varied and conclusions regarding the processing required for each task are inferred. The study of attention produced many theories, for example the bottleneck theory (Broadbent, 1952, reviewed in chapter 4), in an attempt to explain the distribution of cognitive resources amongst the different task components. Task switching is further reviewed in the introduction to the first experimental chapter.

First, the switch in the present paradigm is temporally unpredictable, whereas in most task-switching experiments it is highly predictable. Second, in the task switching literature, the concept of a task (and therefore, the psychological entity that is supposed to be 'switched' is loosely speaking a way of mapping stimuli to responses. The main experimental effect in this thesis (the RT cost of intention) can be obtained even for simple responses without any S-R mapping at all (experiment 1, chapter2). Thus, while this thesis agrees in the end in a switching process, existing concepts of task-switching can be of only restricted value in explaining what is switched in the truncation paradigm studied here.

The next section reviews the BP and evidence that it is the neural correlate of intention. It then goes on to discuss the areas of the brain that are involved in intentional actions. Finally, a motor hierarchy is proposed, the framework within which the internally-generated and externally-triggered systems are postulated to interact.

1.5 NEUROSCIENTIFIC APPROACHES TO INTENTIONAL ACTION

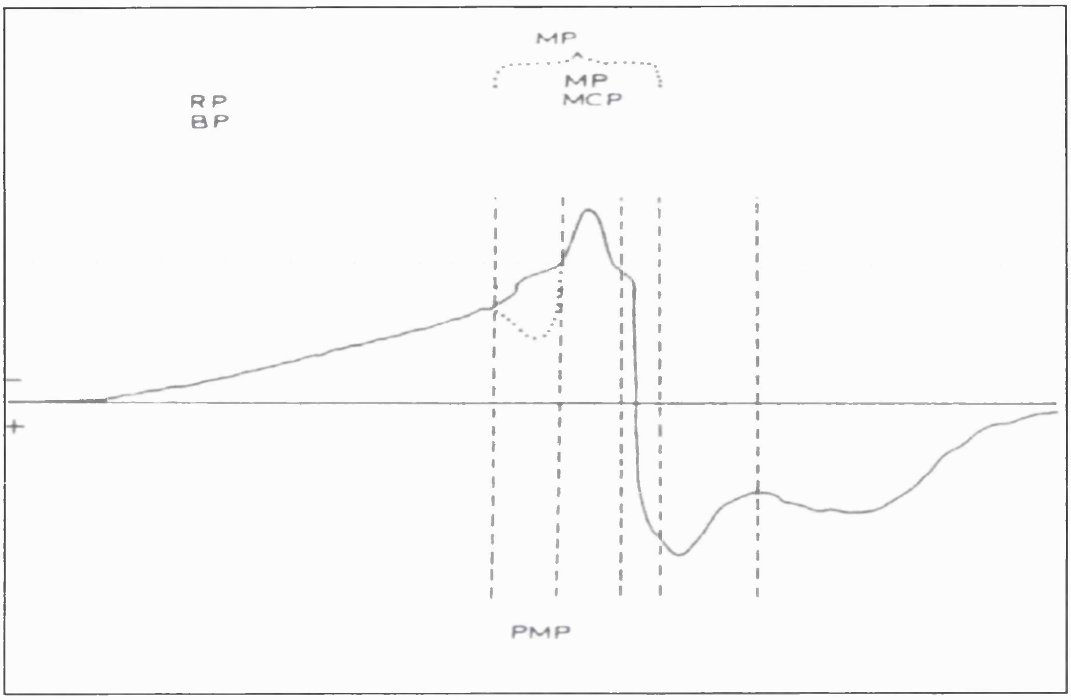
1.5.1 The Bereitschaftspotential (BP)

In a presentation entitled "The Electric Currents of the Brain" to the 43rd Annual Meeting of the British Medical Association, held in Edinburgh, August 1875, Dr Richard Caton gave an account of his experiments on the brains of rabbits and monkeys. "In every brain hitherto examined, the galvanometer has indicated the existence of electric currents...When any part of the grey matter is in a state of functional activity, its electric current wholly exhibits negative variation." (Caton, 1875). This negative variation of "the electric currents of the grey matter" was noted in the absence of external stimulation. However, it was not until the 1960s that research into electrical pre-movement activity reached a scientifically viable stage. The main problem encountered by early researchers was the dearth of equipment to measure this activity.

The BP, discovered in the 1960s by Kornhuber and Deecke marked a new era in the study of intentional movements (e.g. Kornhuber and Deecke, 1965). The BP or readiness potential (RP) is a slow negative potential beginning up to 2000 milliseconds (ms) before the intentional movement and peaking just prior to its initiation. This activity can be further subdivided into distinct components, although researchers classify these components differently.

The first component of the pre-motor processes (the BP) begins approximately 820 ms prior to the onset of muscular activity. The second component, the pre-motion positivity (PMP) is a small positive deflection with an average onset of 86 ms prior to electromyogram (EMG) activity. The third component is the motor potential (MP), which starts roughly 56 ms before EMG activity and is characterised by a rapid acceleration of negativity (Deecke, Scheid and Kornhuber, 1969) [Figure 1.1].

Figure 1.1. Scalp potentials associated with making a voluntary movement. This schematic illustrates the terminologies and their waveform components. BP = bereitschaftspotential ; RP = readiness potential; PMP = pre-motion positivity; MP = motor potential; MCP= motor cortex potential. Adapted from McCallum (1988).[1]



Becker, Hoehne, Iwase and Kornhuber (1973), when examining the BP, PMP and MP prior to voluntary saccades, concluded that the BP was an indicator of "general preparation of premeditated voluntary acts and that it is only indirectly related to the initiation and the motor control of movements." That is, the BP is the first observable stage of the intention to make an action. Due to the different classifications regarding the timings of these components (McCallum, 1988), a different set of classifications is now generally used. These are, for example, the P200, P300, N100 and N200; or P1, P2 etc where the P signifies positivity, the N, negativity, and the numbers signify the time in milliseconds or the number of the trough or the peak, respectively. These times vary hugely between researchers.

Initially the BP is bilaterally symmetrical over the frontocentral midline, which is believed to indicate activity from the SMA. If the movement is unilateral, the BP

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[1] Certain labels have been removed for simplicity, specifically the skilled performance positivity (SPP), the electromyogram (EMG), the alternative names for N1 (N1A) and N2 (N2A, N2B and N1B); and the breakdown of different periods: premotor, motor sensory, motor completion and postmotor.

becomes asymmetric in the contralateral hemisphere in the latter stages. This is appropriately named the lateralised readiness potential (LRP) and is calculated by subtracting the differences in activation between the left and right SMA (approximated to C3' and C4' sites on the scalp), [e.g. Haggard and Eimer, 1999].

1.5.2 Electrophysiology of Intention: Evidence that the Bereitschaftspotential is the Neural Correlate of Intention

Walter (1967), following the discovery of the BP carried out experiments in which he used the subjects' BP or "intention wave" to trigger the event which the subject was intending to do. Subjects prepared to press a button (the intentional action), which would cause a picture to be presented. Ingeniously, the equipment was designed such that the BP triggered the computer and the relevant stimulus generator, so the outcome of the intended event occurred without the subject having to actually press the button. He called this process "auto-start", and observed that it was vital that the "subject should really 'want' the event to occur and [must] concentrate on evoking this particular event." Unsurprisingly, subjects found the experience of the outcome of their intended event occurring without their having to make the required operant action, "a very peculiar experience sometimes accompanied by signs of suppressed excitement" and, in two of the subjects, resulted in marked diuresis (excessive excretion of urine).

Walter's experiments provide clear evidence that the BP (or "intention wave") is the neural correlate of intention. This is because subjects manipulated their intention, which had a direct causal effect on the BP and thus, on the triggering of the operant event.

Using a paradigm similar to Walter (1967), Elbert, Rockstroh, Lutzenberger and Birbaumer (1979) tested subjects' abilities to instrumentally control slow cortical potentials (SCP) and ascertained how these self-regulated changes in the SCP alter with respect to autonomic and behavioural responses. SCPs are equivalent to BPs.

Subjects viewed a rocket ship on a TV screen, which had two possible targets. They were presented with one of two possible tones, one requiring the subject to *negatively* shift their cortical negativity (compared with baseline) to one target; and the other to *positively* shift their cortical negativity (compared with baseline) to the other target. The actual direct current (DC) shift in the six-second flight of the rocket to the target governed which target the rocket hit. Thus, subjects received visual feedback at six-second intervals of their "actual cortical shift". The experiment was also performed without feedback.

Subjects were capable of intentionally (in response to a stimulus) changing their cortical potential, most significantly in the second session in the positive shift trials. This experiment, therefore, also provides evidence that the BP is a neural correlate of intention, because subjects were able to alter their BPs using intention.

The discovery of the BP as detailed above heralded a major turning point in the study of intention and volitional movements. It provides an objective and quantitative method for studying intentional preparation in the pre-movement phase of intentional action.

1.5.3 The Anatomical Substrate of Intention

Until relatively recently, intention was the domain of philosophers. However, with the discovery of the bereitschaftspotential (BP) and other physiological pre-cursors to willed action, intention could be studied empirically by scientists.

These techniques generally agree on the activation of a distinct network of brain regions in a specific and hierarchical order during intentional actions. This network centres on the supplementary motor area (SMA) and also includes the basal ganglia, the prefrontal cortex and the motor cortex.

Libet and colleagues performed some interesting, if highly contentious, experiments in the early 1980s using the BP (e.g. Libet, Gleason, Wright and Pearl, 1983). His main contribution was to suggest that unconscious preparation precedes conscious intention, hence creating a problem for free will. Libet's experiments will be further discussed in the introduction to the subjective experiments in chapter 7, sections 7.1.1 to 7.1.3.

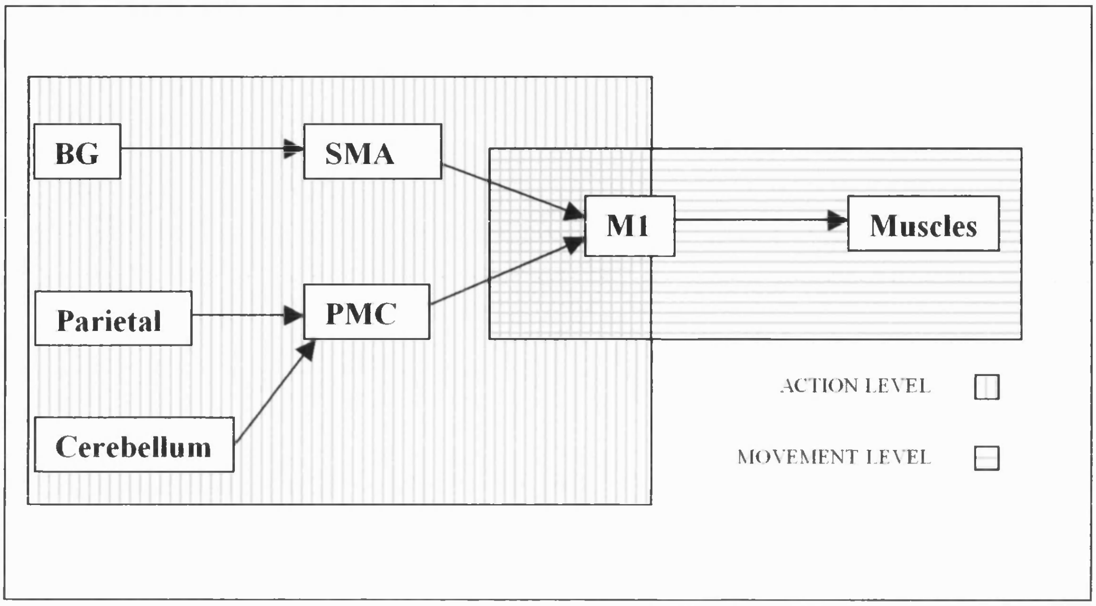
Neuropsychologists and philosophers have continued to postulate on and experiment with intention in an effort to identify and quantify intention in a scientific way. Recently, neuroscientists have discovered areas of the brain (e.g. the supplementary motor area,), which seem to be primarily concerned with intentional action, and other areas (e.g. pre-motor cortex), which are active when the movement is reactive. The localisation of relevant brain areas makes the study of intention a more empirically scientific endeavour.

One useful way to consider intentional action is to compare it with reaction. Therefore, it is worth investigating whether or not the brain systems for these two classes of action overlap. The notion that there are two distinct motor systems, one responsible for internally-generated movements and the other responsible for externally-triggered movements, is a contentious issue in contemporary cognitive psychology. As mentioned by Deecke (1987):

> For the human brain it makes a great difference whether we make movements in response to stimuli from the outer world – *re-actions* – or whether we perform purely 'endogenous' movements, which are really voluntary in nature and deserve the term *actions*.

Deecke (1987) is a proponent of the view that there is a structure in the brain, crucial for initiating voluntary action, which he identified as the supplementary motor area (SMA). The SMA is situated underneath the frontocentral midline where the first signs of cortical activity are seen during voluntary movements. In contrast, the pre-motor cortex (PMC) is believed to be involved in reactive movements. These two areas project to the primary motor cortex (M1), which corresponds to the final output of the voluntary motor system (Figure 1.2).

Figure 1.2. Schematic of the main motor associated projections into the primary motor area, via the SMA and PMC. BG = basal ganglia, SMA = supplementary motor area, PMC = pre-motor cortex, M1= primary motor cortex.



Before presenting evidence in support of these two hypothesised motor systems, it is useful to briefly consider the brain systems that control and generate movement. The notion of hierarchies of function or levels of organisation is a convenient way to do this (Thompson, 1993), particularly when considering at what level of the hierarchy this dichotomy might exist.

1.5.3.1 Hierarchies in the motor system

Many of the structures in the central nervous system (CNS) are concerned with movement, for example, the cerebellum, the basal ganglia, the M1, the PMC and the SMA, (see Figure 1.2). Fittingly, more than half the neurons in the brain are involved in the control of action, either directly or indirectly (Haggard, 2001).

At a broad level, it is clear that these structures are arranged hierarchically. Figure 1.2 schematises the two main levels of movement control: the action level and the motor level. The division between the action and motor level is based on the anatomy of the human body. Thus, a simple model of a hierarchical relationship within the motor system constitutes (i) the higher level consisting of the brain; and (ii) the muscles (and the spinal reflexes which exercise rudimentary control over the muscles).

The spinal cord is complex in humans, containing the motor neurons that are connected to all the body's muscles below the head (Thompson, 1993). The spinal cord can be activated by the brain's motor systems (the higher level), which results in movement, for example, internally-generated and externally-triggered actions. The spinal cord also produces reflex actions, for example the knee-jerk reflex (a stretch reflex). Therefore, the lower level of the motor system can produce actions that are controlled from the higher level (brain → spinal cord → muscles) and those that are not (e.g. the stretch reflex, extensor muscle → spinal cord → flexor muscle).

Information also passes from the lower levels to the higher levels of the motor system, particularly via sensory receptors, which can be visual, auditory, or tactile, for example. However, this thesis is primarily concerned with the motor output associated with the processes that start in the brain.

The action level, the higher level, is wholly located in the brain. The motor level consists of the muscular output and the neural pathways leading immediately to the muscles, i.e. the spinal cord and possibly the M1. There is some controversy over the M1 and its functions, hence the overlap of action and motor level in M1 in Figure 1.2. These issues are briefly considered below.

The controversy concerns the M1 and what is represented there. Traditional views, espoused by Sherrington (1906) and Penfield and colleagues (e.g. Penfield and Kristiansen, 1951) suggest that the musculature of the body is represented in the M1 and is organised somatotopically. That is, the musculature of the body is represented in an orderly fashion, with the body parts that are next to each other represented next to each other in the brain. For example, Penfield and Rasmussen (1950), by stimulating the cortex of fully conscious epileptic patients using local anaesthetic, were able to produce motor maps from the pre-central gyrus or M1. These maps showed, the thumb next to the index finger, which is next to the middle finger and so on.

Should the M1 be considered a high level centre for the control of action or a low level representation of the muscles, akin to the strings that pull a marionette? Penfield and Roberts (1959) considered the M1 to be "an arrival platform and a departure platform. Its function is to transmit and possibly to transmute ... the patterned stream of impulses which arises in the centrencephalic system and passes on out to the target in voluntary muscles." Sherrington (1906) called the "ultimate conductive link to an effector organ," the "*final common path.*" That is, Penfield and Roberts (1959) and Sherrington (1906) imply that the M1 is the beginning of the "*final common path*" to the muscles. Anatomically, this notion is supported: the pyramidal tract, one of the two major systems, which descends from the motor cortex and controls movement, contains neurons, the majority of which make monosynaptic connections with the spinal motor neurons (Thompson, 1993). Hence, many M1 cells are only one synapse away from the muscle. Therefore, the M1 could be considered to be part of the motor, or muscle, level of movement control.

On the other hand, more recent neurophysiological evidence suggested that the M1 represents actions or tasks at quite a high level. This research, using the techniques of intracortical stimulation in conscious animals (e.g. Cheney and Fetz, 1985) and 'spike-triggered averaging' (e.g. Lemon, Muir and Mantel, 1987) has suggested that the M1 contains an overlap in representations of the musculature of the body, and is therefore, more likely to represent movements rather than muscles. Most corticomotoneuronal (CM) cells are involved in activating more than one muscle, for example many of the CM cells that project to the forearm muscle groups are organised reciprocally, e.g. facilitating extensors and inhibiting flexors, (e.g. Cheney and Fetz, 1985).

Spike-triggered averaging involves "averaging the rectified EMG recorded from different limb muscles with respect to the discharges of a single cortical neurone" (Lemon, 1988). These techniques have, therefore shown, that large and discontinuous areas of the cortex can activate single muscles or movements (e.g. Cheney and Fetz, 1985).

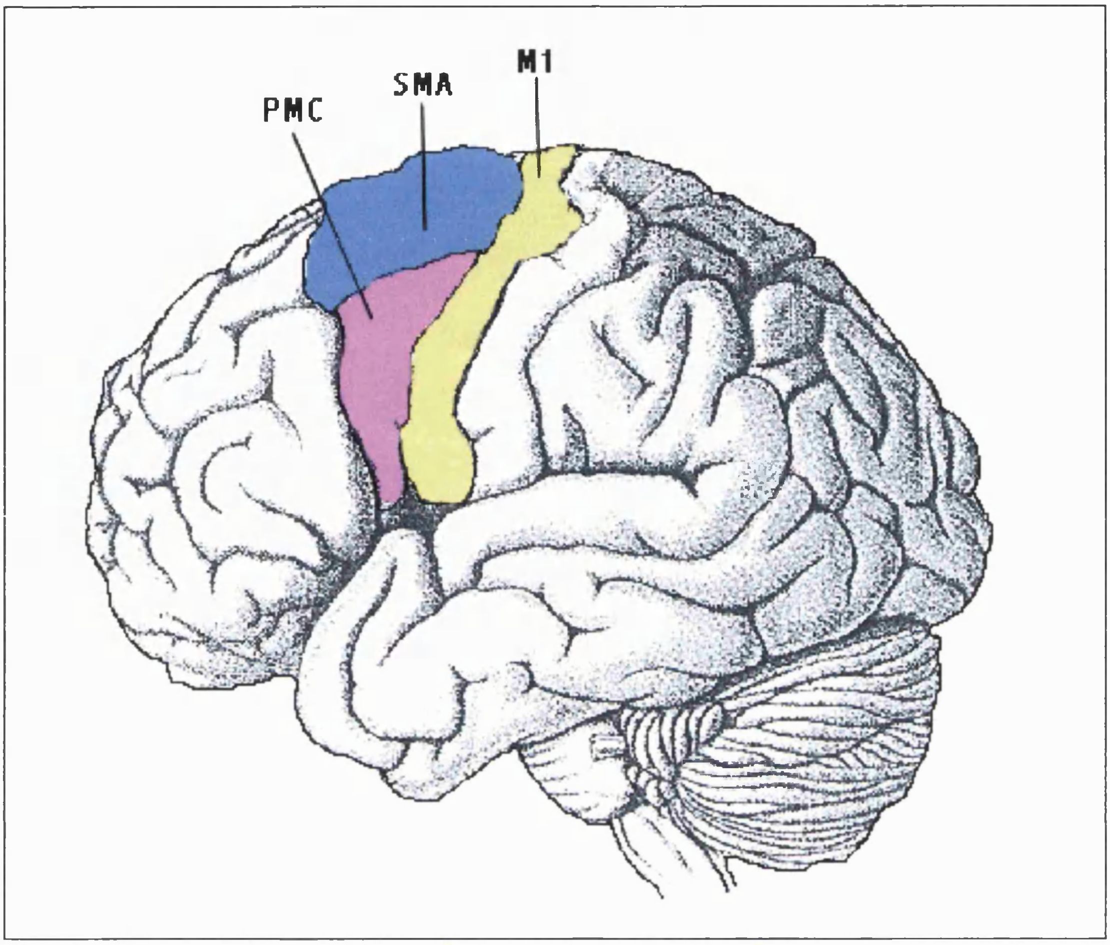
Problems with these techniques and their conclusions arise due to (i) the difficulty in defining a movement, (ii) the fact that every cell in the M1 would need to be tested to produce a categorical conclusion, and (iii) the recent evidence suggesting that the M1 is plastic (e.g. Asanuma, 1991). However, the fact that the M1 codes overlapping representations of muscles and movements, regardless of how precise the coding is, implies that it is part of the action or brain level of movement control. Regardless of which view is correct, all non-reflexive movements can be considered to make use of the "*final common path*" (Sherrington, 1906).

In this thesis, the focus is on the action level. Within this level there are two postulated motor systems: the internally-generated and externally-triggered motor system. The next three sections will consider different types of evidence in support of their dimorphism.

1.6 ANATOMICAL EVIDENCE IN SUPPORT OF TWO MOTOR SYSTEMS

There is varying evidence to support the idea that there are two different motor systems and that they are located in spatially different, but adjacent, areas of the brain. These are the anatomically distinct SMA and the PMC. The SMA and PMC are located in the lateral part of Brodmann's Area 6 and the medial part of Area 6; respectively and together constitute 88.2% of the pre-central tissue in the human brain (Blinkov and Gleser, 1968) [Figure 1.3].

Figure 1.3. Diagram to show the pre-motor cortex, the supplementary motor area and the primary motor cortex. Adapted from Bear, Connors and Paradiso (2001).[2]



1.6.1 The Supplementary Motor Area

The SMA was first reported by Penfield and Welch (1951), who observed the existence of a second motor area, the supplementary motor area. When this area, anterior to the motor area, was electrically stimulated in humans and monkeys; the responses, for example inhibition of voluntary action, suggested that they were not caused by the spread of excitation from the rolandic motor area (the M1); and that the primary motor cortex did not produce the responses seen in the SMA, meaning that this area is not activated by the M1. It is located in the medial frontal cortex above the PMC and immediately rostral to the M1 (Figure 1.3).

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[2] The prefrontal cortex, central sulcus, S1 and posterior parietal cortex labels have been removed. The pre-motor area (PMA) was relabelled as the PMC. The SMA, PMC and M1 were coloured differently.

Recent experimentation (e.g. Humberstone, Sawle, Clare, Hykin, Coxon, Bowtell, Macdonald, and Morris, 1997) has lead to the suggestion that the SMA consists of two hierarchically related areas: the pre-SMA which is responsible for the decisional processes in movement and the SMA-proper which is only active if the decision to actually move has already occurred.

Humberstone et al (1997) used the Go/No Go paradigm, which involved subjects receiving a warning stimulus, indicating that they should start to prepare to move. The imperative stimulus indicated that subjects should or should not move. It was shown that the pre-SMA was active in both Go and No Go situations, but the SMA-proper was only active if the command was Go. This supports the notion that the pre-SMA is active regardless of whether or not the movement actually occurs, i.e. it is concerned with the pre-movement processes, where SMA-proper is specifically a movement execution area.

Anatomically and functionally, there is support of this dichotomy in the SMA. Ikeda, Nagamine, Kunieda, Yazawa, Ohara, Taki, Kimura and Shibasaki (1999) performed subdural recordings in patients with epilepsy. Clonic EMG discharges produced positive cortical activity at the pre-SMA, preceding the EMG onset by 110 ms, and negative activity at the SMA-proper, preceding the EMG onset by 50-60 ms, i.e. the pre-SMA and the SMA-proper differentially activated during the same muscular convulsion.

The inputs into these two areas are also different: the main inputs in Macaque monkeys to the SMA-proper are the ventral lateral pars oralis (VLo), the ventral posterior lateral pars oralis (VPLo), the ventral lateral pars caudalis (VLc) of the thalamus. However, the inputs to the pre-SMA are the ventral anterior pars parvocellularis (VApc) and area X of Olszewski (Matelli and Luppino, 1996). The SMA-proper forms part of the 'basal ganglia motor loop' and the pre-SMA forms part of the 'basal ganglia complex loop' (Alexander, Crutcher and DeLong, 1990). Matelli, Luppino and Rizzolatti (1995) suggest that this provides further support favouring a hierarchical relationship between pre-SMA and SMA-proper.

There is evidence to support a further fractionation of the SMA. It has been demonstrated by Vorobiev, Govoni, Rizzolatti, Matelli and Luppino (1998) that the SMA-proper is subdivided into two sections: the caudal SMA (SMAc) and the rostral SMA (SMAr). Their post-mortem examinations of three people with no known history of neurological disorders indicated that the architectonic features of SMAc and SMAr differed in some aspects; specifically the number and density of pyramid cells was larger in SMAr. Vorobiev et al's (1998) results can account for contradictory findings regarding the conditions under which the SMA has shown to be activated.

The SMAc is known to be active during the execution of actions (Fink, Frackowiak, Pietrzyk and Passingham, 1997). In contrast the SMAr is active when subjects observe or imagine performing actions (Grafton, Arbib, Fadiga and Rizzolatti, 1996). It has also been demonstrated that the SMAr is activated when subjects perform synchronous tapping movements with or without a tone (Rao, Harrington, Haaland, Bobholz, Cox and Binder, 1997), that is, where the representation of the action is important, regardless of whether the movement is paced or not.

This latter finding was also supported by Jahanshahi, Jenkins, Brown, Marsden, Passingham and Brooks (1995) who found that the SMA was not more activated during self-paced actions (rather than externally-triggered actions). This can be explained by the "predictability of the trigger, stimulus anticipation and motor preparation [which] occurred in the externally triggered condition" (Deiber, Honda, Ibañez, Sadato and Hallett, 1999). That is, the reason the SMA was not *more* active during the self-paced conditions was because the externally-triggered conditions activated the SMA as well. Using Vorobiev et al's (1998) terminology, activation in the SMAr probably contributed to the SMA activity during externally-triggered actions reported by Jahanshahi et al (1995). Thus, the finding that there are further subdivisions in the SMA-proper into SMAr and SMAc, allows the occasionally disparate findings regarding the functions of the SMA to be integrated.

There are currently a number of orthogonal theories, which attempt to explain the functions of the SMA. They appear to be independent and incompatible: there seems to be no obvious way of integrating them into one coherent and completely explanatory theory. The three most prominent theories are discussed below.

1.6.1.1 Role of SMA in the initiation of action

Goldberg (1985) proposed an anatomico-physiological model in which the SMA is considered to be:

> … the key part in a medial, bilaterally organised system which operates in concert with a variety of other cortical and subcortical structures to perform context dependent selection, linkage, initiation, and anticipatory control of a set of 'precompiled' motor subroutines each of which corresponds to a particular component perceptual-motor strategy or schema of the complete action.

The SMA receives inputs from the frontal lobes and the basal ganglia and sends outputs to the M1. It is debatable whether or not the SMA is active prior to the M1, and whether the SMA innervates the M1: different researchers propose different suggestions.

Fried, Katz, McCarthy, Sass, Williamson, Spencer and Spencer (1991) performed a study of patients with intractable epilepsy. These researchers found that subthreshold stimulation of the SMA elicited comments such as "...[I] feel the urge to move." These urges were directed towards the specific body part that would have moved if the stimulation was increased. This discovery provides support for the role of the SMA in the decisional and preparatory stages of intentional movements, i.e. in the initiation stages of intentional movement.

Deecke's (1987) theory provides one of the few models, which explains how intentions are translated into movement. He suggests that the SMA might be involved in the initiation of volitional movements. Support for this statement is provided by the difference of 30 ms between the pre-motion positivity (PMP) and the motor potential (MP) which allows for the direct transfer from the SMA to the M1 as well as the "conveyance of motor command," via the relevant subcortical loops, e.g. cortico-basal ganglia-cortical loop. This is also supported by Deecke's physiological data, and the anatomical arrangement of the SMA and M1.

Rouiller, Babalian, Kazennikov, Moret, Yu and Wiesendanger, (1994), using tracing techniques in monkeys, compared the connectivity of the SMA and the M1. Their evidence indicates that the SMA neurons make direct connections with the cervical motoneurons in the spine. This lends to the idea that the SMA is involved directly in controlling the execution of movements, in line with the M1, and is not purely involved in preparatory processes, is not necessarily active prior to the M1, and does not necessarily innervate M1.

1.6.1.2 Role of SMA in the control of bimanual actions

It has been suggested that the role of the SMA is to control bimanual actions. Halsband, Ito, Tanji, and Freund (1993) and Wiesendanger, Wicki and Rouiller, (1994) provide clinical support for this theory. When the mesial frontal cortical area is lesioned, subjects are impaired in skilled bimanual tasks, such as knitting. However, callosal transections alone do not significantly affect learned bimanual skills (Preilowski, 1975). Thus, it has been suggested that the mesial cortex may have a hierarchically superior role in bimanual action. This clinical data is supported by monkey data (e.g. Brinkman, 1981).

1.6.1.3 Role of SMA in the retrieval of complex patterns from motor memory

The sequence theory suggests that the SMA is crucial for temporal structuring of movements (Tanji and Shima, 1994). Electrical recordings from the SMA-proper were active only when monkeys were about to perform a specific order of multiple movements from memory. Hence the SMA is supposedly associated with internally guided movements, which are based on information stored in the motor memory and rely on proprioceptive cues at the time of movement.

Halsband, Matsuzaka and Tanji (1994) provide electrophysiological evidence for this claim. Monkeys were trained to perform a sequential motor task and their performance was tested in two conditions: a memory based condition and a visually guided condition. The SMA neurons were predominantly active during the memory-based, internally-guided condition, and the neurons in the PMC were mainly active in the visually-based, externally-guided condition.

1.6.2 Pre-Motor Cortex

The pre-motor cortex (PMC), along with the SMA, the parietal cortex and the thalamus, projects to the primary motor cortex (M1) in humans (Passingham, 1993). In Macaques, it was demonstrated that approximately one third of the projections to the M1 are from Area 6 (PMC and SMA), one third from the parietal cortex and the final third from the thalamus (Ghosh, Brinkman and Porter, 1987). Importantly, the activity of these relays might provide mechanisms, which allow movements to be influenced by the context (Passingham, 1993). The PMC is located in the lateral part of Area 6 (Figure 1.3), and has been shown to be involved in externally-triggered actions. Thus, when the PMC is activated, the context of movement-production is reaction.

Evidence that the PMC is involved in externally-triggered actions is provided in three main formats. The first involves observing the awake, functioning brain via for example PET, such that humans can perform externally-triggered actions, and the areas of the brain involved can be observed and mapped. The second method of study observes patients with lesions to the PMC and related motor areas, and establishes what they are capable of doing. In non-human, simian subjects, accurate lesions to the relevant areas can be made, and their abilities can be compared pre- and post-operatively. Finally, invasive recordings of the PMC can be made, in which electrodes are inserted and the pattern of cells firing can be related to particular tasks.

Using PET, normal subjects were scanned performing sequences of movements that were novel and that were therefore, being actively learnt during the scanning procedure (Jenkins, Brooks, Nixon, Frackowiak and Passingham,1994). The sequences were learnt by trial-and-error, with auditory cues of different pitch providing feedback. This was compared with sequences that had been learned prior to the scanning. The PMC was found to be more active during the learning of novel, externally-triggered sequences, rather than during the pre-learned sequences in which the tones were solely presented for pacing purposes.

Experiments have been performed using patients who had had frontal lobectomies. Petrides (1985) devised a test in which subjects had to make a specific hand shape (e.g. make a fist) in response to a visual cue. The subject learns by trial-and-error which cue requires which response. Patients with left and right frontal lobectomies made more than three times as many errors as controls, suggesting that their ability to perform visually-guided actions was impaired. Halsband and Freund (1990), using Petrides (1985) visual conditional motor task tested patients who had suffered tumours or infarcts in the motor areas. Patients with PMC damage showed difficulties with the task, resulting in large numbers of errors. In contrast, patients with M1 damage were more accurate. However, the surgical lesions and damage resulting from tumours and infarcts were not discrete, and although the PMC appeared to be implicated, it cannot be categorically concluded that the inability to learn and perform externally-triggered actions is solely due to the PMC.

Studies using monkeys allow accurate lesioning or removal of the relevant motor areas. Passingham's studies of the PMC seem to suggest that the visual cues instruct the motor cortex via the PMC (e.g. Halsband and Passingham, 1985, Passingham, 1988). Passingham (1988) trained monkeys in a traditional motor task, such that certain stimuli were associated with certain responses. If the stimulus was blue, the monkey was instructed to pull the handle, if the stimulus was red the handle had to be turned. When the SMA was removed, leaving an intact PMC, the monkeys relearnt the task with success (Passingham, 1988). Thus, the PMC seems to have a functional role in the sensory guidance of movements (Rizzolatti, 1987). These ablation studies indicate, that both the SMA and PMC can function efficiently in the absence of the other. The PMC is specialised for directing movements on the basis of visual (i.e. external) cues. Thus, when ablated, external visual cues do not aid the monkeys' behaviour.

It has been demonstrated using physiological studies of cells and their firing patterns that "the activity of cells in the lateral premotor cortex often relates to the type of movement that the monkey makes" (Passingham, 1993). A plethora of studies have indicated that the cells in the PMC are differentially active. For example, 42% of the cells in the PMC are active when food is grasped by the monkey's hand, 7% of which were only active when the whole hand was used to grasp and 38% when only the fingers were used to grasp (Rizzolatti, Camarda, Fogassi, Gentilucci, Luppino and Matelli, 1988). The PMC was also shown to be differentially active when monkeys performed flexion or extensions of the elbow in a Go/No Go task (Weinrich, Wise and Mauritz, (1984). The position of the light moved ('Go') or did not ('No Go') from trial-to-trial. When the light dimmed, the monkey either moved their arm to the required position or did not, depending on whether the trial was a Go or No Go trial.

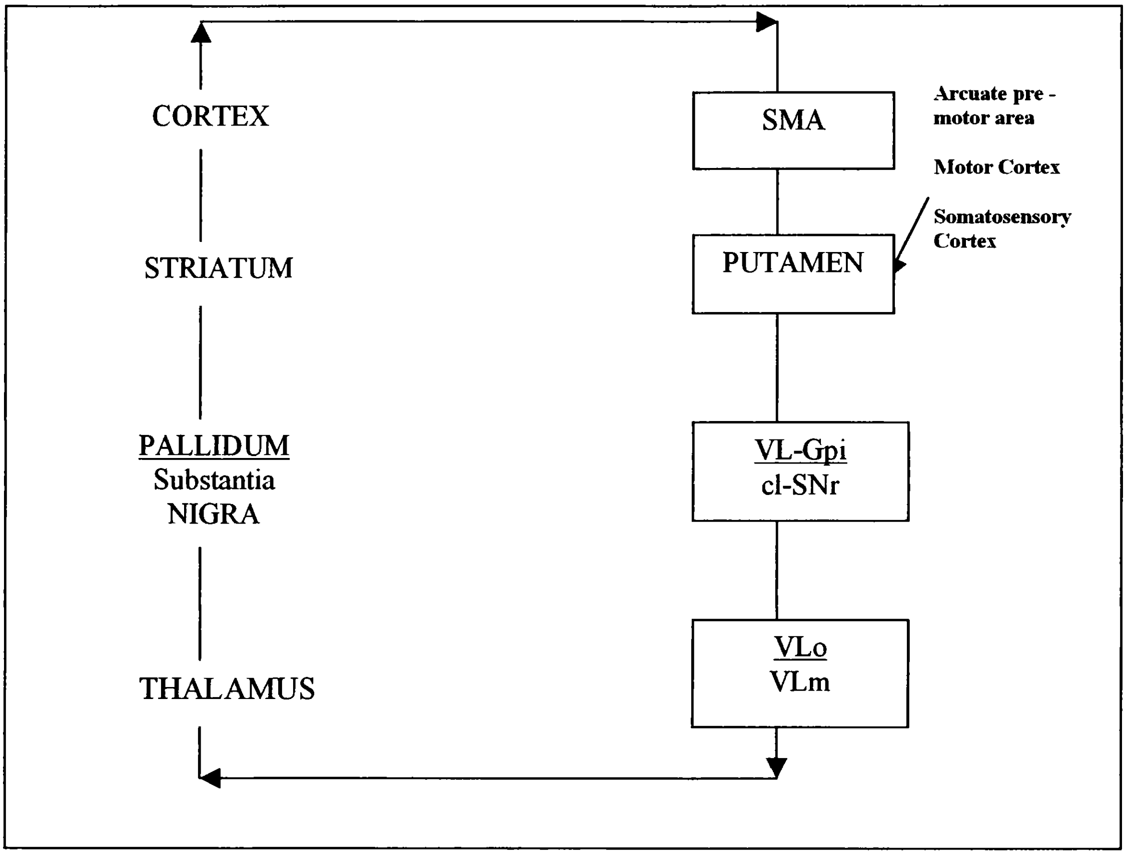
65% of the cells recorded in the PMC were active during the delay in the Go trials and inactive during the No Go trials. This suggests that activity in the PMC was dependent on whether an externally-triggered action would imminently occur. Specifically, it appears that the functions of the cells are to link a stimulus to a response. Halsband, Matsuzaka and Tanji (1994) [see section 1.6.1.3] demonstrated that the neurons in the PMC were mainly active in the visually-based, externally-guided condition. However this dissociation (the SMA and PMC) does not show how these areas inter-relate, just that they are capable of functioning independently.

In conclusion, the PMC appears to be involved in associating stimuli with responses. More specifically, the cells in the PMC may learn to relate stimuli to responses in an often arbitrary manner, such that externally-triggered actions can be performed.

1.6.3 Fronto-striatal Circuits

In an effort to try and localise will and intention, attention has been drawn to the frontal lobes and their connection with the basal ganglia, particularly the striatum. Jahanshahi and Frith (1998) propose that the fronto-striatal circuits are the anatomical substrates of a willed action system. The anatomy of the fronto-striatal circuits consists of five circuits, which connect the frontal cortex and the basal ganglia. The relevant circuit in this context is the motor loop, (Figure 1.4).

Figure 1.4. The motor loop: one of the circuits from the fronto-striatal network; adapted from Alexander, DeLong and Strick's diagram (1986). SMA = supplementary motor area, vl-Gpi = ventrolateral internal segment of the globus pallidus, cl-SNr = caudolateral substantia nigra pars reticulata, VLo = ventralis lateralis pars oralis, VLm = ventralis lateralis pars medialis.



The loop consists of a direct (striatum, GPi, SNr, VL) and indirect (GPe, STN, GPi) pathway, which have opposing effects on the thalamic targets from the basal ganglia outputs. These pathways facilitate or suppress cortically-initiated activity which, according to Jahanshahi and Frith (1998), might be the ideal configuration to suit the mediation of willed actions, because magnification and/or reinforcement or suppression and/or braking of activity that was initiated at the cortical level, can occur.

There are two extreme ways that disruptions of the direct and indirect pathways within the basal ganglia are clinically manifest. The first disorder is *hyper*kinetic, which is due to the degeneration of the inhibitory links from the striatum to the globus pallidus, external (GPe); and the second disorder is *hypo*kinetic, where there is a degeneration of the pathway from the substantia nigra pars compacta (SNpc), which leads to over-excitation of the globus pallidus, internal (GPi).

Hyperkinetic disorders such as Huntington's Chorea are characterised by uncontrollable, rapid movements contralateral to the damage. These disorders are genetically-based, autosomal dominant (caused by a single dominant gene on chromosome 4), degenerative and result in progressive involuntary movements, dementia and early death (Davison and Neale, 1996).

Hypokinetic disorders, for example Parkinson's disease, are due to selective degeneration of the dopaminergic innervation of the putamen and caudate. This progressive, neurological disease results in a reduction of spontaneous freely-willed movements (akinesia). The patients also demonstrate bradykinesia, which is manifested in slow or lack of movements. Tremors are also displayed by parkinsonian patients. Jahanshahi et al (1995) compared externally-triggered movements with internally-generated actions in healthy and parkinsonian patients. This direct comparison of regional cerebral blood flow (rCBF) using positron emission topography (PET) highlighted parkinsonian patients' problems with self-generated actions. Externally-triggered actions, made in response to a stimulus, proved to be the same in both groups. However, there was a marked reduction in activation of the SMA in parkinsonian patients, which suggests that the basal ganglia outputs to the SMA are not functioning appropriately, thus causing problems with the generation of intentional action.

1.7 NEUROPHYSIOLOGICAL EVIDENCE IN SUPPORT OF TWO MOTOR SYSTEMS

With the advent of more advanced technology in recent years it has been possible to non-invasively study activity in different areas of the brain concurrently with motor task performance. These non-invasive methodologies can be divided into two groups: (i) direct and (ii) indirect.

The direct methodologies observe direct brain processes such as neuronal firing/blood flow; for example, electroencephalography (EEG), magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), and PET, which that will be discussed in this section.

Indirect methodologies measure the secondary consequences of brain processes. They do not localise activations within the brain, but can provide information about timing of the activation and how a given experimental factor may modulate brain activity. These consequences may be behavioural (e.g. reaction time) or physiological (e.g. autonomic responses such as skin conductance and pupil dilation).

1.7.1 Direct Methodologies

EEG and MEG are electrophysiological techniques where electrical/magnetic information is sampled and recorded. Electrodes are placed on the scalp and the activity produced is recorded. The traces are locked to events, either the action or the stimulus, averaged over a minimum of 40 trials to improve the signal to noise ratio and then specific pre-movement potentials are isolated for analysis.

In EEG, BP traces are produced, which are slow ramp-like negative potentials maximal over two of the motor areas of the cortex (M1 and SMA). These are associated with internally-generated movements and begin up to two seconds before the intentional movement has occurred (McCallum, 1988 for review). MEG detects the minute magnetic field that changes in relation to electro-cortical activity. It produces evoked fields and movement-related fields, which are very similar to EEG. The evoked potentials associated with internally-generated actions are named Bereitschaftsmagnetfeld. The main advantage of MEG over EEG is its vastly improved localisation (Deecke, 1987).

Alternatively, PET and fMRI measure the changes in the rCBF associated with a particular task. The relationship between the blood flow and neural activity is assumed. In the case of fMRI, 'slices' of the alive, functioning brain are produced which indicate active areas during the task under examination.

These four methodologies have varying positive and negative temporal and spatial attributes and are, therefore often used in a convergent fashion in order to achieve the most comprehensive explanations.

Jahanshahi et al's (1995) study of intentional and reactive movements utilised PET and EEGs. Their results indicated that the BP, which is generally only present before intentional movements, is reduced or absent for reactive movements. The site of this event related potential (ERP) was the vertex (Cz), which is situated approximately above the SMA/M1.

The neural preparation for action can be proportioned into some quite distinct phases via EEGs (e.g. Haggard and Eimer, 1999). The first signs of the BP are bilaterally symmetric. However, at approximately 500 ms prior to the movement, the cortex contralateral to the imminent movement starts to show more activation. It has been suggested that the commencement of this lateralised readiness potential (LRP) might represent the transition from a general unspecified intention to a specific motor output (Haggard and Eimer, 1999); and that it might be related to the conscious experience of willing an action.

Haggard and Eimer's (1999) conclusions suggest that the early activation in the SMA (as shown by the bilateral symmetric BP) is associated with the preparation/intention of intentional movements (and not reactive movements). Hence, this data supports the suggestion by Deecke (1987) that the SMA was electrically active prior to the primary motor cortex (M1). More recent studies of intracranial recordings in humans, however, refute the proposed sequentiality of the SMA becoming active prior to the M1 (e.g. Ikeda, Luders, Burgess and Shibasaki, 1992). The data seem to indicate that the amplitude and time course in both areas was comparable, and that the SMAs contribution to the BP is not influenced by the complexity of the movement (Ikeda et al, 1992). However, these last two points do not necessarily preclude the SMA's role in planning or subserving a "supramotor" function (Alexander, Crutcher and DeLong 1990).

1.7.2 Indirect Methodologies

Indirect methodologies for measuring brain processes can be divided into two main groups: behavioural and physiological. Psychologists have traditionally focused on behavioural measures, most commonly RT. This involves subjects' reactions to stimuli being recorded and compared between different experimental conditions. Following this, the informational processes can be inferred depending on the RTs in the different conditions. Physiological measures involve the recording of physiological events indirectly associated with such informational processes. The autonomic nervous system (ANS), a predominantly involuntary system, controls these secondary physiological consequences.

1.7.2.1 The autonomic nervous system

The ANS is fundamentally concerned with maintaining an optimal internal environment for the body via the *sympathetic* and the *parasympathetic* nervous systems. Basically, the sympathetic system is involved with emergency arousal, such as the fight or flight mechanism, which prepares the body for impending emergency. The parasympathetic system generally acts conversely to the sympathetic system and is considered to be self-sustaining (Thompson, 1993). In both systems, motor nerves exit the brain and spinal cord (which together constitute the CNS), and synapse in peripheral ganglia. The locations of these peripheral ganglia differ in each system.

The ANS is indirectly influenced by the hypothalamus and certain limbic forebrain structures. Therefore, the ANS is involved in mediating the actions of the brain that are most directly involved in the emotional and motivational aspects of behaviour (Thompson, 1993). Arousal affects the ANS and thereafter the behaviours and their performance, which are mediated by the ANS.

There are two main effects of arousal, which are responsible for altering performance: (i) general arousal and (ii) specific arousal (Polich and Kok, 1995). General arousal might facilitate the alerting effects of certain sensory processes. General or tonic changes in arousal occur over minutes or hours and are due to the general background state of arousal, for example: EEG activity. Specific arousal, however, is thought to control the motor processes relevant to the particular act. For example, the "irrelevant 'accessory' stimulus" presented simultaneously with the imperative signal in a choice reaction time condition, which results in vastly reduced voluntary responses (Hackley and Valle-Inclán, 1998). Interestingly, this stimulus specifically speeds the early stage of stimulus processing, namely the orienting to and the perceptual categorisation of the reaction stimulus. Phasic or specific arousal responses are a reflection of the "organism's energetic reaction", for example, ERPs and skin conductance (Polich and Kok, 1995).

In arousing situations such as the cognitive effort required to prepare an intentional movement or to wait for a stimulus, or the classic fight or flight response, certain sympathetic autonomic responses occur. Examples of these phasic arousal effects include pupil dilation, heart rate deceleration and increased conductivity of the skin. Experimentally, pupil dilation, anticipatory cardiac deceleration and skin conductance can all be monitored via a camera aimed at the eye or by placement of electrodes on the relevant body part, thus providing an indirect measure of the relevant brain processes. These data can then be averaged with respect to the stimulus or the movement to produce stimulus-locked or movement-locked traces.

This thesis involves pupil dilation as a measure of cognitive effort (experimental chapters 4 and 5) during reactions to stimuli and preparation of intentional actions, and thus evaluates the history and use of pupil dilation as an indirect measure of brain processes. Since pupil dilation is now infrequently used, the underlying processes are reviewed here in detail.

1.7.2.2 Pupil dilation

Dilation and constriction of the pupil occurs via the sphincter pupillae and the dilator pupillae, which are situated in the iris. The dilator muscles are situated posterior to the constrictor muscle, are controlled by the sympathetic system and are radial, in that they extend outwardly from the pupil to the outside edge of the iris. The sphincter muscles are located in the stromal layer, are controlled by the parasympathetic system, and are circumferential in that they surround the inner edge of the iris (bordering the pupil/iris division).

1.7.2.3 Pupil dilation as a measure of cognitive load

The dilation of the pupil is sensitive to perceptual, motoric and cognitive aspects of a task. Thus, in simple reactions, the dilation of the pupil is an indication of the processing load involved in response preparation and execution, rather than perceptual discrimination (which is more involved in choice reaction times), Richer and Beatty (1987).

There is a long established use of pupil dilation as a measure of cognitive load in neuropsychology. In the early part of the nineteenth century, a German neurologist, Bumke, noted the phenomenon of pupil dilation and its relation to mental activity (as translated by Hess, 1975):

> Every active intellectual process, every psychical effort, every exertion of attention, every active mental image, regardless of content, particularly every affect just as truly produces pupil enlargement as does every sensory stimulus.

Hess and Polt (1964) were among the first to claim that pupil dilation was a measure of mental effort. In an experiment in which subjects were required to solve mental arithmetic problems, they showed that the magnitude of dilation was related to the difficulty of the problem. This claim was later substantiated in many contexts over the following years to include short-term memory tasks (Kahneman and Beatty, 1966), sentence comprehension (Wright and Kahneman, 1971), and paired-associate learning (Kahneman and Peavler, 1969).

Simpson and Hale (1969) demonstrated that pupil dilation was affected by movement decisions. They gave one group of subjects a two-choice decision task in which they were required to produce one freely-selected movement and the other group of subjects' directions to move with no decisional stage. Both groups showed identical dilation prior to the decision. However, the group required to decide which movement to make (i) had a faster increase in pupil dilation following the presentation of the two possible choices, (ii) had an overall significantly larger mean dilation across the decisional stage, and (iii) had a larger peak dilation following the presentation of the 'go' stimulus.

Beatty (1982) provides a more recent review of the uses of pupil dilation, indicating that changes in pupil size have been examined with respect to many types of mental activity, and thus "... as a tool in investigating human cognitive processing." Examples include language processing (e.g. Beatty and Wagoner, 1978), reasoning (e.g. Ahern and Beatty, 1979), perception (e.g. Hakerem and Sutton, 1966) and selective attention (Beatty, 1980).

Kahneman (1973), one of the earliest proponents of pupil dilation, within the information-processing tradition, suggested that pupil dilation "… is the best single index," and "… the most useful autonomic indication" of effort. This was due to the fact that measurements of pupil dilation are sensitive to between-task and within-task variations. Kahneman (1973) used pupil dilation as a momentary measure of effort or arousal, which is produced as a result of the required cognitive effort.

1.7.2.4 Early pupillometry

Early experimenters used a variety of techniques in an attempt to accurately quantify the amount of dilation on a trial-by-trial basis. The earliest pupillometric techniques required experimenters to compare photographs of the pupil, frame by frame and measure the dilation in each processed frame (e.g. Hakeram, 1967). This method was incredibly time-consuming and prone to limitations such as experimenter bias as a result of the repetitive, tedious and highly subjective measurement process.

With the more recent development of computers and videos, further techniques were developed for measuring the dilation of the pupil. Alexandridis, Leendert and Barbur (1991) review the two main techniques that were used at that time, for example those based on infrared reflex photometry and on video-image processing.

More recent technology has enabled the measurement of pupil dilation to be done in the average laboratory, although this is not common. However, modern technology, such as eye-trackers and more advanced computers mean that measuring pupil dilation is no longer problematic. Generally, eye-movements are monitored to ensure that subjects are fixating in the correct place or are not blinking, rather than dilations being measured. The main problem with eye-trackers is the noise they make as they follow the movement of the eye. We have developed a novel methodology for measuring the dilation of the pupil that is low cost and produces accurate recordings. This is described in the methods section of chapter 4 (section 4.2.2).

1.7.2.5 Pupil dilation and movement

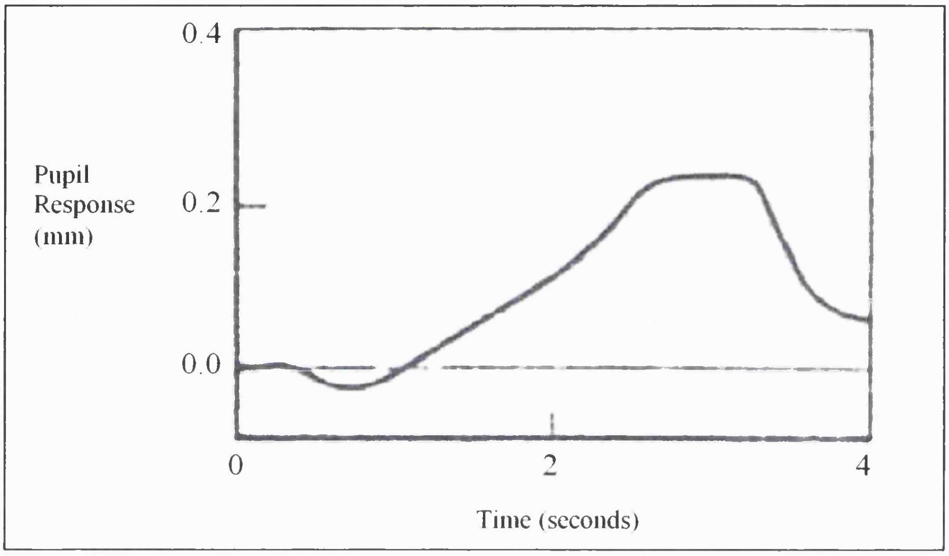
Lacey (1967) hypothesised that there was a connection between the ANS and motor preparation. This has been substantiated during recent years. In relation to motor behaviour, the ANS mediates structures such as the adrenal medulla, which are concerned with the motivational and emotional aspects of behaviour (Thompson, 1993).

With regards to the measurement of pupil dilation during this motor preparation, Richer and Beatty (1985) have observed internally-generated motor actions and Van der Molen, Boomsma, Jennings and Nieuwboer (1989) and Richer, Silverman and Beatty (1983) have examined precued reactive motor actions. Both types of movement have provided different pupil traces, thus demonstrating the use of pupil dilation as a measure of motor preparation and movement.

1.7.2.1.1 Internally-generated movements

The dilation of the pupil during the preparation of internally-generated movements is similar to the BP, which is a direct measurement of brain activity. The major differences are in the timing and the signal to noise ratio (SNR). The dilation of the pupil is controlled by the ANS and has a slow response compared with the rapid changes that occur in evoked neural activity. Thus, the dilation of the pupil is controlled by the ANS, which happens to correlate with brain activity, but does not show it. The SNR in pupil dilation is much better than in BPs, which means that the activity can be seen on a trial-by-trial basis. The pupil dilation associated with preparing an internally-generated movement starts approximately 1.5 seconds pre-response and peaks 0.5 seconds post-response (Figure 1.5). It was suggested by Richer and Beatty (1985), that these movement-related pupillary responses (MRPRs) might demonstrate that the pre-setting of the structures in the nervous systems is an important part of motor action.

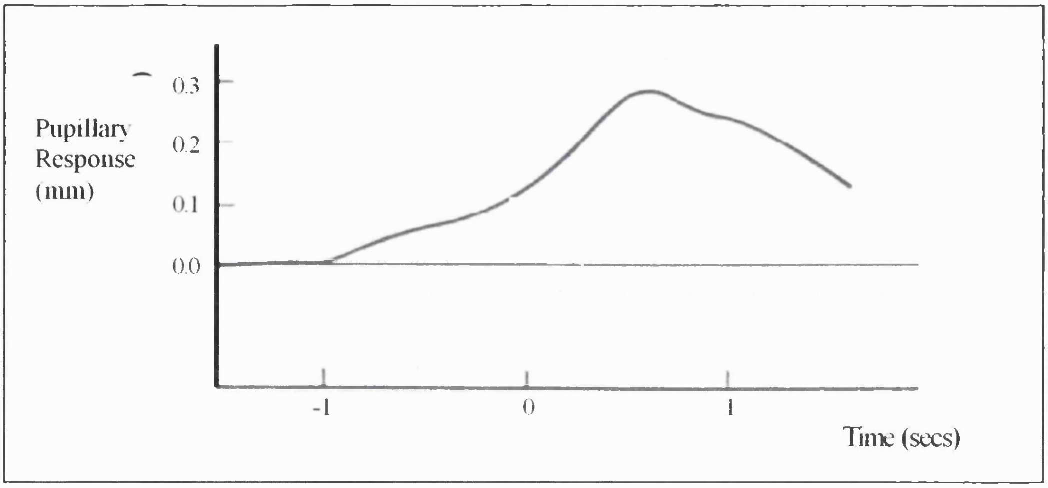
Figure 1.5. Pupil dilation associated with an internally generated action, where 2 = flexor EMG and activation of the response key. Adapted from Richer and Beatty (1985)[3].



1.7.2.1.2 Externally-triggered movements

Richer et al (1983) investigated pupillary responses in reactive movement using the Go/No Go paradigm. This involves subjects being presented with a regularly timed warning stimulus and then an imperative stimulus, which either requires them to react (Go) or not (No Go). Their results suggest that motor preparation is the same for both Go and No Go responses until the presentation (or not) of the imperative stimulus, that is, that the pupil starts to dilate due to the warning stimulus, approximately 1.5 seconds before the imperative stimulus and then further dilates if the subject performs the movement, but not if they do not perform the movement. This implies that there are separate processes for preparation and execution.

Figure 1.6. Pupil dilation associated with Go/No Go reaction time tasks, where 0 = response and the foreperiod is 1 second. Adapted from Richer et al (1983)[4].



1.8 EVIDENCE FROM CLINICAL DISORDERS OF INTENTIONAL ACTION

Neuropsychologists have studied people with disorders and patients with brain lesions following strokes and accidents to identify the psychological motor function. The general methodology involves observing what the patients can no longer do and then to infer that the area of the brain that is damaged must be responsible for that particular function (or is highly likely to be). A number of disorders of volitional action are known to exist and shall be discussed in this section. Some of these disorders follow from known focal physical damage such as strokes, head injuries and may lead to disorders such as alien hand syndrome; whereas others have no known origin, or a possible genetic link, such as schizophrenia.

The four main categories of neurological damage that clarify the relation between intention and reactivity are alien hand syndrome (AHS), utilisation behaviour, Parkinson's disease and schizophrenia. These are discussed in relevant detail in the following sections.

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[4] The x and y axes labels and numbering are identical, however, the EMG trace is not included here.

1.8.1 Alien Hand Syndrome or Anarchic Hand

AHS is an interesting clinical disorder that arises from physical damage to the SMA. The relevance of AHS to the study of intentional movements is that patients suffering from AHS seem unable to inhibit the purposeful movements that the hand contralateral to the damage makes (usually their right hand following left hemisphere strokes).

AHS seems to exist in two different clinical forms (Feinberg, Schindler, Flanagan and Haber, 1992). Frontal AHS follows damage to the SMA and the anterior corpus callosum, medial prefrontal cortex of the dominant hand and the anterior cingulate gyrus, is chronic and is associated with reflexive grasping, groping and compulsive manipulation of tools (also known as utilisation behaviour), [section 1.8.2], (Feinberg et al, 1992). Callosal AHS, is usually acute and results from damage to the anterior callosal region and manifests as intermanual conflict (Feinberg et al, 1992).

Patients often find themselves making movements with both hands, often directed towards the same object, which are motivated (i.e. goal-directed) and appropriate. Patients describe and are aware of, their inability to control their alien hand, which is often in opposition to their intention and the unaffected hand. For example, Della Sala, Marchetti and Spinnler (1991) observed a patient, G.C. who announced that she would wait for the steaming cup of tea in front of her to cool before she drank it. However, her right anarchic hand reached for the cup, followed by her left non-affected hand, which grabbed the right hand and brought it back to her side. G.C. considered her left hand as trustworthy and her right hand as the one that "always does what it wants to do," (Della Sala et al, 1991).

1.8.2 Utilisation Behaviour

Related to AHS is a phenomenon described by Lhermitte (1983) as utilisation behaviour. When patients are presented with objects (visual, visuotactile and tactile presentation) that have functions such as a cigarette and a lighter they are compelled to *utilise* them, hence performing the relevant tasks; in this case using the lighter to light the cigarette.

Lhermitte (1983) proposed that the patients' balance between dependence on and independence from the external world is disturbed. He suggested that the normal activity of the parietal lobe is to create links of dependence between external stimuli and the person, whilst still allowing the person to be independent of the external world and to modulate and inhibit parietal cortex activities. The balance in normal subjects is such that their behaviour is more or less dependent on or independent of the external world as a function of the external stimuli and internal activity (Lhermitte, 1983). Thus, patients seem unable to inhibit their utilisation behaviour, in that they are unable to intentionally inhibit reactive movements made to external stimuli.

1.8.3 Parkinson's Disease

Parkinson's disease is a movement disorder that manifests with motor and cognitive deficits. It is due to the degeneration of the dopaminergic connections in the basal ganglia (specifically the striatum). The motor deficits consist of bradykinesia (slowness of movement), akinesia (poverty of spontaneous movement), rigidity and tremor (see section 1.6.3 for further information on Parkinson's disease).

Parkinsonian patients exhibit significantly less activation in terms of rCBF and BP in the SMA compared to normals during the pre-movement period (Jahanshahi et al, 1995). Accordingly, they have problems with initiating intentional movement. However, they produce equivalent rCBF recordings and BPs to normals during reactive movements. This finding is in accordance with clinical observations that parkinsonian patients have difficulty in initiating intentional movement (compared with reactive movements). Clinicians have observed the improvement in walking patients demonstrated when external stimuli were used such as parallel lines in their line of vision on the floor in front of them. Thus, these patients' deficits appear to confirm the dichotomy between intentional and reactive movements, with intentional action being compromised but reactive movement being spared.

1.8.4 Schizophrenia

There are many symptoms displayed by some, or all, schizophrenic patients. This section will discuss those symptoms relevant to the generation of willed actions and stimulus-driven actions; and the inability of certain schizophrenic patients to monitor their own intentions.

Frith (1992) in his comprehensive book, 'The Cognitive Neuropsychology of Schizophrenia' details the three main impairments in the routes to willed action, which are observed in schizophrenic patients. These are (i) poverty of action, which includes movement, speech and affect, (ii) stereotypies and perseverations, and (iii) inappropriate responses to external stimuli.

Poverty of action (a negative symptom) arises from a failure of the patients' goals to initiate or generate the requisite intentions, which is called abulia (no will). That is, certain schizophrenic patients "cannot want to act" (Frith, 1992). This 'break' is one stage earlier in the poverty of action circuitry (Frith, 1992, Fig. 4.1. p46) than that seen in parkinsonism, whereby goals can generate an intention, but willed intentions fail to generate the intended actions. This similarity in the display of poverty of action, between these two apparently opposite disorders, is due to the pre-frontal areas being modulated by the dopamine system, which is over-stimulated in schizophrenia and reduced in parkinsonism (primarily in the striatum which is part of the basal ganglia).

Stereotypies and perseverations are repetitive types of behaviour, which are clearly demonstrated in clinical 'guessing games'. Frith and Done (1983) asked subjects to guess the colour of the next card (red or black). Young patients in the early stages of their illness and those with less severe forms of schizophrenia displayed stereotyped alternations, for example, red, black, red, black, red, etc. Schizophrenics who were in the later stages of their illness and those with more severe symptoms displayed the more extreme behaviour of perserveration, for example: red, red, red, red, red, etc. Frith (1992) found, however, that if the task had a pattern, which could be *learnt*; for example, the game theorists favourite, win-stay, lose-shift strategy, schizophrenics were able to determine their behaviour by the stimuli, that is the previous event.

The failure of willed action in some schizophrenics, results in their actions being excessively determined by irrelevant stimuli. This manifestation is remarkably similar to utilisation behaviour (Lhermitte, 1983) discussed in section 1.8.2, and is due to the failure of the patients goals to inhibit stimulus-driven actions.

Schizophrenics' inability to monitor their intentions can result in delusions of alien control and certain thought insertions and hallucinations (positive symptoms). Frith (1987) and suggest that these symptoms (delusions of control, etc) result from the failure of a central monitoring system. With reference to 'made volitional acts', schizophrenics sometimes feel that their own intentional movements are being caused by some external agency, that is, patients feel they do not initiate some of these movements (Davison and Neale, 1996). One patient described this feeling as follows: "... I am just a puppet who is manipulated by cosmic strings. When the strings are pulled my body moves and I cannot prevent it," (Mellor, 1970).

These experiential claims, by schizophrenics, of external agents causing their intentional actions have been experimentally supported by Dreher, Trapp, Banquet, Keil, Gunther and Burnod (1999). By recording EEGs during intentional and reactive movements, Dreher et al (1999) demonstrated that the amplitude of the BP is lower, rises more slowly and is less structured over the Cz (approximately the SMA/M1) in schizophrenics compared with controls.

Schizophrenics, therefore, show a "motor preparation deficit" (lower amplitude of BP at Cz) and a "decision-making process deficit" (significantly lower peak amplitude of the negative slope at Cz). These deficits suggest that the decision-making and resultant preparation generated by healthy people when they make intentional movements is absent in schizophrenics. Therefore, schizophrenics have different activations and thus, different experiences of willing an action. Where normals attribute agency to an action that they have actively decided upon, schizophrenics frequently do not feel that they were responsible for causing their actions. These data support their claim.

The impaired conscious awareness of one's own actions, which results from schizophrenics' inability to monitor their intentions was experimentally demonstrated by Frith and Done (1989). They tested acute schizophrenics', healthy people and psychotics' abilities to self-monitor using a specially designed video game. Two men, one on the top left and one on the bottom right, each aiming guns to the other side, were displayed on the screen. The trial began by a bird appearing opposite one of the two men, requiring subjects to move the joystick and 'fire the gun'. The gun produced a slow-moving bullet. Subjects could rectify an erroneous gunshot within the 2800 ms it took for the bullet to reach the bird. In some trials moving left caused the left man to fire and vice versa, the other trials moving left caused the left bird to be shot by the man on the right and vice versa.

In the condition without visual feedback, the majority of the screen was covered, such that subjects could only see the last 800 ms of the trajectory. All groups corrected their errors when provided with visual feedback. However, schizophrenics with "delusions of control", "thought insertion" and "thought blocking" failed to right their incorrect actions in the absence of visual feedback, i.e. during the first 2000 ms in the second condition. All subjects were able to track the sequence of trials accurately since there was no difference between the groups in the number of correct responses or false corrections. Frith and Done (1989) conclude that schizophrenics with "delusions of control", "thought insertion" and "thought blocking" cannot remember or are not aware of the response they had just made.

Franck, Farrer, Georgieff, Marie-Cardine, Dalery, d'Amato and Jeannerod (2000) also examined schizophrenics' inability to monitor their intentions, using a quantitative, rather than a qualitative approach. Three groups of subjects: normals, schizophrenics with "delusions of influence" and "non-influenced" schizophrenics performed two types of conditions. Both conditions required subjects to report whether the hand movements displayed on a computer screen were the same as their own movements. One type of condition varied the angular bias (by 0, 5, 10, 15, 20, 25, 30 or 40 degrees) and the other varied the delay in the movements on the computer screen (by 0, 50, 100, 150, 200, 300, 400 or 500 ms).

Interestingly, normal subjects attribute as their own, movements which are at a rotated trajectory of 15 degrees and those delayed by as much as 150 ms. "Influenced schizophrenics", however, erroneously attribute as their own, movements rotated by up to 30 degrees. "Non-influenced schizophrenics" hardly differ from normals in accurately reporting their own movements. Regarding the delayed movements, both "non-influenced" and "influenced schizophrenics" needed the delay to be as much as 300 ms for them to report that the movements were not their own. These data must, however, be viewed cautiously due to the small numbers of subjects (eighteen "non-influenced" and six "influenced schizophrenics") and the varied levels of significance achieved in the analyses.

1.9 THIS THESIS

The evidence reviewed here suggests that there is anatomical, neurophysiological and clinical evidence to support the notion that there are two distinct motor systems. The philosophical literature points to the idea that there is a subjective difference between movements which we make in response to external stimuli, reactions and those that are generated from within, intentions. Neuropsychology has tended to treat reactive and intentional movements as unique entities. Firstly, however, movements typically involve a combination of internal generation and stimulus-driven behaviour. Secondly, the mind and brain must use some executive or balancing process to reconcile the demands of intention and reactivity. Therefore, this thesis aims to examine intentional action, particularly in relation to reactive movement, using behavioural, psychological and electrophysiological techniques.

Chapter 2

THE INTER-RELATION BETWEEN THE HYPOTHESISED REACTIVE AND INTENTIONAL MOTOR SYSTEMS

2.1 INTRODUCTION

The first part of this chapter delineates the possible interactions between the postulated internally-generated and externally-triggered motor systems. The interaction between the two systems is examined throughout this thesis using a novel paradigm called truncation. Theoretical background to the truncation paradigm is thus presented. The second part of this chapter reports an experiment in which the truncation paradigm is applied to simple reaction time (SRT) and choice reaction time (CRT) tasks.

Reactive movements and the brain activities preceding them have been studied more extensively than volitional movements and their preceding brain processes. This differentiation is due to the fact that experimenters can manipulate stimuli and consequently reactions, whereas volitional movements are, by definition, controlled by the subject. Due to the unpredictable nature of volitional movements, it is difficult to objectively establish, and thus investigate, the onset of the pre-movement processes within a behavioural paradigm.

The relationship between reactive and intentional movement is also rarely studied, largely due to the fact that it is difficult to intervene experimentally and thus examine a volitional movement. However, the majority of our movements are a combination of intentions and reactions, hence, it seems sensible to study their inter-relation. As discussed in chapter 1, there is much evidence to suggest that there are two motor systems: an intentional and a reactive motor system. The study of intentional and reactive movements in this thesis is primarily concerned with the pre-movement processes, since intentional actions do not have external markers such as stimuli. Five hypothetical relationships between these two systems are proposed in the next section, followed by the evaluation of the pre-movement processes of intentional action and reaction.

2.1.1 Five Possible Hypotheses Regarding the Inter-relation of the Internally Generated and Externally Triggered Motor Systems

Five plausible hypotheses are proposed, suggesting ways in which the posited internally generated and externally triggered motor systems may inter-relate. These hypotheses are a combination of suggestive evidence and intuitive reasoning.

i. *The unitary system* suggests that the internally-generated and externally-triggered motor systems either constitute one system or are two co-activated systems. Brodmann (1925) identified the supplementary motor area (involved in internally-generated actions) and the pre-motor cortex (involved in externally-triggered actions) as constituting one area, Area 6.

ii. Two highly inter-connected *facilitatory systems*. This is similar to the first hypothesis in that the activity of one system is dependent upon the other. Theoretical support of these hypotheses is given by the concept of motor readiness (Näätänen, 1971). It is considered to be the single parameter determining whether a movement is made or not. Motor readiness is considered to be the difference between inhibitory and excitatory motor commands. A response is triggered when the criterion (the "motor action limit") of motor readiness, which is set by the subject, is fulfilled. Motor readiness fluctuates as a function of the ongoing central correcting commands, which maintain the required levels of motor preparation. Response speed is influenced by the predictability of the stimulus and by the level of preparation.

iii. *Independence* suggests that these two hypothesised systems actions do not affect each other. Passingham's (1988) research into lesioning the SMA and the PMC in monkeys demonstrates evidence for this hypothesis. It was shown that both the SMA and the PMC could function independently of the other, so even when one was lesioned, the other functioned efficiently. However, the double dissociation, although providing direct evidence for the independence, does not exclude the possibility that there is normally some interaction between them.

iv. *Separate but competing systems.* This is based on the idea that "the central system" has a limited capacity (Broadbent, 1982), which has "neither strict seriality, nor unlimited parallel processing", that is, the idea that there are limited cognitive resources for which there is competition. Once a cognitive task is occupying these central cognitive resources, there is a reduction of processing resources available for other cognitive events.

v. Systems that *directly inhibit* each other are similar to competitive systems in that activation of one system does not facilitate the activation of the other, and different to competitive systems in that, if one system is active, the other cannot be. It is, therefore difficult to experimentally distinguish between competing and inhibiting systems.

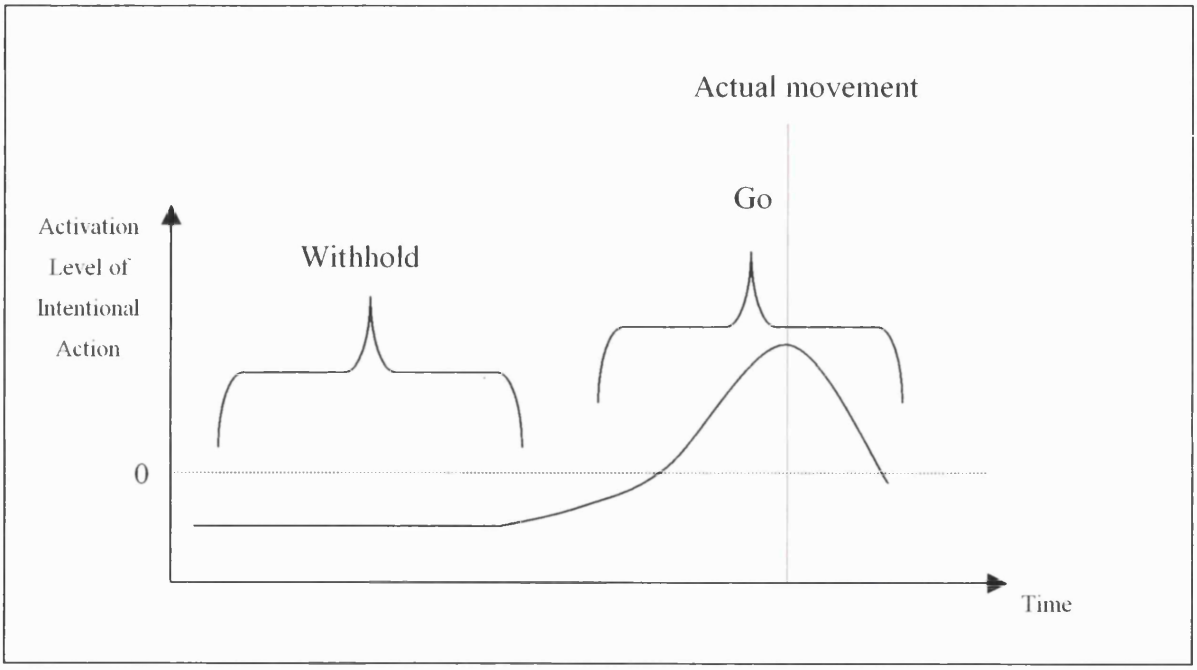
2.1.2 Pre-movement Processes

The pre-movement processes are easier to define for reaction than for intentional action. That is because introspection, which is highly subjective, is generally used to define the pre-movement processes for intentional action. Reaction, on the other hand, can be divided into sub-processes based on more tangible events such as the stimuli, the type of response and their timing. Introspection implies that there are at least three stages prior to a truly freely willed, intentional action. These are (i) volition – the desire to make the movement, (ii) intention – the translation of the desire into the initiation of the action, and (iii) preparation – of the actual movement, which occurs somewhere between intention and the actual muscular contractions that make up the movement. As noted in chapter 1, section 1.2, Jahanshahi and Frith (1998) conceived of the pre-motor processes of a willed action to consist of the "formulation of a goal and an intention to act, ... response selection, programming, and initiation," and "that [these processes] precede the production and execution of an action. "

The experiment reported in this chapter, although primarily aimed at evaluating the relationship between the intentional and reactive motor system, is also designed to investigate the intentional or pre-motor components of simple actions. Investigation of these components is performed by analysing the RT by foreperiod to see if a pattern emerges with regards to the early or late foreperiod, within the framework of a hypothesis that will be called the *withhold-go* hypothesis.

The *withhold-go* hypothesis suggests that when subjects are asked to prepare to make an intentional movement, the pre-motor phase is divided into two parts: the putative 'withhold' and 'go' phases. In the withhold phase, subjects are thought to be inhibiting the motor action (one of the many functions of the frontal lobes, specifically the role of behaviour inhibition). In the go phase, disinhibition begins, and the subject prepares to make the action (Figure 2.1).

Figure 2.1. This schematic shows a trace of some hypothetical level of activation of an intentional action. It is initially inhibited when the subject is in the 'withhold' phase and the line is below 0. As the subject moves into the putative 'go' phase, the activation of the intentional action increases. After the action has been performed the activation dies down again.



Reactions can also be broken down in a number of ways, as previously noted, based on tangible and, thus experimentally manipulable events, such as the stimulus and the resultant response. For example, there are obviously different pre-motor processes in choice reaction time (CRT) compared with simple reaction time (SRT), because there is only one possible stimulus and one possible response in an SRT experiment (Figure 2.2)

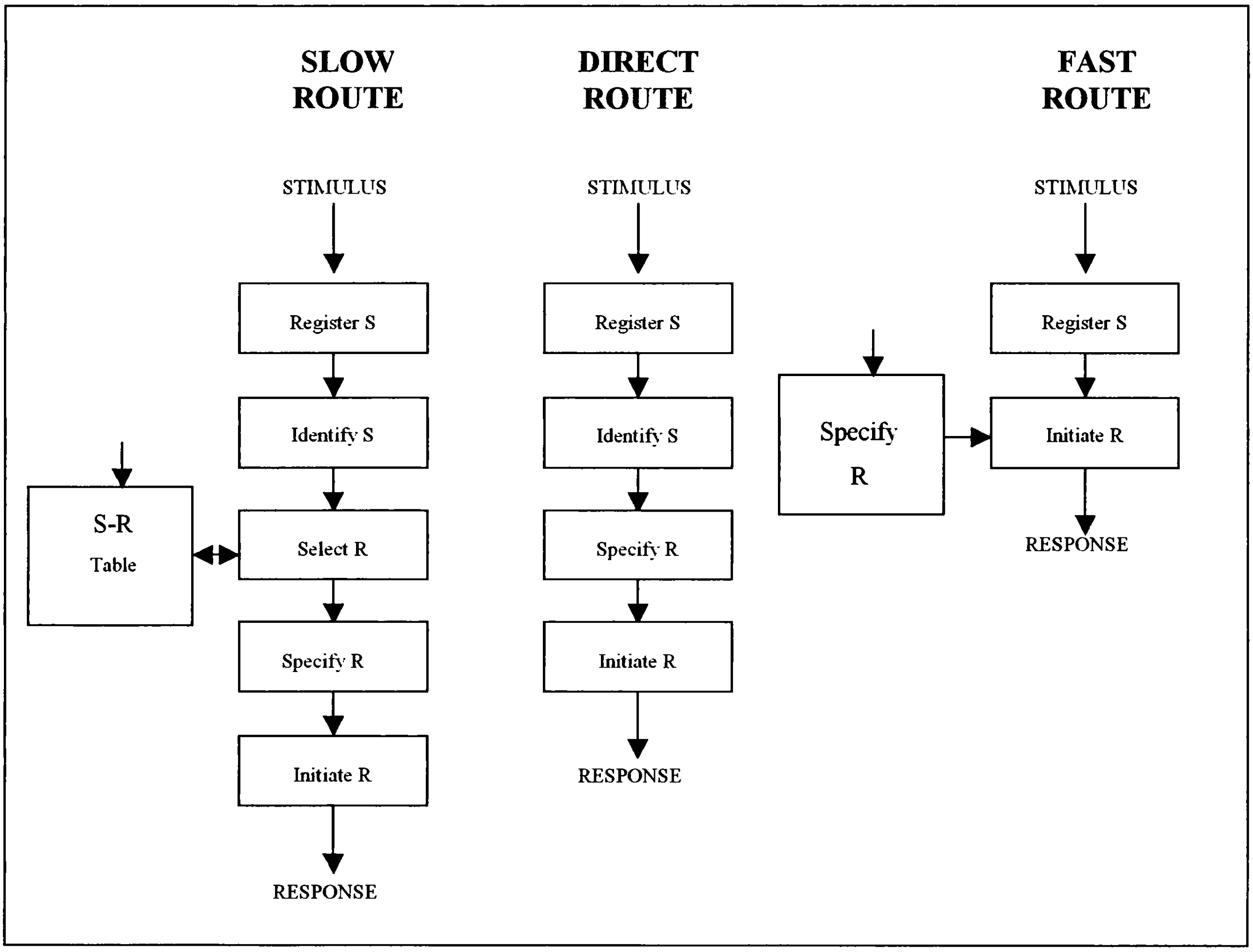
Figure 2.2. A simple schematic of the processes occurring within SRT and CRT.

SRT: Preparation of *known* response → Stimulus → Response

CRT: Stimulus → Preparation of *required* response → Response

Most researchers generally use a more complex framework, which varies between RT tasks. Frith and Done (1986) posit three hypothetical stimulus to response (S-R) routes, modelled on those outlined by Kerr (1978). These are the “slow route”, the “direct route” and the “fast route” (Figure 2.3).

Figure 2.3. In the slow route there is an arbitrary stimulus-response relationship: S1 → R1, S2 → R2. In the direct route, there is only one stimulus and only one response (equivalent to a standard SRT). The fast route assumes that the stimulus and the response are spatially and modally identical, i.e. tactile stimulus on finger that responds. Adapted from Frith and Done (1986).



2.1.3 The Truncation Condition

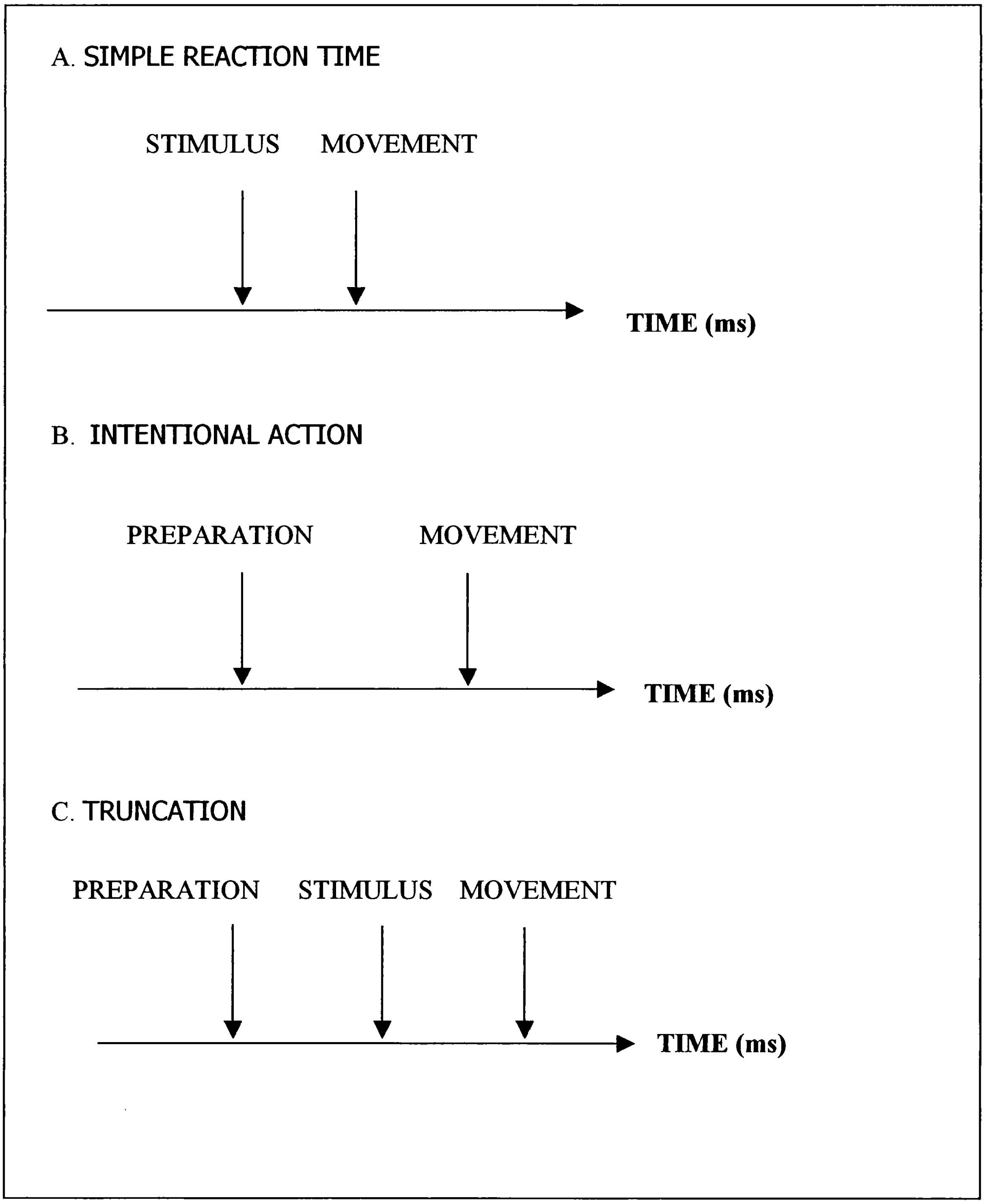
One way to study the similarities between the two proposed motor systems is to study the preparation that produces the movement rather than the output, which is the same. An identical motor response is arrived at by two different routes: intentional preparation and reaction to an external stimulus. These pre-movement processes are the focus of study in this experiment.

The truncation condition is a novel paradigm designed to examine the relation between the preparatory processes for intentional and reactive movements. This paradigm is used throughout this thesis. Thus, comprehension of the truncation paradigm and its affect on trial outcome, is vital. The trial begins with the subject preparing an internally generated, endogenous right keypress, that is, following the instruction "make an internally generated right keypress as and when you feel like it". In random trials, this internally generated preparation might be truncated with a stimulus that indicates that the subject must react with their right hand, that is, subjects are instructed to react with exactly the same movement as they were preparing. Therefore, two types of possible trial may result from this condition: (i) internally-generated keypresses and (ii) truncated reactions. Experimentally, double the number of truncation trials are run (in comparison to the other conditions) resulting in approximately 50% internally-generated keypresses and 50% truncated reactions, assuming that subjects make their intentional movements randomly, thus allowing for the truncating stimulus to occur.

The truncation condition is the combination of a simple reaction time (SRT) condition, where the subject is presented with a stimulus to which they must react, and an intentional action condition. Both intentional and reactive processes occur in each truncation trial, so the possibility of an interaction between them is created. Retrospectively however, each trial can be classified as an intentional action or a reaction. These truncated intentional actions (TIN) and truncated reactions (TRT) can be compared with control blocks involving *only* intentional actions or *only* reactions. Comparisons such as these allow direct assessment of the interaction between the hypothesised internally-generated and externally-triggered motor systems. Figure 2.4 presents schematic representations of these conditions.

This experiment also includes a two-choice reaction time (CRT) condition and a truncated CRT condition. In the truncated CRT, subjects always start the trial by preparing to make a right intentional keypress. This preparation is then randomly truncated with a stimulus. The stimulus indicates to the subject that they must react with their left or right hand.

Figure 2.4. Schematics representing the simple reaction time, the intentional action and the truncation condition.



2.1.4 The Use of Variable Foreperiods

The main difficulty in examining internally-generated movements is that the experimenter does not know when the movement will occur; therefore, the point at which the truncating stimulus should be presented becomes a problem. The intentional action effectively has a variable foreperiod that depends on the actions of the subject, not the experimenter. By arranging for the truncating stimulus to have variable foreperiods means that on average there will be a 50% chance that the truncating stimulus will be presented during the preparation for the internally-generated movement.

Foreperiod lengths and their affects on RTs have been extensively researched but their relationship is equivocal. Woodrow (1914) was the first to report on their relationship: a two-second foreperiod resulted in the fastest RT (compared with longer and shorter foreperiods), which he attributed to the 'maximal adaptation of attention'. Näätänen (1970) observed that with variable foreperiods and a simple RT task, the RT decreased as the foreperiod increased. This suggests that as the probability of the stimulus occurrence increases (as the length of the foreperiod increases), the more prepared the subject becomes, therefore reacting faster.

However, foreperiods that are too long (e.g. more than two seconds, Näätänen, 1970) do not result in faster RTs because subjects' cannot maintain the "preparatory set" which assists performance (Gottsdanker, 1975). With constant foreperiods, subjects can estimate the time of the stimulus occurrence and prepare accordingly (Rogers and Monsell, 1995). Although, the longer the foreperiod, the longer the RT (Niemi and Näätänen, 1981) because subjects become less accurate at judging the timing of the stimulus as the foreperiod increases (i.e. subjects' accuracy on timing judgements decreases as the length of time they have to judge increases). This is seen with foreperiods of up to approximately 500 ms in SRT tasks (see Näätänen and Merisalo, 1977, for review) and CRT tasks (e.g. Bertelson, 1967).

The nature of the truncation condition means that a variable foreperiod must be used. If subjects knew exactly when the truncating stimulus was going to occur the preparation for the internally-generated movement would not be realistic, because they might divide their central attention (or cognitive resources) and spatial attention unequally between internal generation and the external monitoring of the stimulus presentation and the possibility of reacting. It cannot be ascertained that subjects' attention is divided approximately equally between the intentional and reactive task throughout the experiment, but if the stimulus were presented at a constant foreperiod, then it would be assumed that they would divert more attention towards the stimulus at the time when it is expected. Thus variable foreperiods were used in this experiment.

2.1.5 Switch Costs

The truncation condition involves the switching from one hypothesised motor system, the internally-generated motor system to another hypothesised motor system, the externally-triggered or reactive motor system. Thus, 'switch costs' might be incurred. In this experiment, the difference between the RT in the control condition (SRT or CRT) and the truncated condition (truncated SRT or truncated CRT) is defined as the *RT cost of intention.* That is, the amount of time it takes to 'switch' from intentional to reactive movement.

In a study comprising six experiments, Rogers and Monsell (1995), examined the switch costs when subjects switched between two forced-choice tasks in which the two responses for each task were identical. By requiring subjects to react in both tasks with the same pair of responses (left or right index finger), Rogers and Monsell invoked a process that they called "task-set reconfiguration". A task-set is adopted when subjects "form an effective intention to perform a particular task, regardless of which of the range of task-relevant stimuli will occur" (Rogers and Monsell, 1995). Task-set reconfiguration occurs when subjects reconfigure their task-sets in the response-stimulus (R-S) interval between the two different tasks. That is, they must alter the selection, association and composition of the relevant components that make up the sequence of events that constitute the new task.

Rogers and Monsell (1995) demonstrated that switching between two simple cognitive tasks, even when the switch is predictable, incurs a large RT and error rate. The cost does not decrease below an asymptotic level when the R-S interval is increased to as much as one second. That is, a residual switch cost is incurred when subjects' switch between the two tasks, regardless of the length of the R-S interval. However, the brunt of the switch cost seems to be absorbed in the first trial of the new task, that is, there is only significant improvement between the first and second trials and none thereafter. The "active process" of declining switch cost when the R-S interval is predictable, is suggested to be due to the endogenous control exerted on the task-set configuration, for example, by the supervisory attentional system (Shallice, 1988), or the will (James, 1890).

Allport, Styles and Hsieh (1994) observed a similar residual switch cost that was due, they proposed, to task-set inertia (TSI). TSI accounts for the switch cost that arises due to the interference of the residue of the primary task set exerted on the second task. However, TSI would predict that large switch costs would be found in the trials subsequent to trial one, following a change in task-set, which Rogers and Monsell (1995) did not find in their sixth experiment. That is, TSI can account for the residual switch costs found at long R-S intervals, but cannot account for the marked improvement found between trials one and two.

As Rogers and Monsell observe, TSI would need to be a passive process in order for subjects not to be able to suppress it at longer R-S intervals. However, if it was a passive process which decayed outside the control of the subject, then trial two, following a change in task-set would also exhibit a large switch cost, which it does not. Therefore, Rogers and Monsell's (1995) suggestion that the switch cost is, at least in part, actively controlled by the subject when the interval is predictable, appears to be the most logical description of the processes responsible for the changes in switch costs. Endogenous control mixed with exogenous influences (e.g. stimuli) and the limitations of the motor system fits with the phenomenological experience of control over certain actions when we interact with our environment.

Foreperiods and their lengths also affect switch costs. According to Rogers and Monsell's (1995) second experiment, when foreperiods are variable, subjects do not know when the stimulus is going to be presented; thus, they appear not to prepare the relevant task-set until the stimulus indicating the desired response is presented. Fixed-length foreperiods produce a mixed set of responses. Switch costs decreased as the foreperiod increased from 150 ms to 600 ms, with a residual, but not improved, switch cost still found at an R-S interval of 1200 ms. When the foreperiod is 600 ms, as in experiments 3 and 4, subjects can reconfigure their task-set, because they are capable of relatively accurately estimating the time of the prescient stimulus occurrence (Rogers and Monsell, 1995) and they have the time to do it. Rogers and Monsell suggest that as the interval increases above 600 ms, subjects are less accurate at judging the temporal certainty of the next stimulus and therefore, reconfigure too soon, are incapable of maintaining the new task-set, or reconfigure too late.

The truncation condition, detailed in section 2.1.3, is similar to the Rogers and Monsell paradigm, in that the switching is stimulus-driven. However, the experiment in this chapter differs from previous research in that (i) the switching does not occur between two S-R mappings; (ii) the primary task is endogenous, i.e. not requiring an S-R map; (iii) there is no primary S-R relationship which can be varied; and (iv) the truncating stimulus requires that subjects perform the same or similar movement to the one that they were planning. Thus, there is only the S-R mapping to be learnt and that can be manipulated for the secondary task. Therefore, the switch is between two movements, which in the SRT and truncated SRT are motorically identical but psychologically different. Also, subjects are not actively encouraged to prepare the response to the truncation stimulus, as it is the secondary task. Although there are differences in what is being switched, between the truncation condition and Rogers and Monsell's task-sets, there is a clear analogy between switching task-sets and switching from intentional action to reaction.

2.1.6 Locking Stimulus-Response Codes

Stoet and Hommel (1999) hypothesised that action planning was associated with a problem of feature binding. Feature binding refers to the way that the features of objects/events are cognitively organised. For example, if the colour and form of objects are coded separately, how is the cognitive system capable of associating the long stem of a purple tulip and green, and the flower itself and purple (rather than stem and purple being associated together)? This has been extensively studied in perception (e.g. Mozer, 1991), but less so in action control. Stoet and Hommel (1999) suggest that given the evidence supporting bindings between stimulus features (e.g. Kahneman and Treisman, 1984) and between stimulus and response features (e.g. Hommel, 1998), it might be likely that feature-binding also occurs in action planning, particularly between response codes. Following this logic, the authors derived the "code occupation hypothesis" which states that "making an action plan [specifying an S-R code] may involve more than just activating the feature components that make up the action, but rather require an integration of these elements into a common episodic structure" (Stoet and Hommel, 1999).

This supposition is relevant to the truncation condition, in that preparing an intentional action requires a particular action plan to be specified, and the presentation of the truncating stimulus requires the same 'response', that is, the already specified motor effector: a right index finger keypress. Stoet and Hommel examined this "code occupation hypothesis" by interleaving one task with another, similar to the truncation condition. Subjects were presented with a stimulus (A), then with a second stimulus (B) that required an immediate response (B). After the response to B, subjects responded to stimulus A with response A, that is, task B was embedded in task A. These researchers found that the response to stimulus B was delayed (i) if A and B had any shared response features, for example same hand, even if the effectors were different (hands and feet); and (ii) if response A had been planned (prepared) in advance of response B. These findings would lead to the prediction that interrupting the intentional preparation with a truncating stimulus would result in a delayed RT if the intentional and reactive tasks share response features.

2.1.7 Aims

This experiment aims to investigate the posited inter-relationship between internally-generated and externally-triggered motor systems and to examine some of the pre-motor processes in intentional action.

2.1.7.1 Hypotheses

The *unitary* and *facilitatory* systems hypotheses would predict that preparation for an intentional movement would facilitate the reaction to a truncating stimulus; thus, the RT for a truncated condition (of the same movement) would be shorter than the RT for the SRT condition.

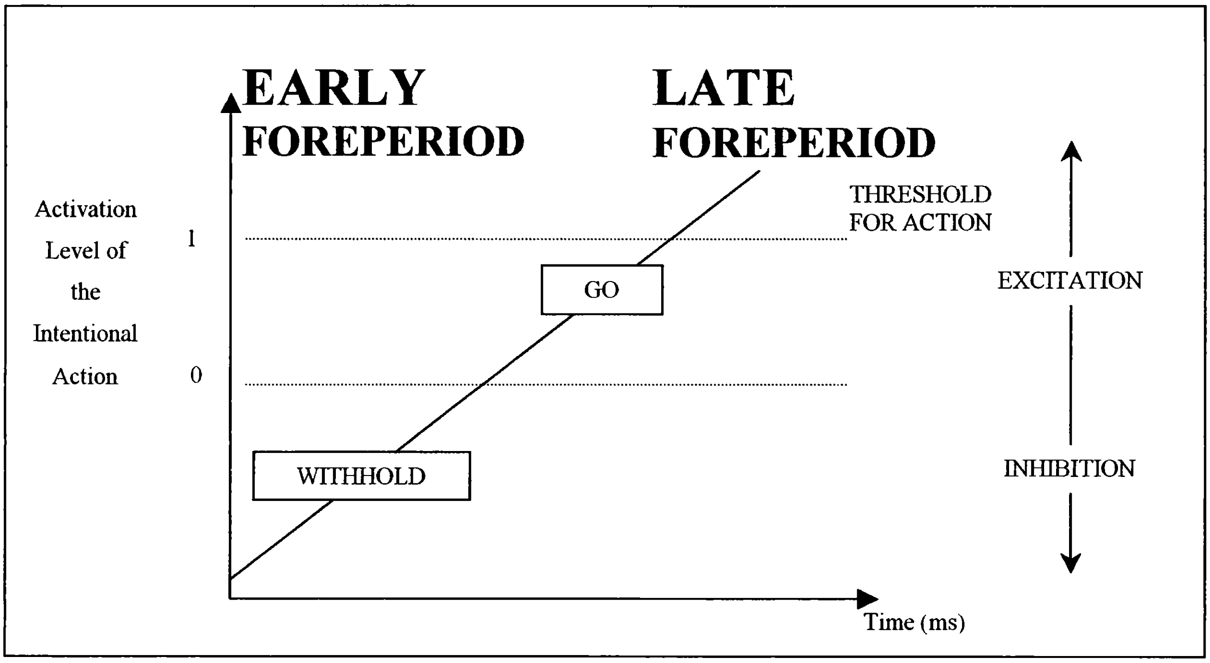
The *independent* systems hypothesis should result in equivalent RTs between the truncation and the SRT conditions because the effect of intentional preparation has no affect on reacting to a truncating stimulus.

The *separate but competing* and the *directly inhibitory* systems hypotheses would result in longer RTs for the truncation conditions compared with the SRT conditions due to the competition/inhibition between the two motor processes of internal generation and reaction. Switching occurs between hands as well as movement types in the truncated left SRT (intend right, always react left) and approximately half the time in the truncated CRT condition (intend right, react left in approximately half the reactive trials). In terms of the hypotheses, it would be expected that if the intentional and the reactive motor systems were competing, then reacting with a different hand to that with which you were preparing would not result in a longer RT than reacting with the same hand. However, if the systems were inhibitory, then reacting with the same hand as you were preparing the intentional keypress would incur a longer RT than reacting with a different hand, due to the direct interference between them.

2.1.7.2 Pre-movement processes

Figure 2.5 schematises the putative "motor action limit" (which will be called the motor activation level), during preparation for the intentional action. The threshold for action is an idea established in Näätänen's "motor action limit" model (Näätänen, 1971). Prior to the "motor action limit", the subject fluctuates in varying stages of motor preparedness, balancing the inhibitory and excitatory commands. It is suggested that the balancing occurs via feedback information from the "muscular effects of its [the organism's] excitatory and inhibitory commands" (Näätänen and Merisalo, 1977). At some point, the motor readiness "flows over" into the action, either when the stimulus is presented, or when the subject inaccurately balances the inhibitory and excitatory commands in an effort to remain at the highest level of motor readiness.

Figure 2.5. This schematic shows the activation of the intentional action in the truncation condition. As the foreperiod duration increases, the subject should be moving from the 'withhold' to the 'go' phase, and therefore the activation of the intentional action should increase.



In the activation of the intentional action of the truncation condition (Figure 2.5), it is assumed that the action occurs when the threshold for action (arbitrarily denoted as1) is crossed. Below the threshold for action, there is still the possibility that the motor system is either inhibited or excited, which could occur at many different levels of the motor hierarchy. Using the supposition that when the net level of excitation is below 0, the intentional action is being inhibited, as the level of motor activation increases over time, the net level surpasses the arbitrarily denoted value of 0 and enters the go phase where the intentional action is being actively prepared.

In any trial, the stimulus could occur at any moment within the delineated foreperiod, either in the withhold phase or in the go phase. Since, by definition, the withhold stage is before the go stage, any stimulus occurring early in the foreperiod is more likely to be in the withhold stage and any stimulus occurring in the late foreperiod is more likely to be in the go phase. This assumption may not hold for every trial, but must be true on average. Therefore, the model can make specific predictions about the reaction times in the truncation task. The predictions will differ, depending on where the interactions between the internally-generated and externally-triggered systems are thought to be occurring.

The inhibition in the withhold phase and the excitation in the go phase could potentially be occurring at either the motor or muscle level (lower); or at the action or brain level (higher) of the motor hierarchy, (chapter 1, section 1.5.3.1, for descriptions of hierarchies). If these processes are occurring at the motor level, then there is one prediction, based on the general level of motor arousal at each stage. If the truncating stimulus was presented in the hypothetical withhold phase, the level of motor activation (or "motor action limit", Näätänen, 1971) would be low due to the inhibition of the intentional action. Therefore, long RTs might result due to the necessary excitation required to activate a response. However, if the subject was in the projected go phase, they would be closer to making the movement and therefore, closer to the level of motor activation. Thus, less activation would be required to trigger the action, that is, less activation would be needed for the preparation to "flow over into the corresponding motor action" (Näätänen, 1971), resulting in a faster RT.

Although Näätänen based this proposition on constant foreperiods, in a later review it was observed that the "modified subjective frequencies" might alter the expectation of when the stimulus is going to occur and therefore, the RT (Näätänen and Merisalo, 1977). That is, the subjects' internal 'averaging' mechanisms of when the stimulus occurs alters their level of expectation and preparation. Näätänen and Merisalo (1977) proposed that the median foreperiods would be subjectively experienced most often, therefore, the RT would be fastest to the stimuli presented in the median foreperiods; compared to the most extreme foreperiods. However, (i) the data reported was unpublished; (ii) the foreperiods used were shorter than the ones in this experiment; and (iii) the RT was the slowest when the foreperiod was short, and approximately the same speed at the median and long foreperiods. Therefore, it is predicted that faster RTs will occur later in the foreperiod.

If these hypothetical withhold-go processes are occurring at the action level then there are three sets of predictions based on the postulated relationships between the internally-generated and externally-triggered motor systems. In each case, the comment is not about the foreperiod affects on the truncation task *per se*, but it about additional foreperiod affects on truncation in addition to those on the SRT control task.

Firstly, if the motor systems were related in a facilitatory or unitary manner, then the same outcome as the motor level occurrences predicted would be expected. Briefly, slower RTs in the withhold stage due to a low level of activation and therefore, long distance away from the criterion of the "motor action limit"; and faster RTs in the go stage due to the higher level of activation and therefore, proximity to the "motor action limit" would result. These predictions fit with the internally-generated and externally-triggered motor systems being related in a facilitatory or unitary manner, in that if the motor activation level of intentional action is low, the corresponding level of motor activation of the reaction will also be low.

Secondly, if the internally-generated and externally-triggered systems were related in an inhibitory or competitive way, then the predictions of the withhold-go hypothesis would reverse. If the truncating stimulus was presented in the withhold stage, the internally-generated motor system would be inhibited, therefore the externally-triggered motor system would not be inhibited, resulting in a faster reaction. However, in the go stage, the intentional action is activated, therefore the externally-triggered system would be inhibited, and the reaction to the stimulus would be slower.

Thirdly, if the internally-generated and externally-triggered systems were independent, then the time in the foreperiod at which the truncating stimulus was presented would not affect the RT.

2.2 METHOD

2.2.1 Subjects and Design

Seven male and nine female University College London students were used as subjects. Their mean age was 24.25 years (s.d. 3.29), they were all right-handed and were not suffering from any known neurological impairment. The design was factorial repeated measures 2 (hand: left or right) x 2 (reaction type: CRT or SRT) x 2 (movement type: intentional or reactive). The dependent variable was the RT in ms.

2.2.2 Apparatus

The experiment was run on a standard PC. The experimental program was written using the labVIEW 5 package. The subjects used two computer mice with the roller balls removed as response keys: one for their right hand and one for their left. The speakers were placed on either side of the computer monitor. Subjects were asked to use their index fingers of their left and right hands to make their responses.

2.2.3 Trial Structure and Stimuli

Each trial began with a warning stimulus, a 'beep'. The SRT and CRT conditions then involved the subject waiting for the presentation of a stimulus to which they had to react as quickly as possible. In the SRT condition, the stimulus was a pair of parallel lines (||) similar to an equals sign turned through 90 degrees. In the CRT condition, the stimuli were a plus (+) sign for the right hand and an equals (=) sign for the left hand. All stimuli were black, of font size 72 and presented in the centre of the screen.

2.2.4 Experimental Conditions

The main body of the experiment involved testing six conditions in pseudo-random order (no more than 2 adjacent SRT/CRT/truncation conditions). A computer generated the condition orders and the first eight orders that satisfied these criteria were used for the first eight subjects. The next eight subjects used the same orders in reverse. This provided some control for order effects[1].

Table 2.1 details the experimental conditions, their abbreviated names and the number (or approximate number) of trials in each condition.

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[1] This measure should control for simple order effects, resulting e.g. from general experience with the task and/or fatigue, provided that they are reasonably consistent across subjects. There is no straightforward method for controlling for order effects that interact with experimental variables.

Table 2.1. The conditions and their constituent number of trials.

CONDITION NAME AND TOTAL NUMBER OF TRIALS	RESULTANT TRIALS	
Right SRT (RSRT) 15	⇒ 15 RSRT	
Left SRT (LSRT) 15	⇒ 15 LSRT	
Truncated Right SRT (TRSRT) 30	⇒ ≈ 15 reactive	
	⇒ ≈ 15 intentional	
Truncated Left SRT (TLSRT) 30	⇒ ≈ 15 reactive	
	⇒ ≈ 15 intentional	
Choice Reaction Time (CRT) 30	15 RCRT	
	15 LCRT	
Truncated CRT (TCRT) 60	⇒ ≈ 30 reactive	⇒ ≈ 15 RCRT
		⇒ ≈ 15 LCRT
	⇒ ≈ 30 intentional	⇒ ≈ 30 R intentional *

*All truncation conditions begin with the subjects' preparing a RIGHT intentional keypress so there were no left intentional action trials.

All subjects performed three practice blocks, in the same order (of increasing difficulty) which were discarded from the analysis: a right SRT block of 10 trials, a CRT block of 10 trials and a truncated CRT block of 15 trials.

The subjects then performed the six experimental blocks, with the truncated CRT being repeated so that 60 trials were collected in order to collect approximately 30 right intentional keypresses and 30 reactive trials consisting of approximately 15 right reactions and 15 left reactions. As stated before, the order of these blocks was pseudo-randomised. Since the conditions were not exactly counterbalanced, a 'wrapper' (a condition present at the very beginning of the experiment and repeated again at the very end of the experiment) of the R SRT condition was included in the design for 15 trials in each block. These 'wrapper' conditions were included to check that the results could not be explained by strong order effects resulting from fatigue. In total, subjects performed twelve blocks of trials, three of which were discarded (practice trials) and two of which (the 'wrapper' blocks) were analysed separately.

2.2.5 Design and Procedure

The single within subjects factor was condition: (right SRT, left SRT, truncated right SRT, truncated left CRT and truncated CRT); the dependent variable was RT.

Subjects sat approximately 30 cm from the computer with a mouse in each hand and their arms at right-angles to their bodies. The beep, which signalled the start of each trial, was produced from speakers that were placed on either side of the computer screen, approximately 45 cm from the subject. The experimenter sat behind the subject and controlled the experiment via the keyboard.

Subjects were presented with separate written instructions for each condition and encouraged to ask questions. In the SRT and CRT conditions, subjects were instructed to wait until the presentation of the stimulus and then to react as quickly and accurately as possible. The stimulus was presented in the centre of the screen until the subject reacted. In the three truncation conditions, subjects were instructed to prepare to make ‘an intentional action as and when they felt like it’.

They were asked to really intend to make the action and to make them as random and un-stereotyped as possible. More specifically, subjects were asked not to respond in a repetitive manner, as if reacting to the trial-start stimulus, but instead to wait a variable amount of time before responding. Subjects were intermittently reminded during the experiment (between blocks) to act when they felt like it, and to avoid acting in a stereotyped manner.

If a beep occurred during this intentional preparation, they were instructed to react as quickly and accurately as possible. Each trial ended when the subject depressed the relevant mouse key. The start of the next trial was signalled by a beep 2000 ms after the previous trial had ended.

Although no explicit limit was set on the amount of time subjects had to make an intentional action, the truncating stimulus would occur at some time between 2 and 10 seconds after the trial-start stimulus. Intentional responses would always have to have occurred before this time. Subjects appeared to find these instructions easy to understand and the task straightforward. The experimenter always observed the subjects throughout the experiment, and watched for any unintended behaviour. On rare occasions it was noted that the subject had begun to respond in a stereotyped fashion. In this case, at the end of the block of trials, the subject was reminded to vary the time of response. No subjects were observed to behave inappropriately after being reminded.

2.3 RESULTS

All intentional trials were discarded from the analyses. The trials of interest were those in which the intentional preparation was truncated with a stimulus that required the subject to react, not the purely intentional trials, which were not controlled within this paradigm due to RT being the dependent measure.

Trials were discarded from the analyses for the following reasons:

i. Truncation condition errors where subjects pressed the wrong key in response to the stimulus, that is, subjects were intending to make a right intentional keypress, a stimulus was presented and they reacted with the wrong hand (*left should have been right* errors or *right should have been left* errors). This occurred in the truncated left SRT and the truncated CRT conditions.

ii. In some cases (truncation conditions), the RT was too short to be a reaction, and must therefore, have been an intentional movement. For the majority of the analyses (except the error analyses, see below) when the RT was less than 150 ms, it was considered to be erroneous and was discarded.

iii. Sometimes, subjects reacted very slowly; hence trials with RTs of more than 1000 ms were not included in the analyses.

iv. Reactive condition errors where subjects pressed the wrong key in response to the stimulus in either the SRT or CRT conditions (*right should have been left errors* or *left should have been right errors*).

v. On occasion, subjects mistakenly pressed the key prior to the stimulus in the reactive conditions (anticipation errors).

In total 6.15% of trials were discarded due to these criteria.

The majority of subjects made their intentional actions early in the trial. 76% of the intentional actions made in the truncation condition occurred in the early foreperiod, that is, in the first 4 seconds.

2.3.1 SRT and CRT analyses

The mean RTs and standard deviations were calculated across subjects from the surviving trials in each condition. In the truncated SRT conditions, 48% of the trials were reactive (TRTs). Similarly, in the truncated CRT conditions, 52% of the trials were TRTs.

Table 2.2. The mean (s.d.) RTs for the six conditions.[2]

CONDITION TYPE	REACTIVE (ms)	TRUNCATED (ms)
Right SRT	304 (72.92)	355 (119.51)
Left SRT	324 (86.21)	433 (91.12)
Right CRT	481 (123.12)	475 (140.28)
Left CRT	500 (111.33)	519 (116.18)

Table 2.2 shows that the RTs for the reactive conditions were faster than the RTs for the truncation conditions, where the subjects' internally-generated movement was truncated with the stimulus to which they had to react. The RTs for the right hands were faster than the left in all cases; however, this was expected because all the subjects were right-handed.

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[2] Statistical analyses of the values in Table 2.2 are presented in section 2.32.

Figure 2.6. The mean RTs including standard error bars for the left and right SRT conditions and the left and right simple truncation conditions.

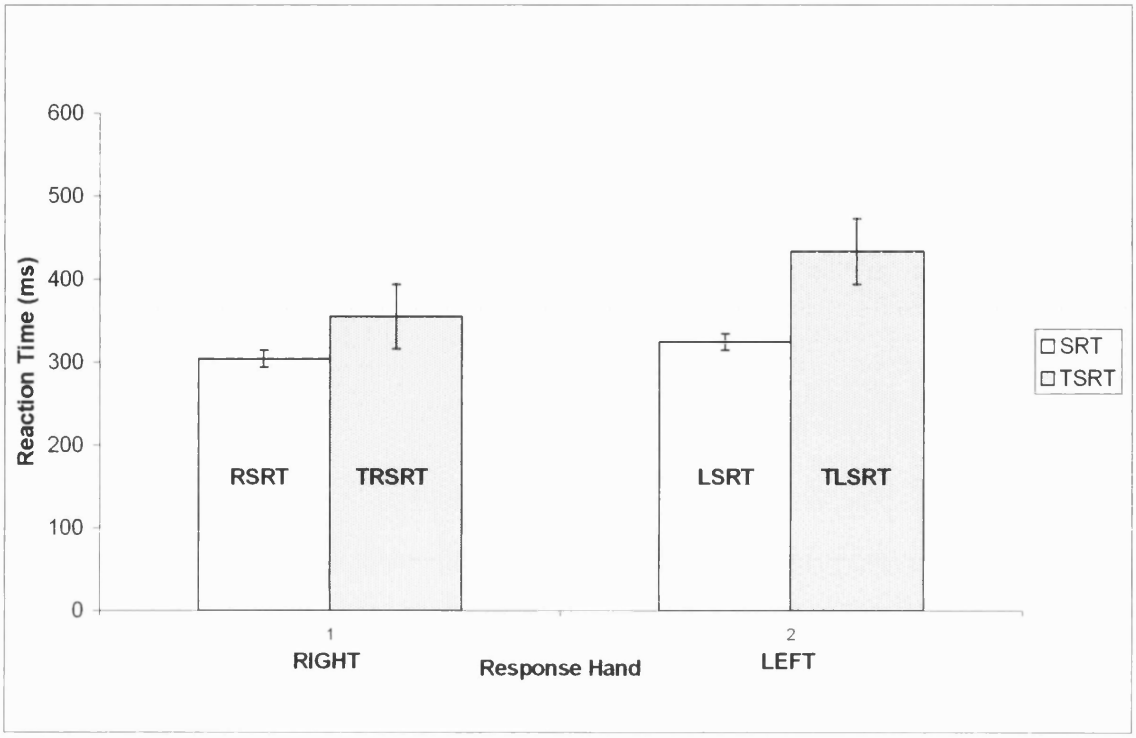
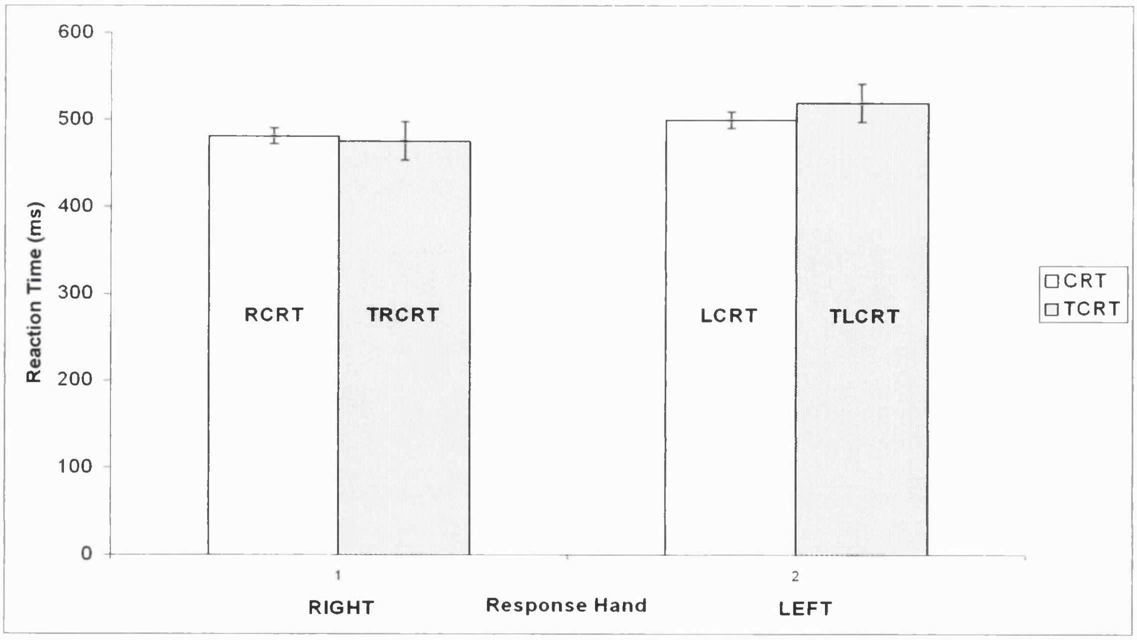


Figure 2.7. The mean RTs including standard error bars for the left and right CRT conditions and the left and right choice truncation conditions.

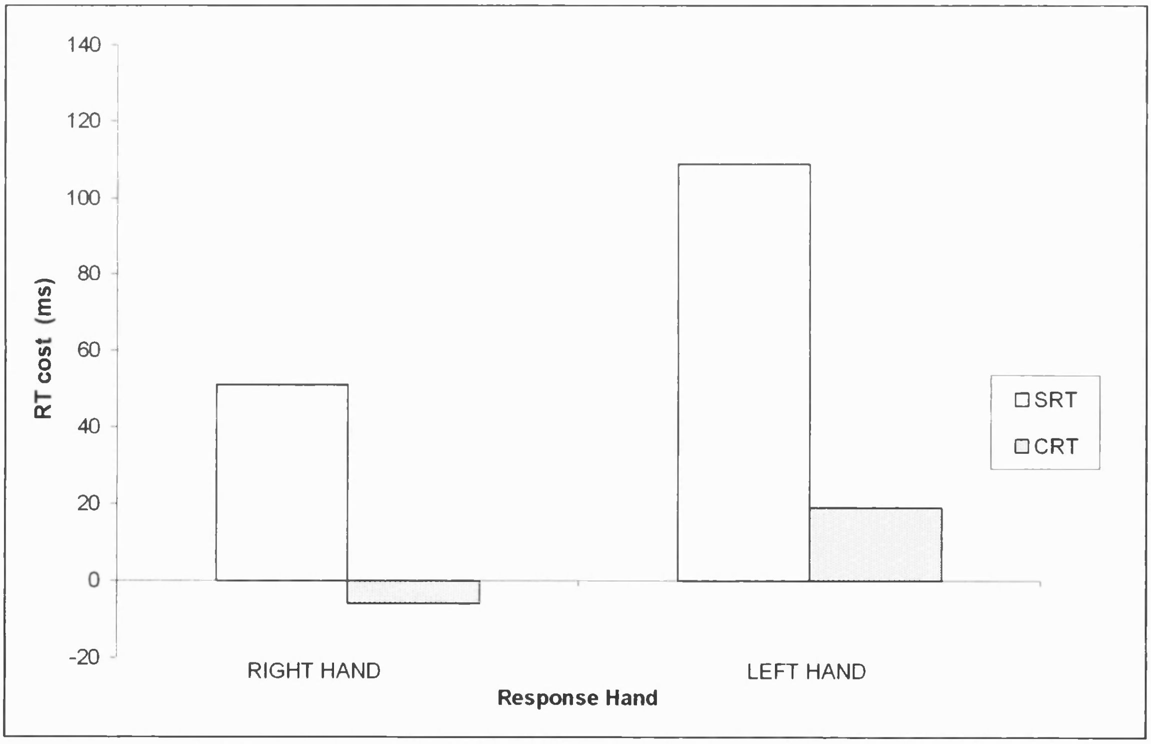


Comparison of Figures 2.6 and 2.7 show that, overall, the mean RTs are longer for the CRT conditions and that there is less variability between truncation and reactive conditions and between left and right hands compared with the SRT conditions.

2.3.2 RT Costs

RT costs are defined as the difference in RT between the reactive condition and the truncated RT condition. That is, the RT cost of intention is the time taken by the subject to exchange intentional preparation for reaction. As can be seen from Figure 2.8, larger RT costs were incurred in the SRT conditions compared to the CRT conditions. In both SRT and CRT, the RT costs are larger for the left hand.

Figure 2.8. The RT costs of intention of the left and right hand for the SRT and CRT conditions.



As can be seen from Figure 2.8, the RT costs are larger and more positive for the left and right hand in the SRT condition. In the CRT condition, the RT costs are smaller, and are negative for the left hand. There is a slightly larger difference between the left and right hand in the SRT condition and a larger difference between SRT and CRT in the left hand.

It is important to note that the RT cost for the right hand involves changing from intention to reaction. However, the RT cost for the left hand involves changing from intention to reaction, changing movement effector and possibly, a shift in spatial attention from the left to the right hand.

2.3.2.1 Comparisons between reactive and truncated SRT conditions

The difference between right SRT and truncated right SRT of 51 ms ($t_{(15)} = 2.70$, $p = 0.02$, uncorrected[3]) was found to be significant (the RT cost of intention when subjects intend to move with their right hand and react to the truncating stimulus with the same hand).

There was a significant difference ($t_{(15)} = 7.15$, $p < 0.0001$, uncorrected) between the RTs for the left SRT and the truncated left SRT. This suggests that reacting to a truncating left stimulus when subjects have been intending to make a right intentional keypress incurs a larger RT cost of intention. This indicates that the additional aspects of the RT cost of intention for the left hand (changing movement hand and shifting spatial attention) are substantial.

2.3.2.2 Comparisons between reactive and truncated CRT conditions

In the CRT conditions, a non significant difference between the right CRT and truncated right CRT conditions was confirmed ($t_{(15)} = 0.79$, $p = 0.44$, uncorrected). This suggests that there is little effect of intentional preparation in the CRT conditions as compared with the SRT conditions.

The comparison between left CRT and truncated left CRT, that is, the effect of intending with the right and reacting with the left, yields a non significant difference ($F_{(1,15)} = 2.62$, $p = 0.13$, uncorrected). This suggests that a CRT incurs a large RT, thus, intention has little effect.

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[3] Follow up t-tests can be regarded as additional tests to investigate these effects for each hand separately, these can be regarded as simple effects (Howell, 1992), or as tests "protected" by the overall ANOVA result, and are therefore, uncorrected.

2.3.2.3 Planned comparisons between RT costs of intention

In SRT, the left and right hand RT costs of intention were not significantly different ($t_{(15)} = 2.05$, $p = 0.06$, uncorrected), though this difference did approach the borderline of significance. Although there is a non significant difference between the RT costs for the left and right hand, the values are quite different – more of an RT cost is incurred when subjects switch from the left to the right hand when they react with the right hand after preparing to make the intentional movement with their right hand. Again, the additional aspects of the RT cost of intention for the left hand are shown to be noteworthy.

The CRT left and right hand RT costs of intention were also non significant ($t_{(15)} = 0.24$, $p = 0.81$, uncorrected). This suggests that when subjects are required to react to a stimulus, which, until presentation, cannot be prepared for (i.e. CRT), they react as quickly to the stimulus indicating 'react left' as they do to the right-hand stimulus.

2.3.3 Analysis of Wrapper Conditions

A planned comparison of the RTs in the RSRT wrapper using a t-test demonstrated that there was no significant difference between the two ($t_{(15)} = 1.09$, $p = 0.29$, uncorrected). Thus there was no evidence of order effects which might result e.g. from changes in vigilance.

2.3.4 Error Analyses

Two errors arose in this experiment, which will be called *left should have been right* errors and *right should have been left* errors. *Left should have been right* errors were those in which a right-indicating stimulus (+) was presented to the subject either in CRT or in truncated CRT, and the subject reacted erroneously with their left hand. *Right should have been left* errors were those in which a left-indicating stimulus (=) was presented to the subject (again in either CRT or truncated CRT), and the subject reacted incorrectly with their right hand.

In the previous analyses, it was decided that if the RT fell outside the range of 150-1000 ms then it was to be discarded. The low-point of 150 ms is particularly relevant in the truncation condition, because very fast reactions are probably intentional actions, which happened to occur just after the stimulus, that is, subjects were unable to inhibit their intentional action at the late stage. It was decided that these 'fast reaction' error trials would be analysed post hoc at three different limits of RT acceptability: 150, 200 and 250 ms, for the reasons, detailed below.

2.3.4.1 Methodological reason

The first reason these error analyses were performed was purely methodological. The data was analysed to see whether the limit of RT acceptability of 150 ms was appropriate, that is, whether the intentional trials were being eliminated correctly, or were analysed as RTs, therefore artificially reducing the RT in the truncation condition, and thus reducing the RT cost of intention.

Table 2.3. Percentage of *left should have been right* and *right should have been left* errors at three limits of RT acceptability for truncation and reactive movements.

				Lower Limit of RT Acceptability		
Type of Condition	**Stimulus**	**Subjects' Response**	**Type of Error**	**150 ms**	**200 ms**	**250 ms**
Reactive	R	L	Left should have been right	1.54%	1.54%	1.54%
Reactive	L	R	Right should have been left	4.96%	4.96%	4.96%
Truncation	R	L	Left should have been right	10.14%	10.14%	10.14%
Truncation	L	R	Right should have been left	7.68%	5.45%	3.97%

Generally there were more errors in the truncation condition compared with the reactive condition (Table 2.3). In the reactive condition (CRT), the number of both types of error did not change as the limit of RT acceptability increased. There was no intentional preparation in the reactive conditions, so the erroneous reactions were not caused by a conflict between intentional preparation and reaction. There were more *right should have been left* errors in the reactive condition, which is probably because subjects were all right-handed so tended to react with their dominant hand.

In the truncation condition, the percentages of *left should have been right* errors were the largest and did not decrease as the limit of RT acceptability increased. Only the *right should have been left* errors in the truncation condition were sensitive to the increased limit of RT acceptability; they decreased as RT acceptability increased. This decrease in percentage of *right should have been left* errors from 7.68% to 3.97% suggests that these 'error' trials were probably intentional actions of the right hand which the subject performed at the same time as the imperative stimulus appeared. This suggests that using the limit of acceptability elsewhere at 150 ms is conservative, that is, treating these intentional actions as quick reactions in all the truncation conditions would tend to reduce the truncated RT and thus underestimate the RT cost of intention. This conservatism counts against the hypothesis that an RT cost of intention exists. Also, the similarity between the truncated CRT and CRT *right should have been left* errors and, the smaller percentage of truncated CRT at the 250 ms limit of RT acceptability (3.97%and 4.96%, respectively) suggests that all the 'leftover' intentions have been removed from the truncated CRT condition by 250 ms.

2.3.4.2 Stimulus processing reason

The second reason that these error analyses were performed was to observe the balance between the stimulus processing in CRT and truncated CRT, specifically, did subjects process the stimulus equivalently in reactive and truncation conditions? It would be expected that both types of error should be more prevalent in the truncation condition compared to the reactive condition because the truncation condition is more complicated. However, because subjects start preparing a right intentional action at the beginning of every truncated CRT trial, the balance between the two kinds of errors should be unequal in the truncated CRT. Therefore, it might be predicted that if subjects were not focusing on the external stimulus, there should be more *right should have been left* errors in the truncated CRT condition, compared with the CRT condition. That is, were subjects erroneously reacting with their right hand to the left-indicating stimulus, due to their focusing on their right hand intention. The CRT error rates, in particular, therefore, provide important evidence about how preparing an intentional action might produce a response bias carrying over into a subsequent reaction.

A 2 x 2 ANOVA examining error type (*left should have been right* or *right should have been left*) and condition type (reactive or truncation) was performed at the 250 ms limit of RT acceptability. The analyses were only performed on the 250 ms limit of RT acceptability because there were clearly intentional actions in the lower limits, and by 250 ms they were removed (as shown by the smaller percentage of *right should have been left* errors in the truncated CRT compared with CRT).

There was a significant effect of condition ($F_{(1,15)} = 19.41$, $p < 0.001$.) This is unsurprising due to the truncation task being harder and therefore, resulting in more errors, and the large percentage of *left should have been* right errors. The non significant effects of error type suggests that there were neither more *right should have been left* nor *left should have been right* errors ($F_{(1,15)} = 0.97$, $p = 0.34$).

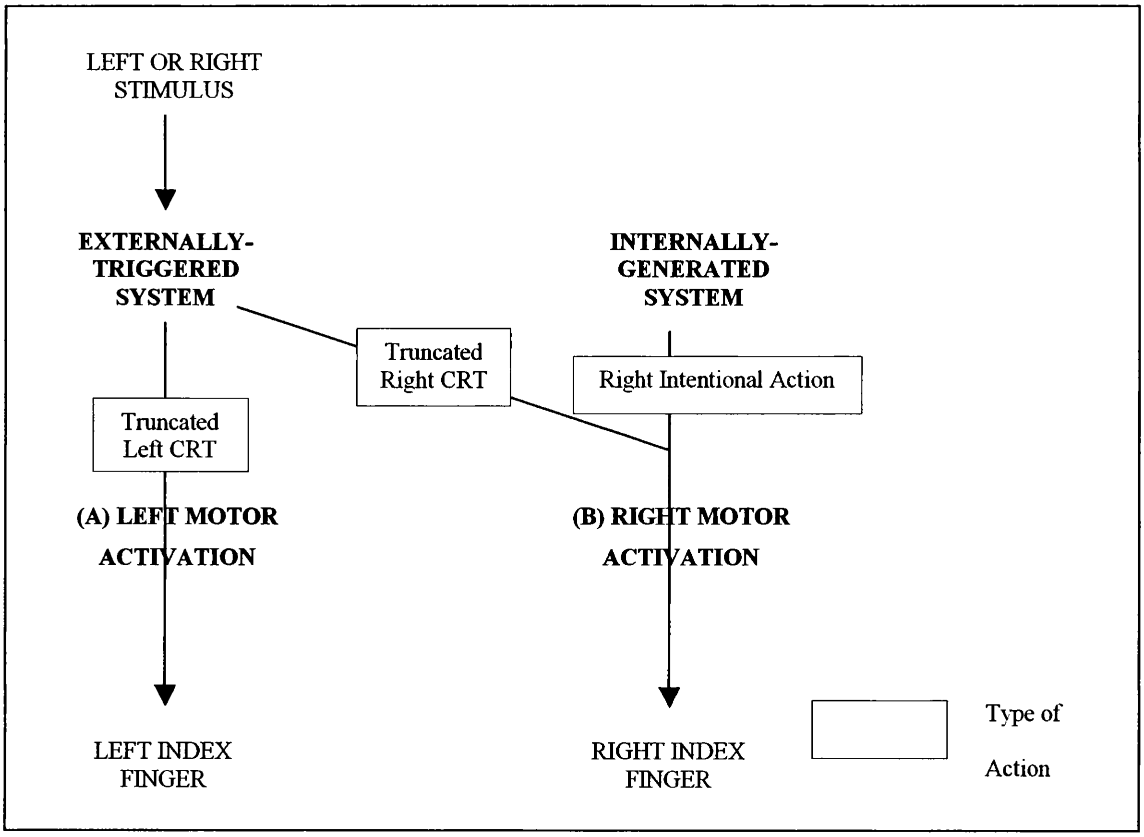
However, the significant interaction ($F_{(1,15)} = 11.59$, $p = 0.004$), due to the reduced percentage of *right should have been left* errors in the truncation condition demonstrates that the main effect of condition cannot be clearly explained due to its relationship with error type. In conclusion, the stimulus processing in CRT and truncated CRT is unclear due to the significant interaction. However, the smaller percentage of *right should have been left* errors in the truncation condition implies that subjects do not process the stimulus less efficiently compared with the reactive conditions.

2.3.4.3 Relationship between the internally-generated and externally-triggered systems

The third reason for analysing the CRT errors was to observe the balance between the two different types of errors. The difference between the *left should have been right* errors and *right should have been left* errors can provide information about how the prepared right intentional action interacts with the truncating stimulus. That is, how the internally-generated and externally-triggered motor systems might be related.

The distribution of *left should have been right* errors and *right should have been left* errors in CRT and truncated CRT depends on the balance of motor activation levels between the left and right hands. Based on Näätänen's (1971) idea of "motor action limits" (which here will be called 'motor activation levels'), there might be two different motor activation levels in this experiment: one for the right hand and one for the left. In the case of *left should have been right* errors less activation was required to force the preparation of the left hand to "flow over into the corresponding motor action" (Näätänen, 1971) because there was already preparation of a right intentional action. The reverse is true for *right should have been left* errors; the action threshold would be reached by the right hand more quickly because the level had previously increased due to the preparation of the right intentional action, therefore resulting in erroneous right reactions. The right motor activation level should always be higher than the left motor activation level in truncated CRT trials, since the trial always begins with the preparation of a right intentional action. This reasoning would predict a predominance of *right should have been left* errors.

Figure 2.9. A schematic assuming unitary motor activation levels for the externally-triggered and internally-generated systems.

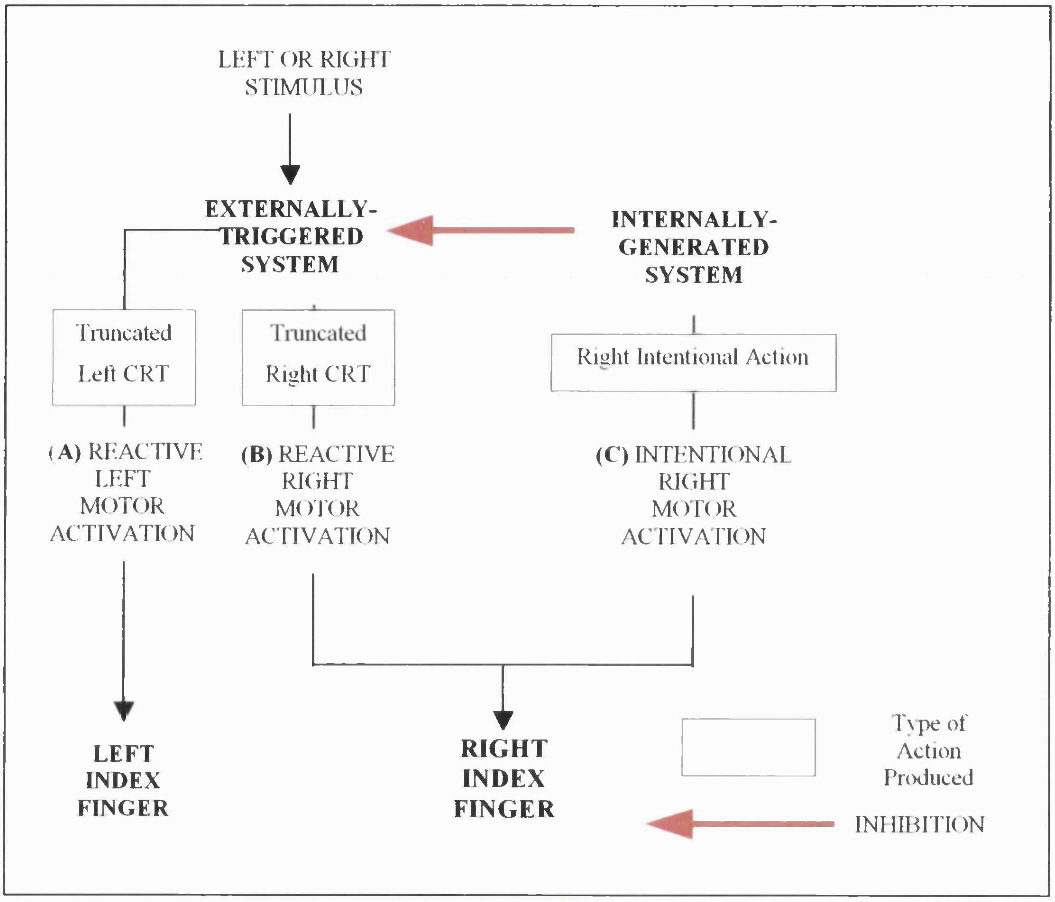


Therefore, if the motor activation level occurs at the low motor level (rather than at the high, action level), as shown in Figure 2.9, the right motor activation, (B) will be elevated, due to the preparation of the right intentional action and will therefore be more activated than (A), resulting in more ***right should have been left*** errors. That is, the critical balance, based on this low level model, is between the left externally-triggered reaction and the right internally-generated action, or between (A) and (B). The effect was found to be in the opposite direction ($t_{(15)} = 2.58$, $p = 0.021$, uncorrected).

There were significantly less ***right should have been left*** errors than ***left should have been right*** errors in the truncation condition: 3.97% and 10.14%, respectively.

The predictions regarding the errors become more complex if the motor activation level is conceptualised at the higher or action level in the posited motor hierarchy (see chapter 1, section 1.5.3.1 and this chapter, section 2.1.7.2). If the motor activation is occurring at the action level of the hierarchy, then separate motor activation levels would exist for the intentional action and for both left and right reactions, that is, based on this model, two motor activation levels occur: one for internally-generated actions and one for externally-triggered actions. This alternative model therefore assumes separate motor activation levels [(B) and (C) in Figure 2.10] for the two motor systems, both trying to drive the right hand. The critical balance is therefore, occurring between the left externally-triggered and right externally-triggered reactions (Figure 2.10).

Figure 2.10. A schematic assuming separate motor activation levels for the internally-generated and externally-triggered systems and the left and right hand.



If the two posited motor systems were unitary or mutually facilitatory, then a similar prediction to that schematised in Figure 2.9 could be made: more *right should have been left* errors due to the higher activation levels of (B) caused by the high motor activation level of the intentional action, (C). However, the statistics indicate that this was not the case; there were significantly less *right should have been left* errors in the truncation condition.

If the two systems were independent, which was unlikely based on the significant RT cost of intention, then there should be equal numbers of both types of error. There were significantly more *left should have been right* errors, suggesting that independence is an unlikely hypothesis.

A competitive relationship would assume that (C), the intentional right motor activation would be using up most of the available resources, leaving few for reaction.

Therefore, there would be competition between (C) and (A and B), that is, the competition would occur between the internally-generated system, manifested by the intentional preparation (C) and the two possible reactive movements (A and B) made by the externally-triggered motor system. It would be predicted therefore that an equal number of both types of error would occur. However, there may be an imbalance between the externally-triggered and internally-generated systems, due to a possible inhibitory relationship. An inhibitory relationship would predict the following: when the truncating stimulus is presented, the reactive right motor activation (B) would be low due to the inhibition by the internally-generated system due to the preparation of (C), therefore, the reactive left motor activation would be higher (A) and more *left should have been right* errors should occur. That is, (C) inhibits (B), and (A) is higher than (B) therefore, more *left should have been right* errors should occur if the systems have an inhibitory relationship.

Clearly, there were more *left should have been right* errors (10.14%) in the truncation compared with *right should have been left* errors (3.97%), which was statistically supported by a significant t-test ($t_{(15)} = 2.58$, $p = 0.021$, uncorrected), and a significant interaction between condition and error type ($F_{(1,15)} = 11.59$, $p = 0.004$, uncorrected).

The error analyses therefore suggest that (i) the 150 ms limit of RT acceptability was conservative; (ii) subjects did not make more *right should have been left* errors in truncated CRT compared with CRT, and the effect of condition cannot clearly be explained due to the significant interaction; (iii) there was no support for the unitary or facilitatory hypotheses because there were clearly less *right should have been left* errors in the truncation condition; (iv) the independent and competitive hypotheses were also not supported because there were different error rates for the *left should have been right* and *right should have been* left errors; and (v) the data were supportive of the direct inhibition hypothesis of more *left should have been right* errors in the truncation condition.

These findings suggest that the higher, action level rather than the lower, motor level, is the critical level of interaction for the two posited systems. That is, there appear to be separate threshold conditions for making the same movement, dependent on whether it is an externally-triggered or internally-generated action. In conclusion, Näätänen's abstract approach to motor activation levels has been extended and localised to the action level of the motor hierarchy.

2.3.5 Foreperiod Analyses

This data was also analysed to investigate foreperiod effects. These are relevant to the nature of preparation in the RT and TRT conditions and, in particular, to the putative 'withhold-go hypothesis' mentioned in section 2.1 and Figures 2.1 and 2.5.

The stimulus was randomly presented between 2 and 10 seconds after the start in every trial. The foreperiod was, therefore, 8 seconds. The withhold-go hypothesis suggested that there were two parts to the preparatory period in intentional action: the putative 'withhold' stage and the putative 'go' stage.

As explained in section 2.1.7.2, there would be different predictions about the RT in the early and late foreperiod, dependent on whether the interactions between the two hypothesised motor systems were occurring at a higher or lower level in the motor hierarchy.

Briefly, if the processes were occurring at a low motor level, then a truncating stimulus presented in the withhold stage would result in the subject being in a state of inhibition, withholding the intentional action. The motor activation would also be low. On the other hand, if the truncating stimulus were presented in the go stage, the subject would be getting ready to act and would be in a higher state of motor activation. It would follow therefore, that the presentation of the truncating stimulus in the withhold stage would result in a slower reaction than in the go stage, due to the necessary disinhibition prior to reacting to the truncating stimulus.

If the withhold-go processes occur at the action level, then the three predictions, based on the postulated relationships between the internally-generated and externally-triggered motor systems are as follows:

i. If the motor systems were related in a facilitatory or unitary manner, the same result as above would be predicted; faster RTs in the go stage, due to higher motor activation.

ii. If the motor systems were related in an inhibitory or competitive manner, and the truncating stimulus was presented in the withhold stage, the externally-triggered motor system would not be inhibited (due to the activation of the internally-generated motor system) and the reaction would be faster. In the go phase, the subject would be activating the internally-generated system and the externally-triggered system would be inhibited, thus resulting in a slower RT.

iii. If the systems were independent, then the RT would not be affected by the time of its presentation.

Based on this logic, a 'median split'[4] was performed on the foreperiod, such that trials in which the stimulus was presented between 2000-6000 ms were classified as early foreperiods (early FP) and those in which the stimulus was presented between 6001-10000 ms were classified as late foreperiods (late FP). The distribution of the trials in the early and late foreperiods were uneven, for example 76% of the right truncated simple reaction trials occurred in the early foreperiod; and coincidentally 76% of the right truncated simple intentional trials occurred in the early foreperiod. This was found in pilot studies and is addressed in chapter 3.

Table 2.4. The mean (s.d.) RTs for the early and late foreperiods.

CONDITION	EARLY FP: MEAN (s.d)	n	LATE FP: MEAN (s.d.)	n
TRUNCATED RSRT	361 (46.51)	16	338 (96.44)	16
TRUNCATED LSRT	435 (37.98)	16	417 (55.41)	15*
TRUNCATED RCRT	498 (87.43)	16	450 (59.20)	15*
TRUNCATED LCRT	531 (73.70)	16	491(78.89)	15*
RSRT	314 (53.59)	16	292 (32.13)	16
LSRT	338 (53.54)	16	325 (50.36)	16
RCRT	461 (53.44)	16	493 (92.56)	16
LCRT	502 (63.53)	16	497 (74.72)	16

*Subject 11 did not have mean RTs for the late FP in truncated right CRT and truncated left SRT and subject 13 did not have a mean RT for the late FP in

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[4] Due to the uneven number of trials in the early and late foreperiod, this is not a median split *per se*, but the logic of a median split is still applicable.

truncated left CRT conditions, that is, when these subjects made intentional actions, they made them early.

The RTs in all except right CRT are longer in the early FP than the late FP. This finding fits with the concept of motor readiness by Näätänen (1971), which proposed that preparation accumulates over time, so stimuli presented in the late FP are reacted to more quickly than stimuli in the early FP (section 2.1.5.). This also concurs with the suggestion that subjects react more quickly due to the increased probability that the stimulus is going to occur as the foreperiod increases (Niemi and Näätänen, 1981).

Figure 2.11. SRT: early and late FP RTs for the left and right hands.

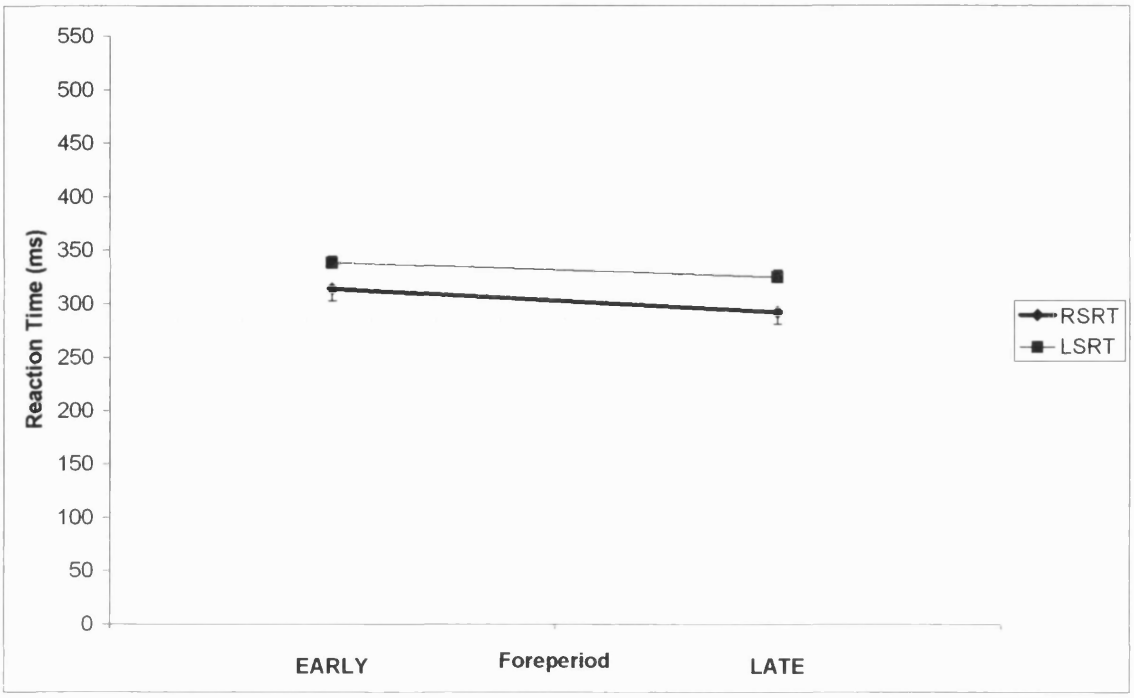


Figure 2.12. Truncated SRT: early and late FP RTs for the left and right hands.

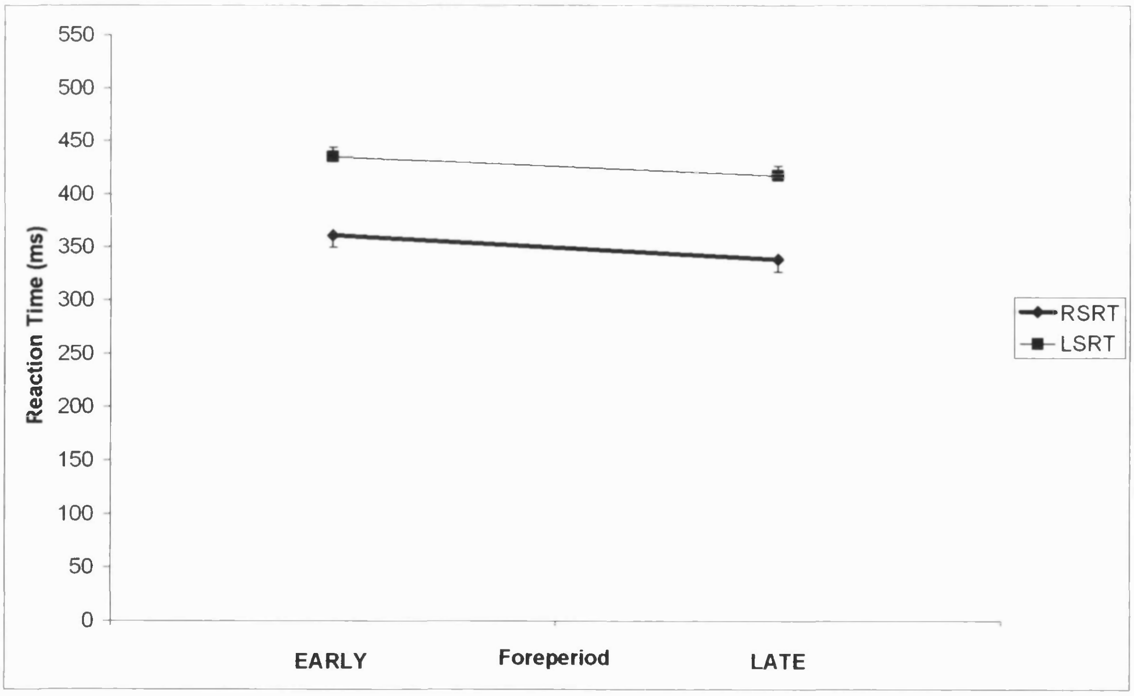


Figure 2.13. CRT: early and late FP RTs for the left and right hands.

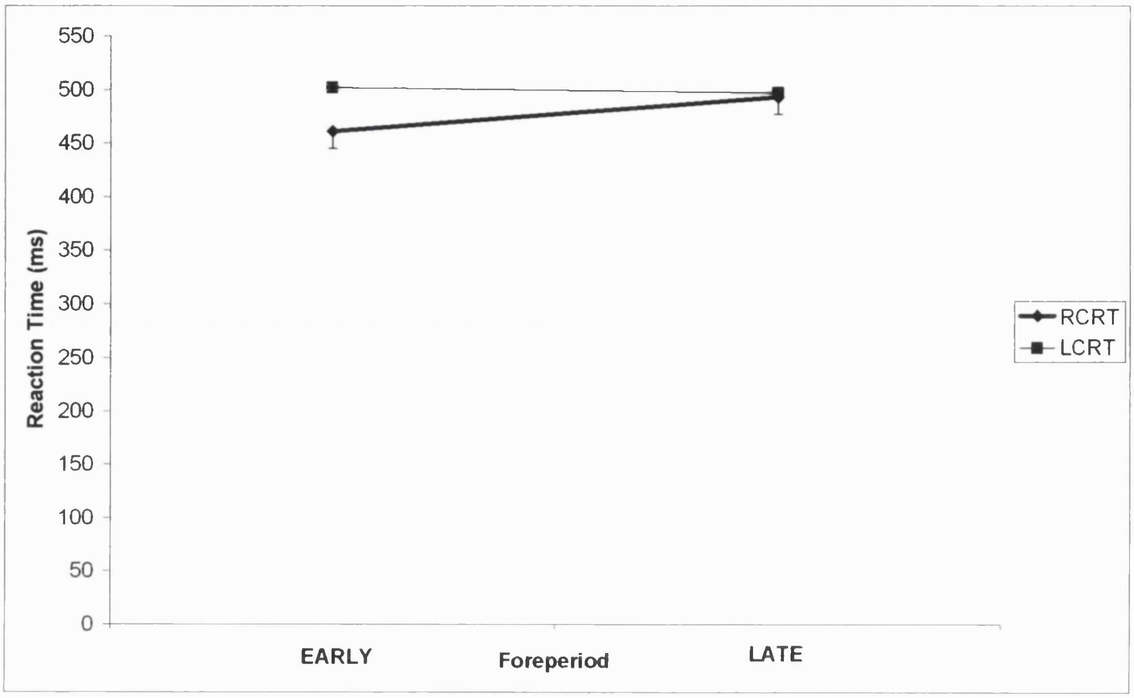
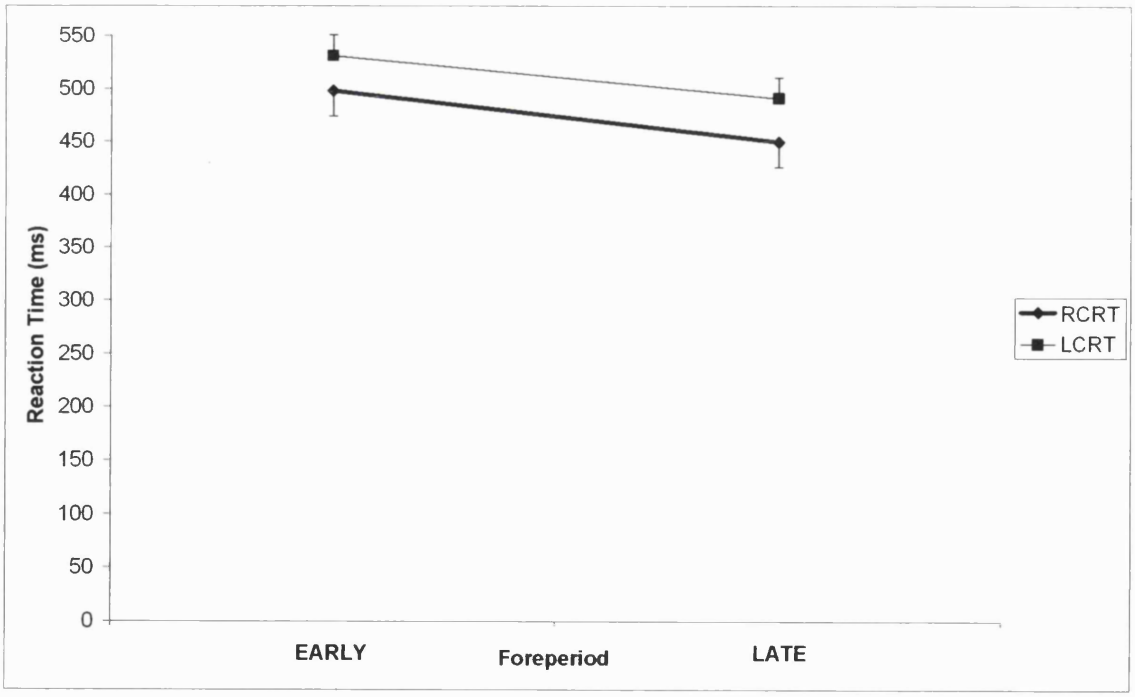


Figure 2.14. Truncated CRT: early and late FP RTs for the left and right hands.



The reactive conditions show slightly more convergence between the RTs for left and right hands in the early FP in SRT (Figure 2.11) and more in the late FP in CRT (Figure 2.13). The truncation conditions, however, have approximately the same differences in RT between left and right hands, regardless of foreperiod (Figure 2.12 and Figure 2.14). In SRT, the difference in RTs between early and late FPs is more marked in the truncated SRT compared with the SRT. That is, the difference between left and right early FP and left and right late FP is small in SRT and relatively similar across both FPs (Figure 2.11), and large in truncated SRT and similar across both FPs (Figure 2.12). In CRT, the difference in RTs between left and right early FP and left and right late FP is large and similar across both FPs in the truncated CRT (Figure 2.14). However, the difference between left and right early FP is large and late FP is small.

A 2 x 2 ANOVA, where the independent variables were condition (truncated RSRT or RSRT) and FP (early or late) yielded significant main effects of condition, $F_{(1,15)} = 11.14$, $p < 0.005$. However, the main effect of FP, ($F_{(1,15)} = 3.12$, $p = 0.10$) and the interaction were not significant ($F_{(1,15)} = 0.00$, $p = 0.96$).

The same 2 x 2 ANOVA was performed for truncated LSRT and LSRT. This produced the same pattern of significance: the main effect of condition was significant ($F_{(1,15)} = 72.99$, $p < 0.0001$). However, FP ($F_{(1,15)} = 3.25$, $p = 0.09$) and the interaction ($F_{(1,15)} = 0.01$, $p = 0.91$) were not significant.

A 2 x 2 ANOVA for the right CRT conditions yielded non significant main effects of condition (RCRT or truncated RCRT), $F_{(1,14)} < 0.001$, $p = 0.95$ and FP (early and late), $F_{(1,14)} = 0.11$, $p = 0.75$ and the only significant interaction ($F_{(1,14)} = 6.34$, $p = 0.02$). Subject 11 was not included due to there being no mean RT for the late FP in truncated right CRT (as noted previously).

The same 2 x 2 ANOVA was performed on the left CRT conditions. The main effect of condition (LCRT or truncated LCRT) was non significant ($F_{(1,14)} = 1.96$, $p = 0.18$) as was the interaction ($F_{(1,14)} =1.35$, $p = 0.26$). However, the main effect of FP (early or late) was significant: $F_{(1,14)} = 6.38$, $p = 0.02$. Subject 13 was not included in the analysis due to there being no mean RT for the late FP in truncated left CRT (as noted previously).

Only two statistically significant comparisons were found with the FP data: one significant main effect of FP in the left CRT versus truncated left CRT (bigger difference between early and late FP in truncated left CRT) and one significant interaction between FP and condition in right CRT versus truncated right CRT (difference in RT between early and late FP is reversed in right CRT compared with truncated right CRT). Foreperiod does not, therefore, influence RT in the SRT conditions, but does in the CRT conditions, and only effects the statistics mentioned above because of the faster RT in early FP in right CRT, that is, the pattern of RT is the SAME in left and right truncated CRT as in left and right truncated SRT; the difference is only in the reactive condition.

Thus, the analyses of RT in the different FPs provide no concrete support for the withhold-go hypothesis. The longer RTs in the early FP are, in most cases, not significantly longer in the truncation conditions compared with the reactive conditions. That is, subjects react more slowly in the early FPs in reactive conditions as well. This concurs with the suggestion that the closer the subject gets to the moment at which the stimulus is presented, the faster they react because the probability that the stimulus is going to be presented sooner rather than later increases (Näätänen, 1970), rather than a withhold-go process occurring. Therefore, the RT cost of intention does not appear to reflect the unavoidable effect of variable foreperiod.

2.4 DISCUSSION

2.4.1 SRT vs CRT

The difference in RT between the left and right SRT and the left and right CRT is in the expected direction: longer for the left than the right hand due to the subjects' right-handedness. In general, the RTs for the truncated conditions were slower than the RTs for the purely reactive conditions. The RT for the truncated right CRT was, however, faster (though not significantly) than the RT for the right CRT. The difference between truncation and reactive conditions and left and right is less in the

CRT conditions than in the SRT conditions. The RTs were faster in the SRT conditions compared with the CRT conditions. However, this was expected because it is well established that RTs are always longer when task complexity increases, particularly from SRT to 2-choice RT (e.g. Frith and Done, 1986). The RT results do not therefore show any unexpected findings.

2.4.2 The RT Costs of Intention

The RT costs of intention are defined as the difference in RT between the reactive and truncation conditions, that is, the 'cost' of intentional preparation on reacting to the truncating stimulus. They were larger for the SRT conditions than the CRT conditions. The largest RT cost was for the left SRT condition, followed by the right SRT condition. Within the SRT condition, there was a larger though non significant difference between the RT costs of intention of the left and right hands. The RT costs of intention were effectively absent in CRT conditions. The difference between the left and right hand RT costs of intention in the CRT condition was also non significant. Interestingly, the RT cost was negative for the left CRT (though not significantly), implying that it is actually beneficial to be intending to make a movement with the right hand and then to react with the left hand.

2.4.3 The RT Cost of Intention and Switch in Effector

The significant difference between the right SRT and the truncated right SRT indicates that there is a significant effect of intentional preparation on RT. There were no significant differences between the left CRT and truncated left CRT, and the right CRT and the truncated right CRT. Thus, the effect of intentional preparation is only seen in SRT when subjects know what the reacting stimulus is going to be in advance of its presentation. The larger RT cost of intention for the left SRT compared to the right SRT is probably due to the additional need to switch motor attention from the right to the left hand.

In the truncated left SRT and truncated left CRT, subjects were required to switch the movement hand and movement type, that is, subjects began each trial by preparing to make a right intentional keypress and possibly react to the truncating stimulus with a left reactive keypress. In the truncated left SRT this seems to have a significant effect on the speed with which subjects reacted to the truncating stimulus. However, in the left CRT the fact that subjects had to switch movement hand and movement type had a positive effect on the RT. As previously noted, in the CRT conditions, subjects could not prepare the response in advance of the stimulus. However, in the SRT conditions, subjects knew that only one stimulus was going to be presented and they knew the required response, therefore, they could prepare. Thus, the locus of interference between intention and reactivity seems to be at the preparational level.

2.4.4 Truncation Conditions

The truncated CRT conditions, in which subjects intended to make a movement with one hand and then had to respond with the other, presented a complex combination of psychological constraints. Spatial attention will presumably be directed initially towards the right hand where the intentional movement is being planned. Thus, when the imperative stimulus is presented, subjects might not be attending to the left effector, leading them to react more slowly than they would if the stimulus presented required a reaction with their right effector. This results in the difference between the left and right hands being falsely biased, reflecting a combination in unknown proportions of the cost of intention, the change in effectors and the attentional change.

Within the domains of attention, there are two key aspects which relate to this experiment: (i) spatial attention, where the subject looks for the stimulus (modality-based), and to where they respond (attention directed towards the left/right index fingers); and (ii) non-spatial central attention which is involved in holding, forming and controlling stimulus-response mappings, and dividing the unit of resources between the task in hand (internally-generated movements) and the possibility of interruption requiring a response (externally-triggered movements).

In the truncation condition, subjects are aware that they need to allocate attention to the primary task, preparing a right intentional keypress, and to the secondary task, the possibility of reacting to a stimulus. This division is more difficult to monitor than spatial attention. The spatial attention can be monitored to an extent by eye-tracking, which would verify where subjects were looking throughout the trials. In this experiment, subjects fixated on the screen, and waited for the visual stimuli.

Therefore, their attention was unlikely to be drawn from the screen and, if it were, the long RT would have resulted in the elimination of the trial. However, central attention is something that even the subjects would find difficult to monitor, let alone an external observer. Based on the findings that the RT costs of intentions were larger for SRT than CRT it can be assumed that they were not due to vulnerabilities in divisions of attention.

2.4.5 Errors

The analysis of the errors with regards to the hypotheses will be discussed in the hypotheses section 2.4.6. The other reasons for analysing the errors were (i) to verify the use of 150 ms as an appropriate limit of RT acceptability (section 2.3.5.1) and (ii) to ascertain whether there was a balance in stimulus processing between the truncated CRT condition and CRT, particularly, whether there were more *right should have been left* errors in truncated CRT (section 2.3.5.2).

The methodological reason for the error analyses, examining three different limits of RT acceptability, verified that the use of 150 ms as the limit of RT acceptability was conservative due to some intentional trials being analysed as if they were reactive trials, producing a lower RT cost of intention.

Attention is difficult to control within the confines of this experimental manipulation. It might have been expected that there would be more errors in the truncated CRT in comparison with the other conditions, especially *right should have been left* errors, which would suggest that subjects were so focused on their internal movement that they did not attend to the stimulus prompting a left response. This was not found. There was a significant main effect of condition (more errors in truncated CRT than in CRT). The non significant main effect of error type and the significant interaction at the 250 ms limit of RT acceptability imply that the main effect of condition cannot be clearly explained. However, the error rates clearly imply that subjects do not make more *right should have been left* errors in the truncated CRT compared with CRT, suggesting that there is no support for the claim that subjects are not processing the stimulus as efficiently in truncated CRT.

2.4.6 Hypotheses

Five hypotheses regarding the possible relationships between the postulated internally-generated and externally-triggered motor systems were presented at the beginning of the introduction in this experimental chapter (section 2.1.1). These hypotheses were (i) a unitary system; (ii) two highly inter-connected mutually facilitatory systems; (iii) independent systems; (iv) separate but competing systems; and (v) directly (or mutually) inhibitory systems.

2.4.6.1 The unitary, facilitatory and independent hypotheses

The unitary and facilitatory hypotheses would predict that preparation for an intentional movement would facilitate reaction to the truncating stimulus; therefore the RT for a truncated condition (of the same movement) would be shorter than the RT for the SRT condition. The independent systems hypothesis would predict equivalent RTs between the truncation and the SRT conditions. None of these patterns of RT were found. The significant difference between the right SRT and the truncated right SRT condition suggest that it is unlikely that the two systems are independent, unitary or mutually facilitatory.

The error analyses performed to further examine the unitary and facilitatory hypotheses predicted that the motor activation levels of the right intentional action would be high due to intentional preparation, which would mean that the motor activation level for the reactive right action would also be high. Therefore, subjects would make more *right should have been left* than *left should have been right* errors because the right externally-generated activation would be larger than the left externally-generated activation due to the right intentional preparation aiding the right externally-triggered activation, that is, the facilitatory link between the internally-generated and externally-triggered motor systems. This was not found to be the case: there were significantly less *right should have been left* errors in the truncation condition, and there was a non significant main effect of error type in the ANOVA.

If the systems were independent, then there should be equal numbers of *left should have been right* and *right should have been left* errors because the right internally-generated activation (i.e. the preparation due to the intentional action preparation) would not be effected by the change to reaction, therefore, subjects should make *left* *should have been right* and *right should have been left* errors with equal probability. The non significant difference between error types superficially supports this hypothesis, however, the significant interaction and the significantly more *left should have been right* errors found in truncation lends no support to this hypothesis.

Accounting for the RT data and the error data, there is no conclusive support for any of the first three hypotheses.

2.4.6.2 The separate but competing systems and direct inhibition hypotheses

The RT results are unclear with regards to the direct inhibition and competing systems hypotheses. The separate but competing systems hypothesis would predict that reacting with either the left or the right hand in the truncated CRT should produce the same RT because the intentional preparation would not inhibit reacting with the same hand as the one that is being prepared. That is, when the subject is preparing an intentional action, there is a reduction of processing resources available for reaction. On the presentation of the stimulus, subjects would react slowly to either a left- or right-indicating stimulus because the cognitive resources would have to be switched from the intention to the reaction, therefore, reacting with either the left or right hand would incur equivalent, but positive RT costs. Non significant and minimal RT costs were found, which provides no support for the competing systems hypothesis. The error analyses also provided no support for the competing systems hypothesis due to there being more *left should have been right* error rates rather than equal numbers. Equal numbers of both types of error was hypothesised because the competition was posited to occur between (i) the externally-triggered left and right activations [(A) and (B) in Figure 2.10] and (ii) the internally-generated right activation [(C) in Figure 2.10].

If the systems were mutually inhibitory, then preparing a right intentional keypress, which is truncated with a stimulus to which the subject reacts with the right hand, would produce a longer RT then reacting with the left hand. That is, the presentation of the stimulus would not only inhibit the right intentional activation, but would also inhibit the right reactive activation, due to the posited direct inhibition being a high level (action based) relationship between the two systems (Figure 2.10). Therefore, subjects would react faster to a left-indicating stimulus than a right-indicating stimulus because the right reactive activation would be de-activated by any stimulus which required an immediate change from the internally-generated motor system to the externally-triggered motor system. The RT data did not support this prediction: the RTs for both left and right truncated CRTs were small and the RT costs for both the left and right hand were not significantly different.

Support for the direct inhibition hypothesis was sought in the error data following the large number of *left should have been right* errors found in the truncated CRT condition. As proposed in the previous paragraph, the de-activation of the right reactive activation brought about by the presentation of a stimulus might result in the left reactive motor activation being comparatively more highly activated, therefore resulting in more *left should have been right* errors. This was clearly the case since significantly more *left should have been right errors* were found in the truncated CRT and a significant interaction between error type and condition were also found.

2.4.7 Pre-movement Processes

The data was analysed by foreperiod in an attempt to examine the pre-movement processes. The withhold-go hypothesis, posited in section 2.1.7.2 and schematised in Figures 2.1 and 2.5, proposed that the pre-movement processes in an intentional action are divided into two sections: the 'withhold' section and the 'go' section. In the withhold section, the intentional action is being withheld and in the go phase, the intentional action is being activated. The predictions regarding RTs were dependent upon whether these processes were thought to occur at the motor or action level (sections 2.1.7.2 and 2.3.6). The RT foreperiod analyses seem to suggest that there is no conclusive evidence in support of this theory. Although the RTs are suggestive of a motor level or facilitatory relationship, with the early FP RTs generally longer than the late FP RTs, this is probably due to the effect of the variable foreperiod, which results in subjects' increasing preparedness to react as the foreperiod time increases due to the increased probability of the stimulus occurring.

2.4.8 Conclusions

The main difference between SRT and CRT is the locus of preparation in relation to stimulus presentation. In the SRT condition, preparation for the response can occur prior to the presentation of the stimulus because there is only one possible response.

In the CRT condition, however, subjects can only prepare the response once the stimulus has been presented. Since this is the common difference between the two conditions, preparation might be the point at which the two motor systems diverge. Perhaps there are two types of preparation, one for intentional movement, 'intentional preparation', and one for reactive movement, 'reactive preparation'. In the case of the SRT, the intentional preparation and the reactive preparation have an inhibitory or competing relationship, thus causing the RT cost. In the CRT condition, however, because reactive preparation does not start before the stimulus is presented, the truncation of the intentional preparation does not result in inhibition or competition; thus, smaller RT costs are found.

This idea fits with the proposal by Roger and Monsell (1995) relating to the reconfiguration from one task set to another. They suggest that the reconfiguration involves two distinct types of control operation, endogenous and exogenous. Endogenous is one that is initiated by subjects in advance of the stimulus so that they can 'set' themselves; thus, by the time the stimulus arrives, they have done some of the reorganisation of cognitive and motor resources required for the new task. Exogenous control is needed to complete the reconfiguring process and can only occur once the stimulus is presented.

Regarding the hypothetical relationships between the putative internally-generated and externally-triggered motor systems, it seems that none of the suggested hypotheses are totally supported by all the data. The RT data clearly indicate that there is a significant RT cost of intention, therefore, there is a switch cost between switching from an internally-generated to an externally-triggered action. The error data clearly suggested that these posited systems were related in a mutually inhibitory manner, at the higher action level of the motor system. However, the significant interaction between condition and error type, the non significant effect of error type and the significant difference between *left should have been right* and *right should have been left* errors suggest that subjects were not so focused on their right intention that they did not attend to the left-indicating stimulus, that is, they did not make more *right should have been left* errors. This implies that the right intentional action is truly stopped by the stimulus and does not affect the reactive CRT task. This finding, therefore, suggests that there is a 'switching' mechanism, which relates the two hypothesised motor systems, and that when subjects are forced to switch from intention to reaction, a switch cost (the RT cost of intention) is incurred. This switching mechanism would probably include an inhibitory stage, which would explain the large SRT RT costs of intention, and the large numbers of *left should have been right* errors.

The next chapter in this thesis examines the suggestion that the RT cost of intention is an artefact of the variable foreperiod. This will be done using the yoking procedure, which is explained in section 3.1.2. By yoking the RT in the truncation condition to the SRT condition, the temporal distributions of both conditions will be equated, therefore allowing for comparison without the effect of the variability of the foreperiod.

Chapter 3

FOREPERIOD CONTROL EXPERIMENT: IS THE RT COST OF INTENTION AN ARTEFACT OF FOREPERIOD?

3.1 INTRODUCTION

This control experiment was designed to examine whether the RT cost of intention is an artefact of the foreperiod preceding the RT signal. There are two reasons to suggest that variable foreperiods alter subjects' reactions to stimuli. The first is based on the observation that subjects react faster in the later stages of a variable foreperiod (e.g. Näätänen, 1970). The second is based on the distribution of truncating stimuli in the truncation condition, specifically, that more trials occur in the early foreperiod (chapter 2).

Näätänen (1970) observed that, "as time passes after the warning signal without presentation of the stimulus, the (objective) probability that the stimulus would be delivered at the next possible instant, continuously increases." That is, as the 'age' of the foreperiod increases, subjects react more quickly because they are more prepared, due to their knowledge that the imminent presentation of the stimulus is more probable. However, foreperiods that are too long do not result in faster RTs because subjects cannot maintain indefinitely the "preparatory set" that assists performance (Gottsdanker, 1975). It should also be noted that very short foreperiods do not allow for beneficial preparation and therefore do not result in faster RTs either because "the state of preparedness cannot be held at optimum level for more than a fraction of a second, so ... the subject prepares for the mean or modal foreperiod and is less than fully prepared if the signal comes earlier" (Welford, 1968). These observations highlight the influential effects of foreperiod on the RT independent of the experimentally manipulated conditions.

The truncation condition typically skews the distribution of foreperiods in favour of more short foreperiods. If the truncating stimulus does not arrive early in the foreperiod, then it is likely that the subject will make the intentional action that they have been preparing. Therefore, the majority of both reactive and intentional trials in the truncation condition occur in the earlier rather than the later foreperiod. The early foreperiod is defined as ‘pre-median’ and the late foreperiod is defined as ‘post-median’. Note that the median here refers to the distribution of foreperiods generated by the computer in controlling the experiment, rather than by the subject. For example, in the previous experimental chapter (chapter 2), 76% of the right truncated simple reaction trials occurred in the early foreperiod; and coincidentally 76% of the right truncated simple intentional trials occurred in the early foreperiod.

Based on the above observations, it is important to exclude the effect of foreperiod variability on the RT in the truncation condition and thus the RT cost.

3.1.1 Yoking

The method of yoking has a long established usage in psychology (e.g. Laughlin, 1975). It is now predominantly used in studies involving reinforcement paradigms with humans and animals such as rats and pigeons (e.g. Reed, 1994) and in functional imaging paradigms (e.g. Jahanshahi et al, 1995; Jenkins, Jahanshahi, Jueptner, Passingham and Brooks 2000). However, the yoking procedure can be used in any experiment in which the temporal distributions of different conditions are required to be the same.

The yoking procedure basically involves a variable within a condition, for example, the time taken to complete a trial or the foreperiod being recorded, re-used and therefore *yoked to*, another condition. Jahanshahi et al (1995) and Jenkins et al (2000) performed a series of experiments examining the differences in regional cerebral blood flow between self-initiated and externally-triggered movements, comparing normals with parkinsonian patients (Jahanshahi et al, 1995) and within normals (Jenkins et al, 2000). In both experiments, subjects performed the self-initiated condition first, making the movements at an average of one every 3 seconds. The time taken to make each movement was recorded and re-used as the times of stimuli presentation in the externally-triggered condition. The trials from the self-initiated condition were *yoked* to the trials in the externally-triggered condition, therefore, equating the temporal distributions of the event outcomes in both conditions.

In this experiment, the foreperiod from each trial in one condition (the truncated SRT[1]) was recorded and used as the foreperiod in the other condition (the SRT). Therefore, every trial in the truncation condition had a partner trial in the SRT.

3.1.2 Hypothesis

It was predicted that the RT cost of intention would still occur when the foreperiods from the truncation condition and SRT condition were yoked, that is,. that the RT cost of intention is not an artefact of variable foreperiod.

3.2 METHOD

3.2.1 Subjects and Design

The subjects in this experiment were the same ones as in the previous experiment (chapter 2), that is, 16 undergraduate and postgraduate students comprising of seven males and nine females. Their mean age was 24.25 years (s.d. 3.29), they were all right-handed and were not suffering from any known neurological disorder.

This experiment consisted of two conditions: (i) the truncation condition in which subjects prepared to make an intentional action with their right index finger and reacted to the randomly presented truncating stimulus with their right index finger; and (ii) a right SRT condition in which they reacted to a randomly presented stimulus with their right index finger.

The independent variable was condition (truncation or yoked SRT) and the dependent variable was time (in ms). Due to the yoking of the foreperiods from the trials in which subjects reacted in the truncation condition, all subjects performed the truncation condition first followed by the yoked SRT condition. Therefore, the conditions could not be counterbalanced across subjects.

3.2.2 Apparatus

The apparatus was identical to that used in chapter 2, section 2.2.2. Briefly, speakers presented a warning beep to indicate the start of each trial. Visual stimuli (= signs,

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[1] There are no other truncation conditions in chapter 3, thus truncated right SRT will be called truncation.

font size 72) were presented centrally on a standard PC as an imperative signal in the RT conditions. Subjects used a standard computer mouse to make both intentional actions and responses to the visual stimuli.

The experimental program was re-written to include the recording of the foreperiods of the reactive trials in the truncation condition. This resulted in the foreperiods from the trials in which subjects reacted being recorded, randomised and re-used as the foreperiods for the SRT condition. This meant that the number of trials in the SRT condition varied between subjects, dependent upon how many reactive trials there were in the truncation condition.

3.2.3 Design and Procedure

Subjects did not perform practice trials as they had performed the experiment reported in chapter 2 immediately beforehand. They were, therefore, already familiar with both conditions in this experiment. The single within subjects factor was condition (truncation and yoked SRT); and the dependent variable was RT.

3.2.3.1 The truncation condition

Subjects began the experiment with 30 trials of the right truncation condition. Each trial began with a warning sound, a computer generated beep. The subject then began to prepare an intentional movement with their right index finger “as and when they felt like it”. If the stimulus appeared during this preparational stage, they were required to react with the same right index finger key press as quickly as possible.

3.2.3.2 The yoked SRT condition

The recorded foreperiods from each subjects' truncation condition were randomised and then used as the time of presentation of the visual imperative stimulus in the yoked SRT condition. Thus, the stimuli were presented at the SAME time in this condition as they were in the reactive trials in the previous truncation condition. Each trial had a mirror partner in the other condition.

3.3 RESULTS

There were 16 subjects in this experiment. Table 3.1 details the number of trials that occurred in the SRT condition following yoking from the truncation condition and trimming of the erroneous trials (RTs outside the range of 150 -1000 ms and intentional key presses). 2% of the trials were discarded based on these criteria. The number of SRT trials in Table 3.1 was determined by the number of reactive trials that occurred in the truncation condition.

Table 3.1. The number of trials in the yoked SRT condition.

SUBJECT NUMBER	NUMBER OF SRT TRIALS
1	14
2	14
3	19
4	14
5	20
6	15
7	12
8	14
9	16
10	16
11	14
12	14
13	17
14	21
15	16
16	10
Mean (s.d.)	15 (2.85)

The mean number of trials was 15, which indicates that, on average, subjects reacted to the stimulus in half of the truncation trials, thus, the number of reactive trials was the same as intentional trials.

Table 3.2. The mean (s.d.) RTs for the yoked SRT and reactive trials from the truncation condition (TRT).

CONDITION	Yoked SRT	TRT
Mean **(s.d.)**	298 (63.35)	347 (111.96)

48% of the remaining truncation trials were truncated reactions (TRTs). The mean RT for the reactive trials from the truncation condition (TRT) was larger than the mean RT for SRT. The direction is therefore, the same as in the previous experiment (chapter 2). A related samples t-test indicates that these RTs are highly significantly different ($t_{(15)} = 4.25$, $p = 0.0007$). The RT cost of intention is: 347-298 = 49 ms. There is, therefore, a significant RT cost of intention, found between the SRT and TRT conditions, which is almost identical to the RT cost of intention of 51 ms found in experimental chapter 2.

The hypothesis that the RT cost of intention will still occur when the foreperiods from the truncation condition and SRT condition are yoked can be accepted. Thus, the RT cost of intention is not an artefact of variable foreperiod.

3.4 DISCUSSION

This control experiment was designed in order to exclude the possibility that the foreperiod differences were responsible for the increased RT in the truncation condition. When the foreperiods were made exactly the same in the truncation and SRT conditions, the effect of the RT cost of intention remained virtually unchanged. Intending to make a right intentional key press produces an RT cost of intention, which is manifested in the slower response to the truncating stimulus.

The fact that the RT cost of intention remains approximately the same as that found in chapter 2 also provides evidence that it is relatively stable across time and across trials. If practice and familiarity with the truncation condition resulted in a reduction in TRT, then the difference between the SRT and TRT would also be reduced. However, the RT cost of 49 ms found in this chapter is remarkably similar to the value of 51 ms found in chapter 2, suggesting that the RT cost of intention is not reduced by practice.

Chapter 4

THE EXAMINATION OF PRE-MOVEMENT PROCESSES USING PUPIL DILATION

4.1 INTRODUCTION

The previous chapter established that the RT cost of intention did not appear to be significantly influenced by the variable foreperiod. The next stage in this thesis is to try and establish at what stage of action preparation the subjects were, when the truncation occurred. That is, while subjects were instructed to prepare intentional actions in every trial, and on that subset of trials in which the truncating stimulus did not occur, they did indeed make an intentional action; there is no independent evidence to indicate that they were preparing an intentional action in those trials in which the truncating stimulus occurred resulting in a reaction. An independent measure of intention and preparation would confirm that the truncating stimulus did indeed interrupt an intentional action. Furthermore, this independent measure might indicate whether there is any covariation between RT and the level of intentional preparation. For example, one might ascertain whether there is an effect on RT dependent upon how close to making the movement the subject is.

A useful objective external measure of preparation in movement is pupil dilation (e.g. Richer and Beatty, 1985). When a subject prepares/intends to perform an intentional movement, their pupils dilate up to 1500 ms before they move (Richer and Beatty, 1985). When subjects react after a constant foreperiod, there is also pre-movement dilation beginning up to 1000 ms before the movement (e.g. Richer, Silverman and Beatty, 1983). Thus, combining the behavioural RT data found in chapters 2 and 3 with a physiological measurement such as pupil dilation might provide more evidence as to the pre-movement occurrences in internally-generated actions.

Pupil dilation has a long established usage as a measure of cognitive load in neuropsychology, particularly for "… its sensitivity to the global processing demands on the CNS in a variety of … reaction time tasks" (Richer and Beatty, 1987). Kahneman was one of the earliest proponents of pupil dilation as a useful autonomic indicator of effort. His experiments in the 1960s (e.g. Kahneman and Beatty, 1966) and the plethora that followed (a review by Beatty, 1982, contains almost 50 references) verify the link between cognitive effort and dilation. However, the use of pupil dilation has waned in recent years.

The physiology of pupil dilation, its use as a measure of cognitive load, early pupillometry and pupil dilation and movement were reviewed in sections 1.7.2.2 to 1.7.2.5 (chapter 1).

Recent research using pupil dilation has focused on pupil dilation as an index of processing demands and whether pupil dilation and other psychophysiological measures of preparation and RT correlate. These aspects of pupil dilation are briefly summarised in the following sections, due to their relevance to the use of pupil dilation as a tool to examine pre-movement processes.

4.1.1 Pupil Dilation and Processing Demands

Richer et al (1983) demonstrated that the dilation of the pupil was sensitive to response selection, response preparation and execution in a choice reaction time (CRT) experiment. They estimated (from the pupillary amplitude) that the pupil dilation concomitant with response selection was approximately half that concerned with response preparation and the response itself. The sensitivity of the pupillary response to these varying processing demands confirms the validity of pupil dilation as a measure of cognitive effort.

4.1.2 Pupil Dilation and RT

Richer and Beatty (1987) observed that a dissociation existed between the measures RT and pupil dilation, which they suggest might indicate a “differential emphasis in the processing demands indexed by these two measures.” These researchers measured the pupil dilation and RT in a SRT, 2-choice RT, 4-choice RT and two Go/No Go conditions (the Go/No Go conditions are discussed in chapter 5, section 5.1.2). The RT was found to increase at a different rate to the amplitude of the pupil dilation. When the probability of a response is reduced from 1 to 0.5 (SRT to 2-choice RT) and from 0.5 to 0.25 (2-choice RT to 4-choice RT), the effect on the pupil dilation is the same at both levels of change (increasing by approximately 34%).

However, a reduction in response probability from 1 to 0.5 causes an increase in RT by 60%, and by 30% from 0.5 to 0.25. Richer and Beatty (1987) tentatively concluded that this difference might be due to the relative sensitivity of RT and pupil dilation to the motoric and decisional processing demands.

Jennings, van der Molen and Steinhauer (1998) used non-ageing foreperiods in a visual RT task, to examine whether brain negativity, heart rate deceleration and pupil dilation index different stages of preparation. The use of a non-ageing foreperiod ensured that the probability of the stimulus occurrence was the same at any given moment in the foreperiod thus, subjects' expectations of the stimulus occurrence was (ideally) not affected by time. These non-ageing foreperiod trials were compared to trials in which the foreperiod was not fixed. A subset of the trials involved the stimulus being triggered by a physiological preparatory response. They found no strong correlations between RT and each physiological measure of preparation, or between any of the physiological measures. Also, triggering the stimulus from physiological measures did not influence the RT. These differences provide support (i) for the use of a variety of measures in the study of reaction time due to each one revealing different aspects of the preparatory stages and (ii) are consistent with a multiprocess model of preparation (Jennings et al, 1998).

4.1.3 Using Attentional Theories as a Means of Conceptualising Cognitive Effort

In the 1960s, before the widespread use of imaging techniques that allow us to observe functioning brains, psychologists were developing theories to explain how people processed information under a variety of conditions. Using behavioural tasks, they inferred the possible underlying 'mechanics' of the brain to explain the differences in RT between different conditions. The present experiment re-uses the truncation condition, in which one task, an intentional action, is interrupted by a stimulus and another, a reaction, is performed. In the following paragraphs, dual-task interference and related theories will be discussed because they provide a useful way of conceptualising cognitive effort.

Dual-task interference can be defined as the decrement in performance on one task when it is performed concurrently with another task (sometimes called a 'secondary task'), as opposed to when it is performed alone. There are three main types of theories that are concerned with dual-task interference.

The first theory, the bottleneck or single-channel model concept suggested by Broadbent (1958), focused on the idea of central cognitive resources and the competition between events for these limited resources. In brief, the bottleneck theory states that certain mental operations can only be carried out sequentially; thus, in a dual-task situation, when two tasks require a critical mental operation simultaneously, a *bottleneck* occurs. This single-channel model allows sequential processing controlled by the limited resources.

The second concept, capacity sharing, suggests that there may be one or more "pools of processing 'resources'" (Paschler and Johnston, 1998), which can be shared between different tasks in a graded fashion. Task processing occurs in a parallel fashion within the confines of the available capacity. Another term for this concept is parallel processing. These two models differ in their processing, which can occur simultaneously in the capacity sharing and occurs sequentially in the single-channel model.

Crosstalk, the third concept, suggests that interference occurs when the two tasks are very similar and there is *crosstalk* between them. In this case, there may be enough processing capacity for the two tasks but, if they are very similar, keeping the streams separate may be difficult, although is important, in order to reduce interference (e.g. Navon and Miller, 1987). It has been observed that this theory is compatible with the bottleneck theory of dual-task interference (Pashler and Johnston, 1998). Specifically, that sequential processing of mental operations might occur because concomitant or parallel processing may result in crosstalk.

The above discussion of the three main approaches to the processes occurring in dual-task interference does not attempt to review all possible theories of dual-task interference, solely to provide a brief overview. These attentional theories compliment the use of pupil dilation as a measure of cognitive effort, (i) because they conceive of there being certain processing capacities for events for which there is competition and (ii) that this processing can be measured and quantified.

4.1.4 Aims

The experiment uses two conditions from chapters 2 and 3, the SRT condition and the truncation condition. The third (new) condition is an intentional action condition with a variable foreperiod, where the subject only performs an intentional right key press, at a time of his or her own choosing. The aim of this experiment is to examine more closely the pre-movement processes in the truncation condition in an effort to try and explain what factors contribute to the RT cost of intention that was found in chapters 2 and 3. It will also provide evidence of whether subjects are intending, as requested in the truncation condition.

The data from this experiment will also be used to examine the withhold-go hypothesis that was posited in section 2.1.2 (chapter 2).

4.1.5 Experimental Hypotheses

i. Richer et al (1983) have shown that when the presentation of the stimulus is constant, the pupil dilates due to expectation (Figure 1.6, chapter 1). In the SRT condition, the foreperiod is variable, so expectancy should be absent, therefore, it is predicted that the pupillary dilations for the SRT condition will show little or no pre-movement dilation.

ii. The dilations for the internally-generated movements will show the pre-movement preparatory increase (Figure 1.5 chapter 1). This will replicate the work by Richer and Beatty (1985).

iii. The dilations in the truncation condition will be similar to those in the internally-generated condition, in that there will be obvious preparatory dilations. However, they will be larger due to the added cognitive load of possibly having to react whilst preparing. This hypothesis is based on (i) the findings in chapter 2, that the RT is slower and therefore the process is possibly more effortful, and (ii) the findings of Hess and Polt (1964), for example, who showed that increasing the task difficulty increases pupil dilation.

iv. To confirm the RT cost of intention that was found in chapters 2 and 3.

4.2 METHOD

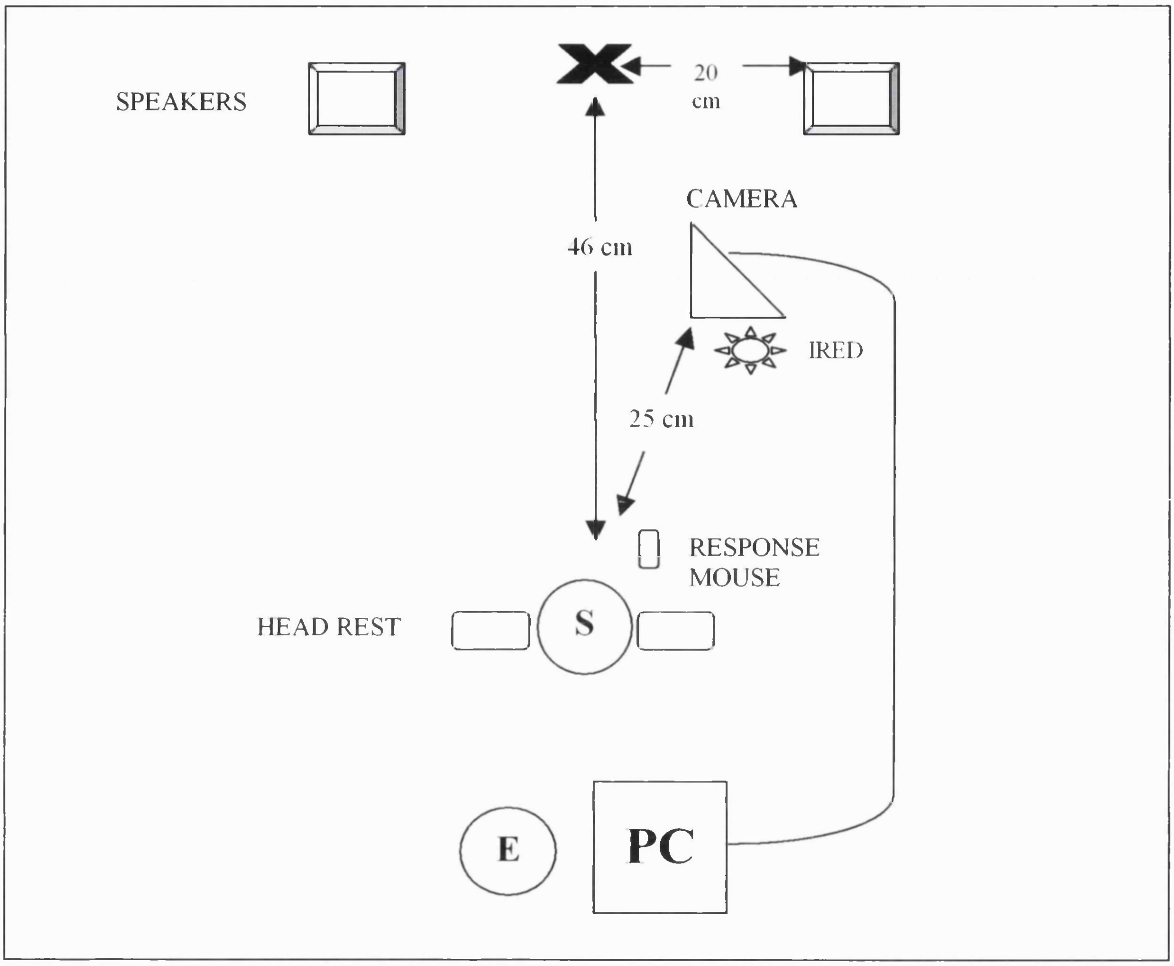
4.2.1 Subjects

Twelve subjects, seven females and five males were used. The mean age was 26.83 years (s.d. 3.08), range 23-35. All subjects were right-handed and had normal or corrected to normal vision via contact lenses (subjects were asked to refrain from wearing glasses because the reflection disturbed the data collection from the camera). None of the subjects were suffering from any known neurological disorder. Subjects were asked to refrain from smoking and drinking caffeinated drinks for 2 hours before the experiment, as these stimulants can affect the dilation of the pupil and cause hippus (fluctuations in dilation and constriction).

4.2.2 Apparatus: Novel Pupil Recording Equipment

The equipment that was used to measure the pupil dilation in this experiment was assembled specifically for the study. It involved a frame grabber being installed on a regular PC, an infrared spy camera and the labVIEW programming package. The subject's eye was illuminated with an infra-red emitting diode (IRED), which was placed under the eye. The camera was aimed at the right eye of the subject at a distance of 25 cm. The subjects' heads were stabilised by a chin and forehead rest that also restricted movement within the experiment and subjects focussed on a cross directly ahead of them (i.e. they did not look at the camera) [Figure 4.1].

Figure 4.1. Experimental set-up. E = experimenter, S = subject, IRED = infra-red emitting diode, X = fixation point.



The data collection involved the experimenter focusing the camera on the subject's eye, to insure that the whole eye was in vision. At the beginning of each block, the experimenter delineated the area of interest via cursors, that is the area from which the data was collected. During the experiment, the camera's view was monitored on-line by the experimenter to ensure that the subject did not move their head out of the delineated area of interest. This was done in order to exclude the eyebrows and the shadow between the nose and the eye. The labVIEW package was only programmed to perceive the dark/light contrast, which is obvious between the iris and the pupil. LabVIEW was programmed to collect frames of data at a sampling rate of approximately 20 Hz. Each frame was time stamped with ms accuracy to accommodate slight variations in sampling rate.

The dilation of the eye was measured by the change in the number of pixels that represented the pupil, that is, the background was black and the pupil consisted of white pixels, which changed in number over the course of each trial. These numbers of pixels were then converted into a pupil diameter in mm at the end of the experiment assuming the pupil was circular.

Subjects made their responses via a computer mouse, which was attached via the serial port and had the roller ball removed.

4.2.3 Design and Procedure

All subjects performed three practice conditions in the same order which were discarded from the subsequent analyses: 5 trials of the right simple reaction time (SRT), 5 trials of the right intentional action and 10 trials of the truncated SRT condition[1]. Then subjects performed these three conditions in varying order, such that they were counter-balanced. The single within subjects factor was condition (SRT, intentional action and truncation); and the dependent variables were reaction time (RT) and pupil dilation.

4.2.3.1 SRT condition

The SRT condition involved the subject being presented with a warning – the experimenter's voice saying "Blink, Fixate, OK." The experimenter started the trial simultaneously with the "OK" command. A computer generated beep was presented between 2 and 10 seconds after the trial was activated. Subjects were instructed to respond as quickly as possible with a right key press.

4.2.3.2 Intentional action condition

The intentional action condition involved subjects receiving the warning as before. Subjects were instructed to make a make a right intentional key press as and when they felt like it. They were discouraged from making repetitive actions.

4.2.3.3 Truncation condition

The truncation condition involved the presentation of the same warning. Subjects were instructed to prepare to make a right intentional key press, with the possibility that this preparation might randomly be interrupted with a beep to which they were to react with the same movement as they were preparing: a right key press. Two types of trials arose from this condition: right intentional key presses where the subject made an intentional action before the presentation of the beep, termed truncated intentional trials (TIN); and truncated reactive trials (TRT) where subjects' intentional action preparation was truncated with a stimulus to which they reacted.

4.3 RESULTS

4.3.1 Reaction Time Data

As can be seen from Table 4.1, the RT for the truncation condition is much slower than that of the SRT condition. This difference was found to be significant when subjected to a t-test: $t_{(11)} = 2.51$, $p = 0.03$ (uncorrected). The RT cost of intention = 379-320 = 59 ms. This is very similar to the values of 51 ms and 49 ms found in the previous two chapters and therefore, supports hypothesis four. Also, it is interesting to note that this value was produced when the stimuli were auditory. Thus, the RT cost of intention occurs whether stimuli are presented visually (Chapters 2 and 3) or auditorily (Chapter 4).

Table 4.1. Mean (s.d.) RTs for the SRT and truncated SRT conditions in ms.

CONDITION	Mean (s.d.)
SRT	320 (81.83)
TRT	379 (155.60)

4.3.2 Pupil Dilation Data

The pupil data were processed in similar stages to the processing of event-related potentials (ERPs). Each trial was manually inspected for blinks. Short blinks were interpolated using a linear algorithm between two manually placed cursors before and after the blink (Figure 4.2). The post-blink cursor was placed just after the artificially increased dilation in order not to artificially inflate the dilation.

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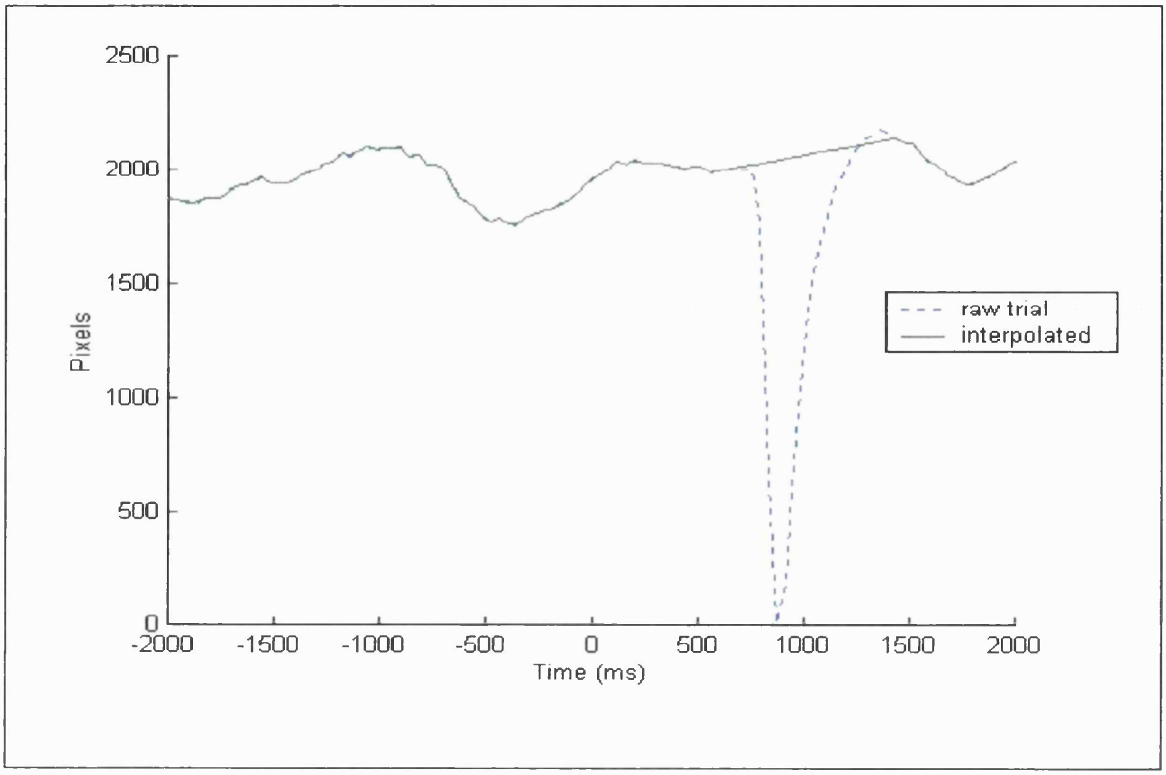
[1] There are no other truncation conditions in chapter 4, thus truncated right SRT will be called truncation.

Figure 4.2. A randomly selected trial in which a subject had blinked. The overplot[2] is a corrected trial, after linear interpolation.



Erroneous trials were deleted based on the following criteria:

i. The RT was outside the range 150-1000 ms.

ii. There were 3 or more blinks.

iii. The subject blinked for too long (this artificially increases the dilation after the blink).

iv. The trial was very noisy due to subject hippus (continuous dilation/constriction) or the subjects' eye moved out of the delineated area of measurement.

v. The subject made the action less than 2000 ms after trial onset, thus making it impossible to collect sufficient pre-movement pupil data.

8% of the trials were discarded due to these criteria. 63% of the remaining truncation trials were truncated reactions (TRTs).

The remaining trials were aligned to the keypress, thus producing movement-locked epochs extending from 2000 ms before the keypress to 2000 ms afterwards. These

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[2] Overplot is where two sets of data are plotted on the same Figure.

4000 ms epochs were then baseline corrected (i.e. large fluctuations in overall dilation level were removed) by subtracting the mean value of the signal from 2000 to 1800 ms before movement onset. The traces were then smoothed using a dual pass second order Butterworth filter with a cut-off frequency of 4 Hz. The key parameters were calculated for statistical analyses; the peak dilation (in mm), the latency (time) of the peak dilation (in ms) and the pre-movement mean dilation (in mm). The averages for each subject in each condition were calculated and then, for graphical display purposes, the grand averages were calculated for each condition. These are shown in Figures 4.3 - 4.6.

The following pupillograms, Figures 4.3 - 4.6 are movement-locked, which means that zero is the time of the movement. Figures 4.3 and 4.4 are two separate conditions: SRT and the intentional action condition. Figures 4.5 and 4.6 are respectively reactive (TRT) and intentional (TIN) trials from the truncation condition.

Figure 4.3. Simple reaction time condition (SRT): movement-locked. 0 = time of movement.

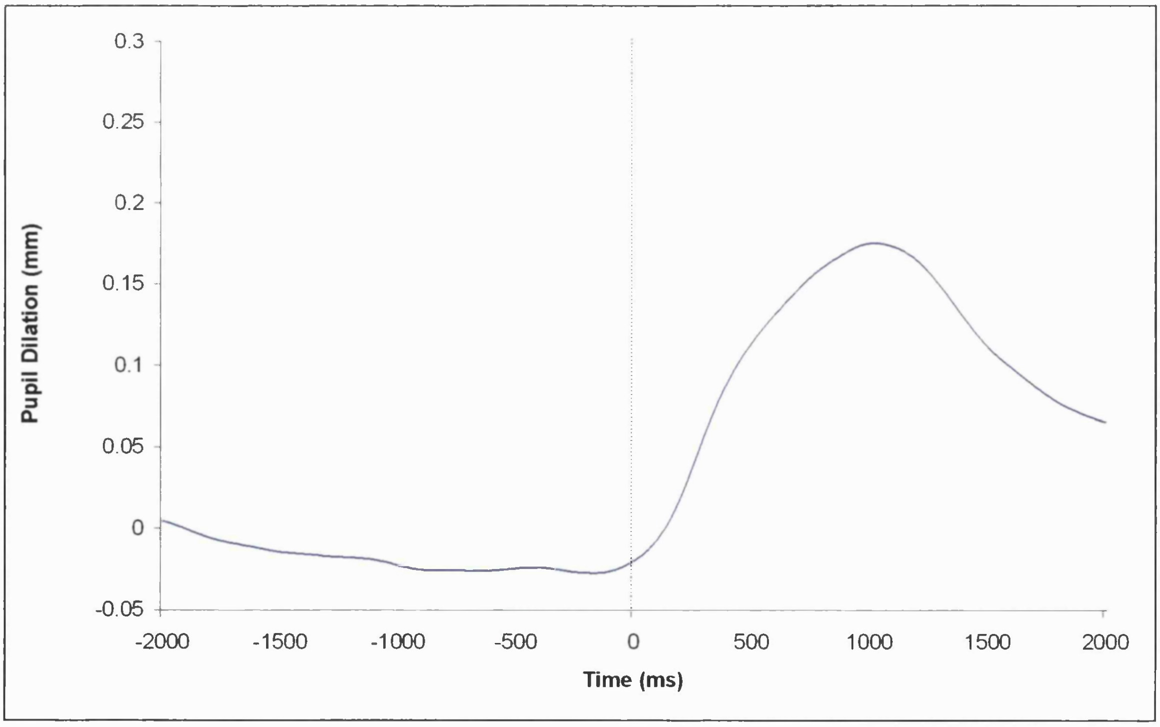


Figure 4.4. Intentional action condition: movement-locked. 0 = time of movement.

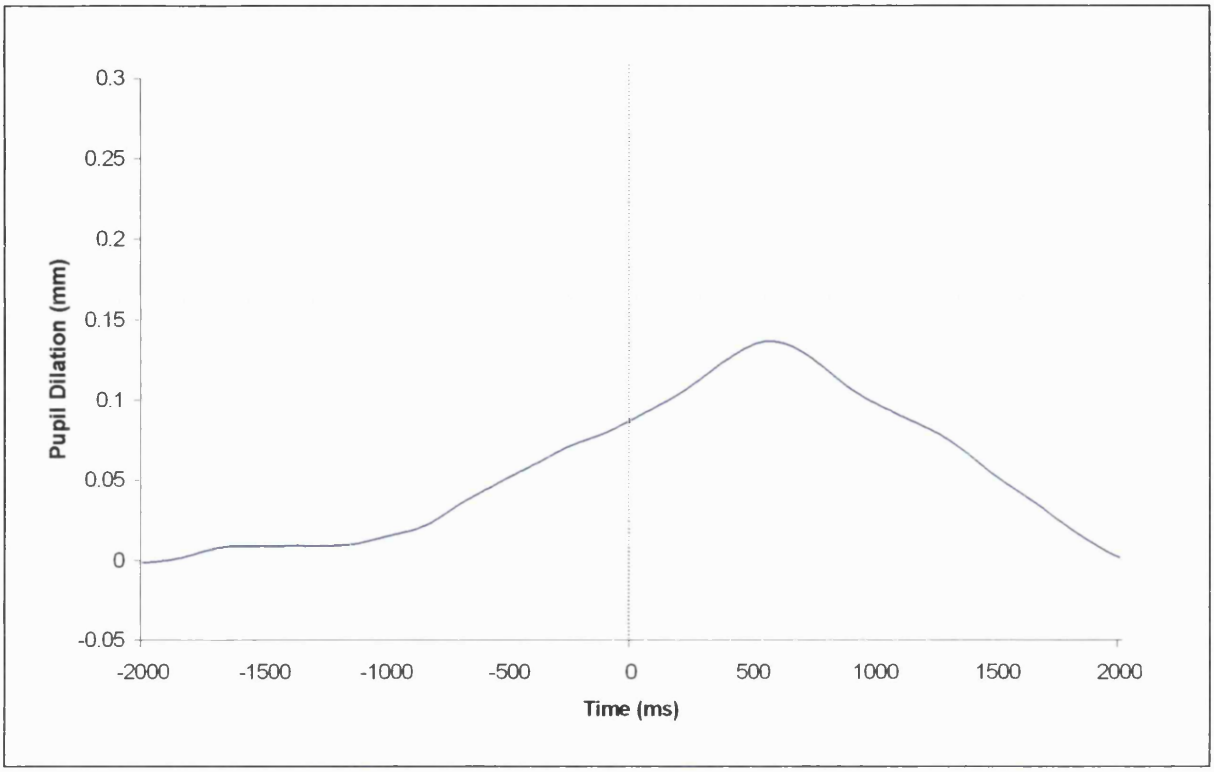


Figure 4.5. Truncation condition, reactive trials, (TRT): movement-locked. 0 = time of movement.

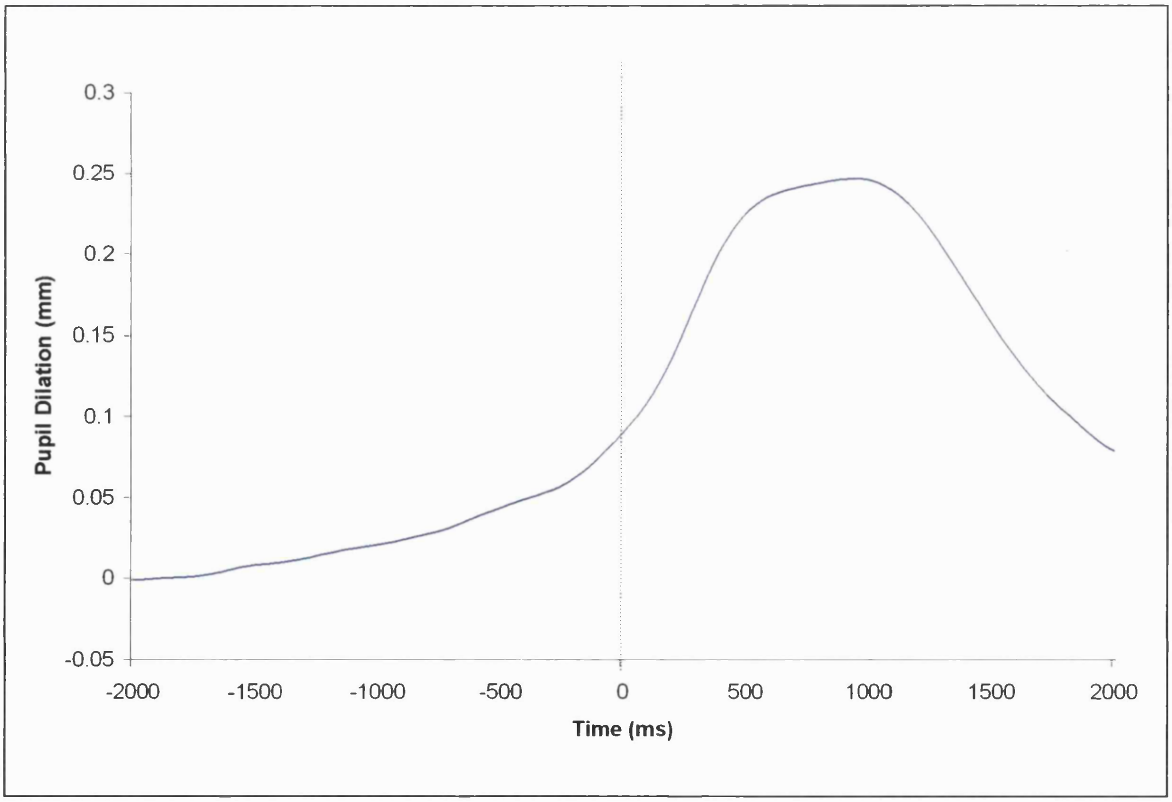


Figure 4.6. Truncation condition, intentional action trials (TIN): movement-locked. 0 = time of movement.

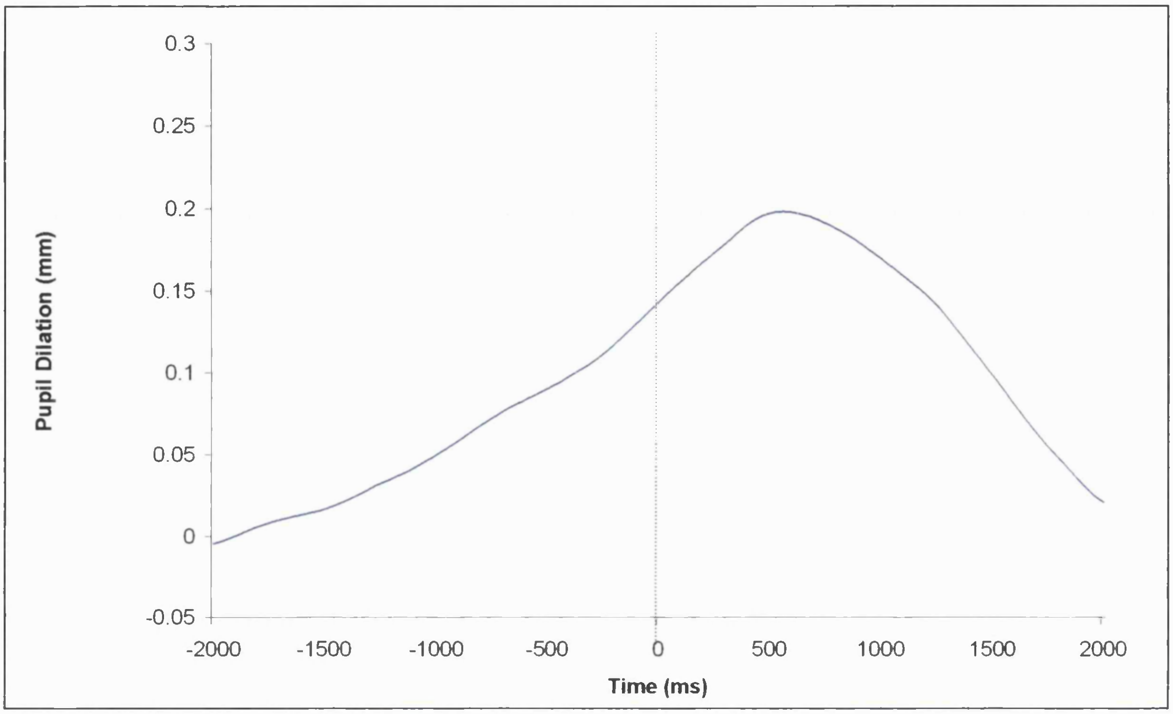


Figure 4.3, the SRT condition, indicates that when the foreperiod is variable, that is the subject cannot predict when the stimulus will occur, there is no pre-movement dilation. The reason that the graph is negative pre-movement is due to the baseline correction. Figure 4.4, the intentional action condition, shows that, consistent with intentional movement preparation, there is pre-movement dilation.

The peak dilation is larger in TRT (Figure 4.5) compared with TIN (Figure 4.6), probably due to the extra cognitive load of reacting whilst preparing to make an intentional movement. The TRT pupillogram (Figure 4.5), unlike the TIN pupillogram (Figure 4.6) shows a sudden slope change around -400 ms, indicating the change from intentional action to reaction and the increased effort required to react to the stimulus. TIN (Figure 4.6) shows all the intentional action trials from the truncation condition. Clearly there is pre-movement dilation occurring. If this graph is compared with Figure 4.4, the intentional action condition, it can be seen that the peak dilation is larger due to the possibility of having to react to a stimulus, therefore increasing the cognitive load.

To analyse these effects statistically, three measures were selected: the peak latency, the latency of the peak and the pre-movement mean dilation. These features were based on established literature (e.g. Richer and Beatty, 1985). Peak and latency reflect the amount of cognitive effort and its timing and the pre-movement mean dilation (not used in Richer and Beatty, 1985) reflects preparation. Table 4.2 shows the mean (s.d.) of the four conditions (SRT, intentional action, TRT and TIN) for three features of the data: peak dilation, the latency of the peak dilation and the pre-movement mean dilation (PMMD).

Table 4.2. The mean (s.d.) peak dilation, latency of peak dilation and pre-movement mean dilation (PMMD) of the four conditions.

CONDITIONS	PEAK (MM)	LATENCY (MS)	PMMD (MM)
SRT	0.20 (0.08)	901 (238)	-0.02 (0.05)
INTENTIONAL ACTION	0.16 (0.08)	707 (427)	0.03 (0.05)
TRT	0.29 (0.09)	800 (293)	0.03 (0.02)
TIN	0.22 (0.06)	637 (309)	0.06 (0.04)

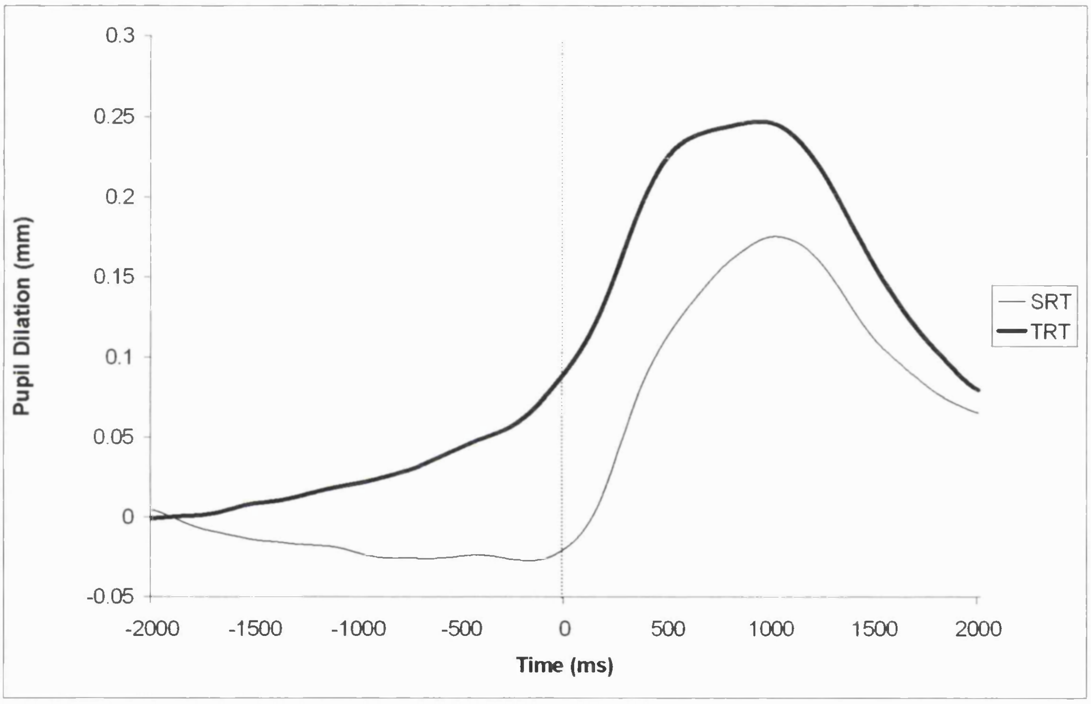
NB. The grand average values that appear in the Table are different to the values that appear in the Figures. This is because, in real time the pupillograms are smeared across subjects and trials. They have a tendency to be cancelled out and reduced by the process of event-locking, necessary for graphical presentation.

Sections 4.3.2.1 to 4.3.2.4, below detail the four planned comparisons: SRT versus TRT, intentional action versus SRT, intentional action versus TIN and TRT versus TIN for the three features of comparison: peak dilation, latency of the peak dilation and the pre-movement mean dilation.

4.3.2.1 SRT versus TRT

The significant difference found between SRT and TRT, plotted together in Figure 4.7 in peak dilation ($t_{(11)} = 4.77$, $p = 0.0006$, uncorrected) supports the idea that it is more effortful to react, following intentional preparation. Although significance is not reached ($t_{(11)} = 2.17$, $p = 0.053$, uncorrected), the latency of 901 ms found in SRT compared with 800 ms found in TRT definitely implies that the RT cost of intention, found in this and previous experiments, cannot solely be attributed to a delay in the processing of the truncating stimulus. In fact the TRT latency is *earlier* than the SRT latency. The larger and significantly different pre-movement mean dilation found in the TRT compared with the SRT ($t_{(11)} = 3.86$, $p = 0.0033$, uncorrected) supports the first hypothesis that no pre-movement mean dilation would be found in SRT due to the variable foreperiod. It also provides independent evidence that subjects did in fact prepare an intentional action at the start of each trial in the truncation condition, as requested. This supports the view that the differences between SRT and TRT in RT, are attributable to the intention in the former case.

Figure 4.7. The overplot of the SRT and TRT pupillograms. 0 = time of movement.



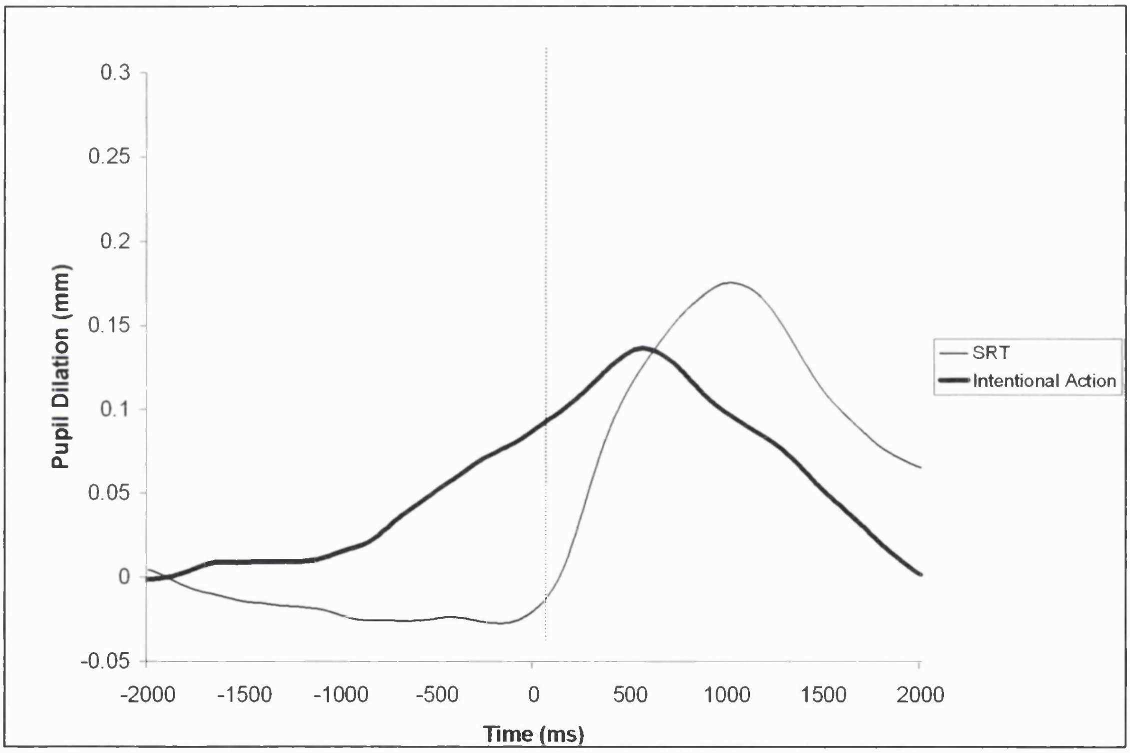
4.3.2.2 Intentional action versus SRT

Figure 4.8 shows the intentional action and SRT conditions plotted on the same graph. The non significant difference found between the intentional action condition and the SRT in their peak dilation ($t_{(11)} = 1.32$, $p = 0.21$, uncorrected) suggests that making a simple action, be it intentional or reactive, is not hugely different in terms of the overall effort required.

Although there appears to be a difference in latency between SRT and TRT, the values were shown to be non significantly different ($t_{(11)} = 2.09$, $p = 0.060$, uncorrected), although this result approached the borderline of conventional significance.

The intentional action peak occurs earlier than the SRT. This is unsurprising because in an intentional action the subject has prior knowledge of when they are going to act, so the action appears to be completed earlier by the physiological marker (pupil dilation). The highly significant difference found in pre-movement mean dilation ($t_{(11)} = 3.35$, $p = 0.0064$, uncorrected) supports hypothesis two, that the internally-generated actions will show pre-movement dilation and hypothesis one, that there will be no pre-movement mean dilation in the SRT condition.

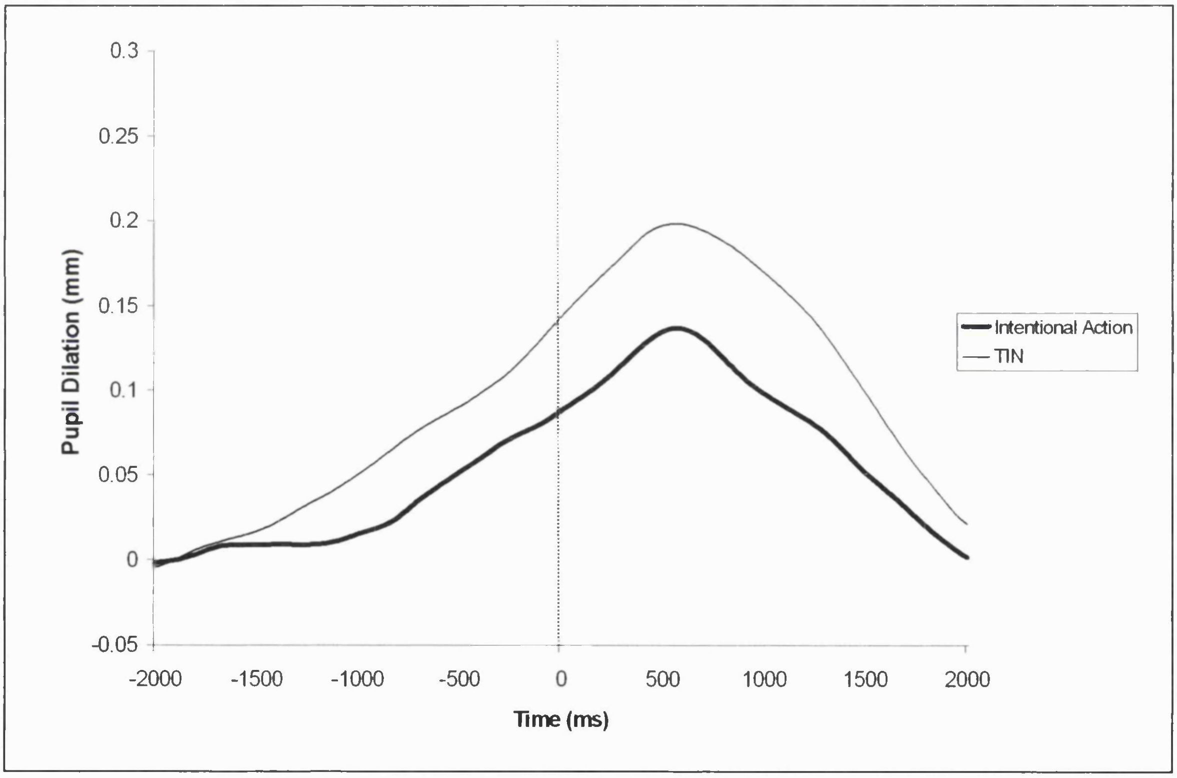
Figure 4.8. The overplot of the SRT and intentional action pupillograms. 0 = time of movement.



4.3.2.3 Intentional action versus TIN

The significantly larger peak dilation found in TIN ($t_{(11)} = 3.09$, $p = 0.010$, uncorrected) suggests that it is more effortful to make an intentional action when the possibility of reaction is present (Figure 4.9). The non significant difference in the latency of this peak dilation ($t_{(11)} = 0.64$, $p = 0.54$, uncorrected) suggests that when subjects make the intentional action in the truncation condition, the action appears to finish as early as in the intentional action condition due to prior knowledge of the movement being available in both conditions. That is, once the subject is making the intentional action, they complete it just as fast as they do in the intentional action condition, only that it is more effortful. The fact that it is more effortful is also shown by the significantly larger pre-movement mean dilation ($t_{(11)} = 2.73$, $p = 0.020$, uncorrected) found in TIN (twice the size), which suggests that subjects preparational effort is increased by the fact that they might have to react (Figure 4.9). These larger peak and pre-movement mean dilations found in TIN support the third hypothesis that the dilations in the truncation condition will be larger than those in the intentional action condition.

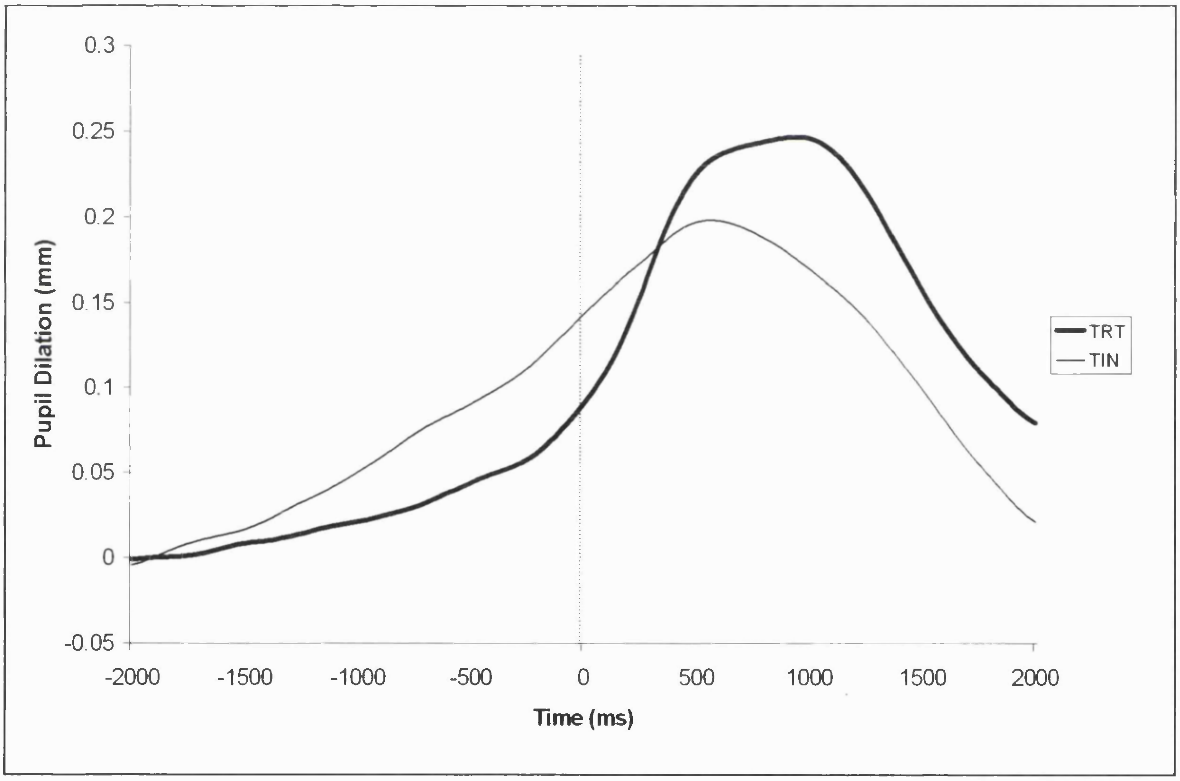
Figure 4.9. The overplot of the intentional action and TIN pupillograms. 0 = time of movement.



4.3.2.4 TRT versus TIN

The significantly larger peak dilation found in TRT ($t_{(11)} = 3.19$, $p = 0.0086$, uncorrected) suggests that the dual-task nature of the truncation condition, manifested in TRT, makes reaction following intentional preparation more effortful than making an intentional action under the threat of reaction (TIN) [Figure 4.10]. The non significant difference between the latency of the peak ($t_{(11)} = 2.06$, $p = 0.064$, uncorrected) approaches a trend similar to that found in the SRT versus TRT and intentional action versus SRT comparisons. Again, this suggests that the intentional, and thus prior knowledge component, of the TIN makes it appear to be completed earlier. This is a similar pattern to that found between SRT and the intentional action condition (Figure 4.8). The highly significant difference found in the pre-movement mean dilation ($t_{(11)} = 3.32$, $p = 0.0069$, uncorrected) supports the idea that the subject switches from intentional action preparation to reaction in the TRT. That is, the dilation before the movement stops when the subject reacts.

Figure 4.10. The overplot of the TRT and TIN pupillograms. 0 = time of movement.



4.3.3 Stimulus-locked Comparison

The trials were re-averaged, locking the trials to the stimulus, that is, 0 equals the stimulus (beep) instead of the movement, following the same procedure detailed in section 4.3.2. This was performed in order to see if there were any effects that were due to the stimulus processing rather than the response or movement production. Table 4.3 presents the peak dilation, the latency of the peak dilation and the pre-stimulus mean dilation for the two conditions in which a stimulus occurred (SRT and TRT).

Table 4.3. The mean (s.d.) peak dilation, latency of peak dilation and pre-stimulus mean dilation (PSMD) of the two conditions with stimuli: SRT and TRT.

CONDITIONS	PEAK (MM)	LATENCY (MS)	PSMD (MM)
SRT	0.19 (0.09)	1218 (195.67)	-0.03 (0.05)
TRT	0.28 (0.12)	1187 (202.41)	0.01 (0.03)

In the SRT stimulus-locked graph, the dilation begins around 400 ms after the stimulus has been presented. Figure 4.11 shows that there is no mounting arousal before the stimulus. In the stimulus-locked graph of reactive trials from the truncation condition (Figure 4.12), there is clear evidence of pre-stimulus dilation, which suggests that subjects were preparing an intentional movement as requested. These differences in pre-stimulus mean dilation reached statistical significance ($t_{(11)} = 2.50$, $p = 0.030$, uncorrected) and were similar to those found in the movement-locked analyses. However, more of the dilation occurs after stimulus presentation and before movement than before stimulus presentation, that is, the difference between the movement-locked and stimulus-locked dilations indicates more dilation after the stimulus has occurred.

Figure 4.11. Simple reaction time condition (SRT): stimulus-locked. 0 = imperative auditory stimulus onset.

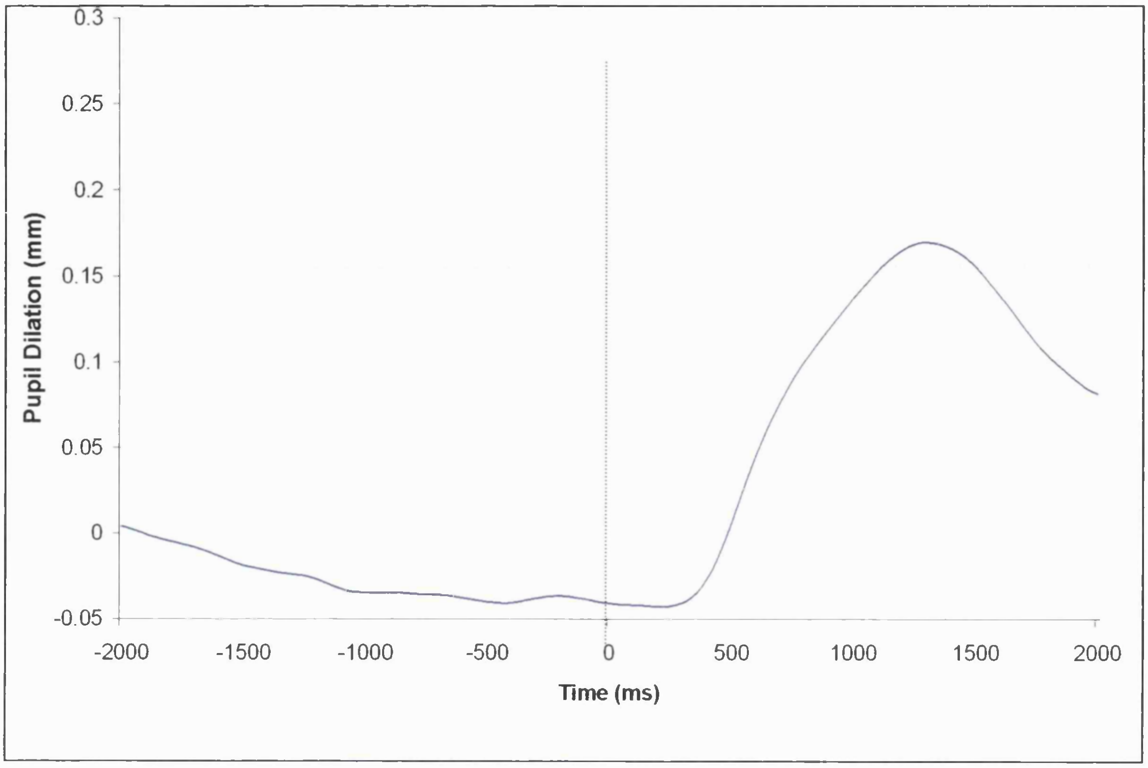
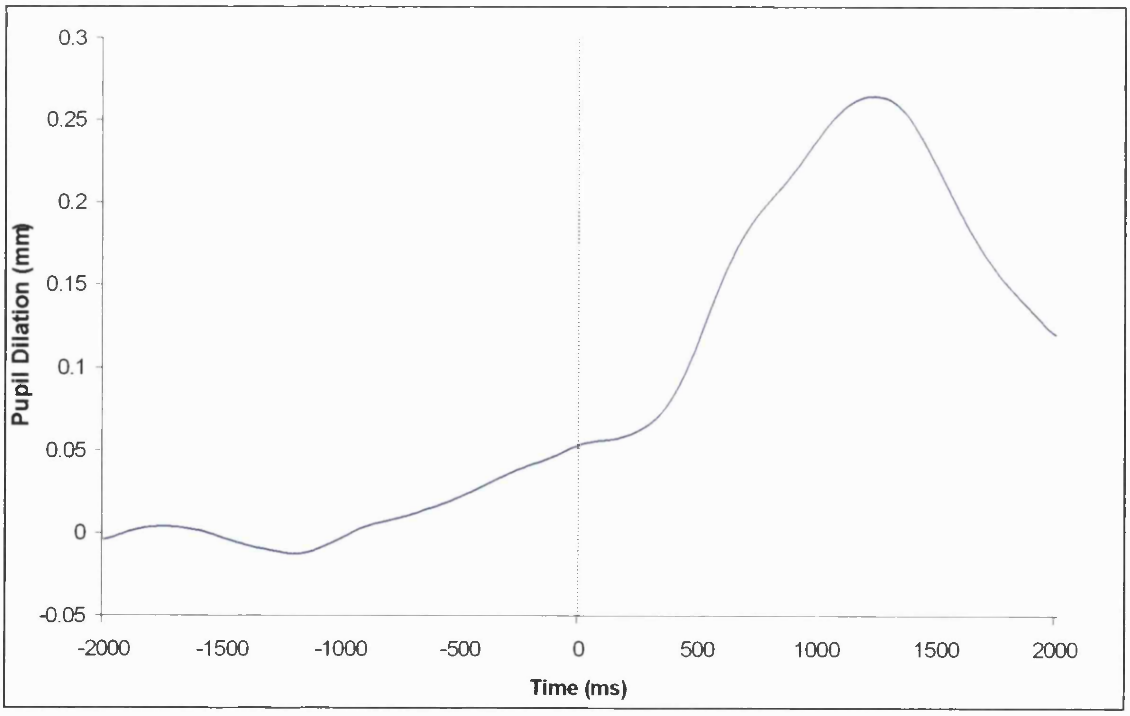


Figure 4.12. Truncation condition, reactive trials (TRT): stimulus-locked. 0 = imperative auditory stimulus onset.



There was a non significant difference between the stimulus-locked SRT and TRT conditions in the latency of the peak amplitude ($t_{(11)} = 0.73$, $p = 0.48$, uncorrected). This implies that the timing of the processes post-stimulus is not substantially earlier in TRT compared with SRT, that is, stimulus processing is not delayed in TRT.

The peak dilation was clearly larger in TRT compared to SRT ($t_{(11)} = 4.24$, $p = 0.0014$, uncorrected). The most obvious interpretation is that the stimulus-locked TRT pupillogram is a composite of the intentional action pupillogram (Figure 4.4) and the stimulus-locked SRT pupillogram (Figure 4.11). These SRT, TRT and intentional action pupillograms cannot be plotted on the same Figure, due to the SRT and TRT being stimulus -locked and the intentional action pupillogram being necessarily movement-locked. However, this interpretation seems sensible for two reasons: (i) the stimulus-locked TRT pupillogram (Figure 4.8) shows a steady increase in pupil dilation in the pre-stimulus phase similar to the pre-movement dilation in the intentional action pupilllogram (Figure 4.4); and (ii) there is a kink at approximately 400 ms in the TRT pupillogram (Figure 4.12) where the slope increases suddenly, which is also seen in the SRT (Figure 4.11). This is presumably the first pupillary consequence of the auditory stimulus onset.

An artefactual reason to explain the increased RT and peak dilation in TRT might be that pupil constriction is slow; therefore, the pupil does not fully constrict between stopping the intention and starting the reaction. Two 'psychological processing' reasons for the longer RT and increased amplitude are: (i) the intention remains as an effortful cognitive process, even after the stimulus occurs, that is, there is some residual intention, or (ii) some third process in addition to intention and reaction, for example, there is a switch between the hypothesised intentional action motor system to the reactive motor system which creates an effortful switch cost and resultant dilation.

In Figure 4.12, it can be seen that there is a steep increase in pupil dilation at approximately 400 ms after the stimulus has been presented. Therefore, the time constant of pupil dilation is approximately 400 ms, i.e. the pupil takes 400 ms to react to the stimulus (400 ms onset time). Assuming a similar 400 ms time constant for pupil constriction, it would therefore, take 400 ms to return to baseline. Alternatively, the peak starts to decrease at approximately 1400 ms, which is about 1000 ms after the reaction, so the offset time of the pupil could be considered to be approximately 1000 ms. The peak amplitude occurs at approximately 1250 ms, which is more than one offset response (400 or 1000 ms) later. Also, the drop-off from the peak amplitude in the TRT graph is not attenuated which would be expected if the delayed offset response were to blame. The artefactual explanation of slow offsets seems implausible. Therefore, the larger peak in TRT is unlikely to be merely a prolonged offset response of intention, but is more likely to reflect an additional psychological process, such as a switch between intention and reactivity.

4.3.4 Post Hoc Foreperiod Analyses

The reactive trials from the truncation condition data were divided by foreperiod length to examine (i) whether the pre-movement mean dilation could be attributed to the expectation of the stimulus and (ii) the withhold-go hypothesis.

4.3.4.1 Expectation of stimulus

Based on the lack of pre-movement dilation in the SRT condition, where subjects were not intending but were expecting a stimulus, the pre-movement dilation in the truncation condition is unlikely to be due to stimulus expectation. A further check can be done, since if the dilation was due to expectation it might be expected that the early foreperiods would have smaller pre-movement mean dilations than the late foreperiod (FP). This is because "the subject's expectancy is said to increase with the aging of the fore-period" (Näätänen, 1971). Thus, pre-movement mean dilation should increase with foreperiod, similar to the contingent negative variation, a slow brain potential, prior to an imperative stimulus following a warning stimulus (e.g. Walter, Cooper, Aldridge, McCallum and Winter, 1964). The contribution of expectancy to the pupil dilation, and its effect on the RT cost of intention is addressed in chapter 5.

The foreperiod was 8 seconds. Thus, as in chapter 2, the SRT and TRT trials were split into those where the stimulus was presented in the first 4 seconds (early) and those where the stimulus was presented in the last 4 seconds (late).

Table 4.4 presents the pre-movement mean dilation (in mm) for the SRT and TRT conditions early and late foreperiod.

Table 4.4. Early and late foreperiods mean pre-movement mean dilations (PMMD) [s.d] in mm of SRT and TRT conditions.

Conditions	Early PMMD	Late PMMD
SRT	-0.018 (0.045)	-0.023 (0.065)
TRT	0.030 (0.027)	0.0013 (0.056)

NB. There were no late FP trials for subject 8, TRT.

The difference in pre-movement mean dilation between the early and late foreperiods was larger in the TRT condition compared with the SRT condition. There was more dilation in the early foreperiod in TRT.

A 2 x 2 ANOVA with independent variables foreperiod (early or late) and condition (SRT or TRT) and dependent variable pre-movement mean dilation was performed. There was a significant main effect of condition ($F_{(1,10)} = 5.29$, $p = 0.045$) and a non significant effect of foreperiod ($F_{(1,10)} = 2.03$, $p = 0.18$) and interaction ($F_{(1,10)} = 0.76$, $p = 0.40$). This suggests that the dilation occurring in the TRT condition is unlikely to be due to expectation, because (i) the early foreperiod pre-movement mean dilation is clearly larger than the late FP dilation, which is the reverse of the predicted direction; (ii) the main effect of condition implies that there is more dilation in the TRT condition, suggesting that the difference between SRT and TRT, which is intentional preparation, is the probable cause of the difference; and (iii) the main effect of foreperiod is non significant suggesting that the pre-movement mean dilation is not affected by the length of the foreperiod.

There was a non significant difference between the early and late foreperiods pre-movement mean dilations for the truncation condition ($t_{(10)} = 1.63$, $p = 0.14$, uncorrected). Although the values suggest that there is much more pre-movement mean dilation in the early foreperiod, they have large standard deviations, which probably explains the lack of significance. Again, this statistic contradicts the prediction, that if expectancy were the reason for the pre-movement mean dilation, the early FP trials would have smaller dilation. Overall, the results imply that it is unlikely that expectation is the cause of pre-movement dilation.

4.3.4.2 Withhold-go hypothesis

The data from this experiment can also be analysed to examine the proposed withhold-go hypothesis that was posited in chapter 2 (section 2.1.2 and 2.1.7.2 and examined in 2.3.5). Briefly the hypothesis states that the foreperiod of an intentional action is divided into two phases: the putative 'withhold' stage and putative 'go' stage.

Briefly, these processes could be occurring at the lower (muscle) level or at the higher (brain) level of the posited motor hierarchy (section 1.5.3.1, chapter 1). If these processes are occurring at the lower level, there is one set of predictions (chapter 2, section 2.1.7.2): in the withhold stage, the level of motor activation would be low, due to the inhibitory processes, *withholding* the intentional action. The truncating stimulus might be reacted to slowly in this stage, due to the required disinhibition prior to excitation. In the go phase, the motor activation level would be higher because excitation of the intentional action would be occurring, therefore, less activation would be required to make the preparation "flow over" into the reaction (Näätänen, 1971).

However, if the processes are occurring at the higher level, the predictions depend on how the posited motor systems might be related. Based on the findings from chapter 2, the posited systems have a relationship, which consists either of inhibitory features or a switching mechanism. Therefore, the following predictions are based on the systems being related in an inhibitory manner: if the intentional action is being withheld, the internally-generated system would be inactive and the externally-triggered system would not be inhibited. Reaction to the stimulus should therefore be faster in the withhold stage. In the go stage, the internally-generated system will be activated due to the increased motor activation of the intentional action, therefore, the externally-triggered system would be inhibited, resulting in longer RTs. Since the early foreperiod trials are most likely to occur in the withhold phase, and late foreperiod trials in the go phase, these hypotheses make directional predictions about foreperiod effects on RT. These predictions can be directly tested.

Table 4.5 presents the RT for the SRT and TRT conditions early and late foreperiods.

Table 4.5. Early and late foreperiods mean (s.d.) RTs of the SRT and TRT conditions in ms.

Conditions	**Early RT**	**Late RT**
SRT	332 (65.53)	309 (52.70)
TRT	398 (106.27)	336 (104.94)

Faster RTs were found in the later FPs for both SRT and TRT. This finding, similar to that found in chapter 2, fits with Näätänen's proposal of a "motor action limit", in which this author suggested that preparation accumulates over time, so stimuli presented in the late FP are reacted to more quickly than stimuli in the early FP (Näätänen, 1971). However, it also corresponds with the suggestion that subjects react more quickly due to the increased probability that the stimulus is going to occur as the foreperiod increases (Niemi and Näätänen, 1981).

A 2 x 2 ANOVA was performed where the independent variables were condition (SRT or TRT) and foreperiod (early or late) and the dependent variable was RT. The effect of condition was not significant, $F_{(1,10)} = 3.72$, $p = 0.082$, while the effect of foreperiod was significant, $F_{(1,10)} = 8.41$, $p = 0.016$. The interaction was non significant $F_{(1,10)} = 2.41$, $p = 0.15$.

This suggests that the subjects react faster in the late foreperiod, regardless of condition. There is no strong support for the concept of an additional foreperiod effect in truncation, which the withhold-go hypothesis predicts.

There was a significant difference between early and late foreperiods reaction times in TRT ($t_{(10)} = 2.52$, $p = 0.030$, uncorrected) [faster RT in the late FP]. This result implies that subjects find it harder to switch from intention to reaction in the early stages of the foreperiod. This finding could support the low motor level version of the withhold-go hypothesis, or its occurrence at the higher level with facilitatory links between the two systems. This is because subjects would be in the withholding phase in the early foreperiod and, therefore, reacting to the truncating stimulus would take longer. However, there is also a significant difference between the early and late foreperiods in the SRT condition ($t_{(11)} = 2.30$, $p = 0.042$, uncorrected). Therefore, this effect is not specific to truncation and cannot support the withhold-go hypothesis.

There are a number of reasons why the withhold-go hypothesis is unlikely to be true. The first is due to the projected results of the withhold-go hypothesis being contingent on the hypotheses relating to the way that the motor systems might be related. Although the previous chapters have indicated that it is unlikely that the systems are linked in any of the five posited ways, there are clear repetitions of the RT cost of intention, which would suggest that an effortful process, consisting of perhaps inhibitory processes and a switching mechanism, is occurring between the two hypothesised systems. Therefore, the faster RT in the late FP may not be due to the "motor action limit" theory (Näätänen, 1971), which cohered with the facilitatory hypothesis and a motor level processes in the motor hierarchy, but may simply be due to the increased preparation that occurs as a result of the increased probability that the stimulus is going to occur as the foreperiod increases (Niemi and Näätänen, 1981).

4.4 DISCUSSION

4.4.1 Hypotheses

There is support for the SRT condition showing no pre-movement mean dilation (-0.02 mm). There is significantly more pre-movement mean dilation in the intentional action condition than in the SRT condition. Hypothesis one (section 4.1.5, i) can therefore be accepted. This statistic also provides support for hypothesis two (section 4.1.5, ii), that there would be pre-movement dilation in the intentional action condition (0.03 mm).

Hypothesis three (section 4.1.5, iii) stated that there would be larger pre-movement mean dilations and peak dilations in the truncation condition. This was again supported by the data; the pre-movement mean dilation and peak dilation was larger in the truncation condition intentional action trials compared with the intentional action condition.

The fourth hypothesis (section 4.1.5, iv) was also confirmed; an RT cost of 59 ms was found, which was similar to those previously found in chapters 2 and 3.

4.4.2 Stimulus-locked Analyses

The stimulus-locked analyses of the truncation condition showed that subjects were clearly intending before the stimulus was presented. There was a clear change in dilation at approximately 400 ms, where the pupil dilation started to increase more steeply. If the pupil has an onset time constant of 400 ms, then this increase in dilation could be due to the presentation of a task-relevant stimulus; stop intending and react to this truncating stimulus. Figure 4.12, therefore, shows that presentation of the stimulus has a marked affect on pupil dilation resulting in a steeper slope and larger pupil dilation.

Although the TRT pupillogram seems slightly to be a composite of the intentional action and the SRT pupillograms, the whole is less than the sum of the parts. The peak dilation in the SRT condition is 0.2 mm and in the intentional action condition is 0.16 mm. However, the TRT condition has a peak dilation of 0.29 mm. This preparatory intention, although slowing the resultant response, constitutes a proportion of the overall dilation. Therefore, although the intentional preparation is not facilitatory to the speed at which the subjects react, the preparation does mean that less overall effort is required when the subject reacts.

One possible reason for the slower RT in the truncation condition could be that it takes longer for the stimulus to be processed because the subjects are focusing their attention on preparing an internally-generated movement, and not on the external environment. To examine this proposal it is necessary to compare the latencies of the peak dilation in the SRT and TRT condition. Although the difference between the latencies was non significant, the TRT peak was earlier than the SRT peak. However, this difference is somewhat less pronounced when the data are stimulus-locked than when the data are movement-locked, though the TRT peak still precedes the SRT peak. Furthermore, the fact that the differences are in that direction suggests that the stimulus is not processed more slowly in the TRT condition. Therefore, the longer RT in TRT is highly unlikely to be due to delayed stimulus processing and is more likely to be due to the RT cost of intention or a switch cost.

4.4.3 Foreperiod Analyses

The foreperiod analyses were performed in order to examine whether the pre-movement dilations could be attributable to expectation and to investigate the withhold-go hypothesis.

4.4.3.1 Expectation of the stimulus

The TRT and SRT trials were divided into two groups, those in which subjects reacted in the first 4 seconds of the foreperiod, termed early FP, and those in which subjects reacted in the last 4 seconds, termed late FP. In both the SRT and TRT conditions, there was more pre-movement mean dilation in the early foreperiod.

The analyses suggested that the pre-movement dilation occurring in the TRT condition was unlikely to be due to expectation because the early foreperiod pre-movement mean dilation was larger than the late FP dilation; the significant effect of condition implies that the difference between SRT and TRT (intentional preparation) was the probable cause of the difference; and the non significant main effect of foreperiod suggested that the pre-movement mean dilation was not affected by foreperiod length. This pattern fits with the suggestion that the pre-movement dilation, particularly in the early foreperiod is not attributable to expectation and is probably due to intentional preparation.

4.4.3.2 Withhold-go hypothesis

The longer mean RT in the early foreperiods (compared with the late foreperiods) in the TRT condition does implicate 'withholding' as a possible occurrence. However, the late RT is also faster in the SRT condition, which indicates that this difference is not specific to the TRT condition. This difference also fits with the findings that subjects react more quickly as the FP increases due to the increased probability that the stimulus is going to occur (Niemi and Näätänen, 1981). Thus, this data does not provide any support for this hypothesis.

4.4.4 Conclusion

The results of this experiment indicate that subjects do prepare an intentional action in the truncation condition, and that when the stimulus is presented to them, during this intentional preparation, they react significantly more slowly. The stimulus-locked graph of the TRT condition indicated that there was a marked effect of stimulus presentation on the dilation of the pupil whilst the subject is preparing the intentional movement, which results in a steeper slope and larger peak dilation. However, the latency of the peak dilation is not significantly slower in the TRT condition.

This experiment provides evidence to suggest that the pre-movement dilation is probably due to intentional preparation rather than expectation. However, this will be further examined in the next experiment, chapter 5.

Although the results were non significant, it appears that the stimulus is not processed more slowly in the TRT condition and, therefore, the longer RT is likely to be due to switching between the intentional and the reactive motor systems. This will be examined using EEG in chapter 6.

Chapter 5

DOES STIMULUS EXPECTANCY AFFECT PUPIL DILATION AND THE RT COST OF INTENTION?

5.1 INTRODUCTION

This control experiment was designed to examine the affect of stimulus expectancy on pupil dilation and the RT cost of intention. Specifically (i) does stimulus expectancy cause the pupil to dilate, therefore artificially enlarging the pre-movement mean dilation and the peak dilation; and (ii) could the RT cost of intention be explained by reduced stimulus expectancy in the truncation condition?

5.1.1 Stimulus Expectancy and Pupil Dilation

Subjects expect an imperative stimulus in RT tasks. Physiological indicators, controlled by the autonomic nervous system (ANS), for example, the contingent negative variation (CNV), reflect the expectation of the imperative stimulus.

The CNV is an electrophysiological phenomenon characterised by a slow negative brain potential, usually *contingent* upon the connection between two successive stimuli in a constant foreperiod paradigm (Walter et al, 1964). More recently attempts to equate the CNV with a specific process has lead to the suggestion that (i) the early component is associated with a non-specific orienting response to the warning stimulus and is therefore an indicator of general arousal; and (ii) the late component that terminates prior to the imperative stimulus is associated with the expectation of and attention to the imperative stimulus (Loveless and Sanford, 1975).

Although the cause of the CNV is thought to be due to many factors such as expectancy, intention, attention and motivation (Tecce, 1972), it is clearly difficult to disentangle all the relevant contributing components and solely attribute its cause to one factor in particular. However, Walter et al (1964) initially interpreted the CNV or "expectancy wave", in terms of expectancy; the relative certainty that the imperative stimulus will follow the warning stimulus. This is still the favoured interpretation. Extrapolating from event-related potentials (ERPs) to pupil dilation (because they both provide measures of neural processes associated with action), the pre-movement pupil dilation in the truncation conditions in chapter 4 could feasibly be due to the expectation of an imperative stimulus in addition to the intentional preparation. The results in the previous chapter (chapter 4, section 4.3.5.1) suggested that the pre-movement dilation was not due to expectation, but was not wholly conclusive. The pre-movement mean dilation and the RT cost of intention could therefore be attributable to the stimulus. Hence, it is important to try and exclude the factor of stimulus expectancy, or *whether or not* the stimulus occurs.

Richer et al (1983) concluded that the pre-movement processes occurring in SRT were not associated with the anticipation of the imperative stimulus. This was because the similarity between a simple reaction and an internally-generated pupillogram in terms of the time the pre-movement dilation started and the time the peak dilation occurred implies that the "slow dilation may primarily reflect response preparation" (Richer et al, 1983). The use of variable foreperiods, in this and previous experiments, rather than constant foreperiods, reduces the effect of expectancy and therefore, the likelihood that it is responsible for the pre-movement mean dilation. However, it is important to exclude expectancy if the RT cost of intention is being attributed to the preparation of an intentional action, that is, it is important to show that making an intentional action does not alter expectation. This means that if the RT cost of intention is being attributed to the preparation of an intentional action, and this is being indicated by the pre-movement mean dilation, it is important to verify that expectancy is not the cause.

5.1.2 Stimulus Expectancy and the RT Cost of Intention

If a stimulus requiring a response occurs very infrequently, for example in a Go/No Go paradigm (Richer and Beatty, 1987), the RT is longer than normal. In the experiment (discussed in chapter 4, section 4.1.2) performed by Richer and Beatty (1987), there were five conditions, three of which are relevant to this experiment. The SRT condition involved reacting with one response to all four tones; the Go/No Go condition involved reacting with one response to two of the tones and not reacting to the other two tones; and the double Go/No Go condition involved reacting with one response to one tone, another response to the second tone and not reacting to either of the other two tones. The median RTs for each condition were 273 ms (SRT), 406 ms

(Go/No Go) and 528 ms (double Go/No Go). These findings demonstrate that successive reduction of stimulus expectancy increases RT. Richer and Beatty (1987) also found that the peak dilation increased from SRT to Go/No Go and then to double Go/No Go. However, this may have been due to increased task complexity.

If the RT cost of intention is supposedly caused by processes occurring between the internally-generated and externally-triggered motor system, the longer RT found in the truncation condition must not be attributable to reduced stimulus expectancy. Therefore, the effect of stimulus expectancy must be eliminated.

5.1.3 Hypotheses

This experiment was designed to examine whether the RT cost of intention and the pre-movement dilation could be due to expectation of stimulus presentation. It is hypothesised that the pupil will not dilate due to expectation of the stimulus because (i) the foreperiods are variable, therefore, the time of the imperative (truncating) stimulus is unpredictable; (ii) the truncating stimulus does not always occur, and (iii) it is believed that intention is responsible for the pre-movement dilation in the truncation condition. It is also hypothesised that the RT cost of intention is not due to the reduced stimulus expectancy in the truncation condition.

The hypotheses were examined experimentally using an SRT condition in which there was a 50% chance that the stimulus would not be presented. This condition was compared with a normal SRT condition and a truncation condition.

5.2 METHOD

5.2.1 Subjects

Twelve subjects performed this experiment; six had previously done the experiment described in chapter 4 and six had not. The mean age of the six males and six females was 26.92 years (s.d. 4.01). All subjects were right-handed and had normal or corrected to normal vision using contact lenses. Subjects were asked not to wear glasses as the reflection interrupted pupil data collection. None of the subjects suffered from any known neurological disorder. Subjects were asked to refrain from smoking or drinking caffeinated drinks for two hours before the experiment.

5.2.2 Apparatus

The apparatus used was the same as that used in the experiment described in chapter 4 (section 4.2.2, Figure 4.1). Briefly, subjects fixated on a cross, their heads were stabilised by a chin and forehead rest, the camera measured the dilation of the right pupil and movements were made using the index finger of their right hand on a standard mouse with the roller ball removed.

5.2.3 Design and Procedure

All subjects performed the same sequence of practice trials: 5 trials of the SRT, 5 trials of the 50% SRT condition and 10 trials of the truncated right SRT condition (truncation condition). Subjects then performed three experimental blocks. These three blocks consisted of one block of 15 trials of the SRT condition, and two blocks totalling 30 trials of the truncation condition and two blocks totalling 30 trials of the 50% SRT condition. The conditions were counter-balanced. The single within subjects factor was condition (SRT, 50% and truncation); and the dependent variables were: RT and pupil dilation, which are behavioural and physiological measures, respectively.

5.2.3.1 SRT condition

The SRT condition involved the subject being presented with a warning stimulus which was the experimenter's voice saying "Blink, Fixate, OK," followed by a computer-generated beep between 2 and 10 seconds after the trial was activated. Subjects were instructed to respond as quickly as possible with a right key press.

5.2.3.2 50% SRT condition

The 50% SRT condition was very similar to the SRT condition except that 50% of the time no stimulus was presented. Therefore, 50% of the trials would be the same as the SRT condition (post-movement dilation) and the other 50% should show no dilation if, as predicted, expectation does not cause dilation.

5.2.3.3 Truncation condition

The truncation condition involved the presentation of the same warning stimulus described in section 5.2.3.1 for the SRT condition. Then, subjects were instructed to prepare to make a right intentional key press, with the possibility that this preparation might be interrupted with a beep to which they were instructed to react with the same movement that they were preparing, that is a right intentional key press. Thus, two types of trials arose from this condition: right intentional key presses where the subject moved before the presentation of the truncating beep; and truncated reactions where subjects reacted to the stimulus before they had made the intentional movement.

5.3 RESULTS

5.3.1 Reaction Time Analyses

Similar to the previous experiments, only the trials with the trimmed RT data are presented in Table 5.1. A total of 12% of the trials were not included due to the RT criterion (150-1000 ms), the pupil dilation criterion (as in chapter 4, section 4.3.2, also section 5.2.3) and subject error. Of the remaining trimmed trials, 58% of the trials in the 50% SRT condition were reactive trials, that is, where the imperative stimulus occurred (50% SRT); and 64% of the trials in the truncation condition were reactive trials (TRT).

Table 5.1. Mean (s.d.) RT for the SRT condition, the 50% SRT condition and the reactive trials from the truncation condition (TRT), in ms.

CONDITION	Mean (s.d.)
SRT	309 (93.0)
50% SRT	351 (97.5)
TRT	337 (106.3)

As expected, the RT was shortest for the SRT. However, the RT for the TRT was shorter than the RT for the 50% SRT condition. Although the RTs were longer in the TRT than in the SRT, they were both shorter than those found in the experiment in chapter 4 (section 4.3.1).

The comparison of SRT and TRT yielded non significant results ($t_{(11)} = 1.68$, $p = 0.12$, uncorrected) even though there was a clear difference in the predicted direction with longer RTs in the truncation condition. The RT cost of intention was 337-309 = 28 ms.

Although the difference in RT between SRT and TRT is non significant, the RT cost in the predicted direction was still found to be present. This may be due to reduced stimulus expectancy, however, one cannot be certain since this is dependent on the subject. This therefore suggests a subtle interaction between intention, the endogenous, subject-controlled aspect and reactivity, the exogenous component, which could be further researched. Models of expectancy where the probability depends on the subject and not on the external environment as yet appear not to have been produced.

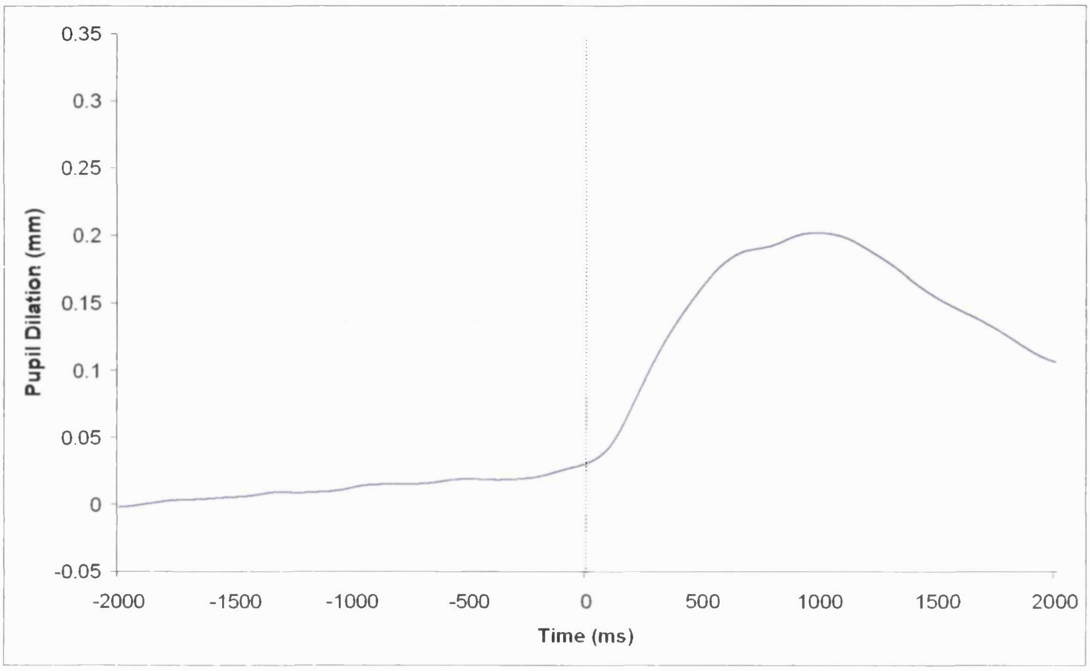
The comparison between the 50% SRT condition and the SRT condition showed a highly significant difference ($t_{(11)} = 3.47$, $p = 0.005$, uncorrected). The comparison between the 50% SRT condition and TRT was non significant ($t_{(11)} = 1.15$, $p = 0.27$, uncorrected).

5.3.2 Pupil Analyses

The pupil data was treated to the same trimming and averaging procedures as in the previous experiment (chapter 4, section 4.3.2). Briefly, the blinks were interpolated, and the trials with RTs outside the range 150-1000 ms, 3 or more blinks, long blinks, hippus and/or pre-movement dilation of less than 2000 ms were discarded. The trials were movement-locked, producing epochs of -2000 to 2000 ms around the event (movement), baseline-corrected, and smoothed. The peak dilation (mm), latency of peak dilation (ms) and pre-movement mean dilation (mm) were calculated for each condition for each subject, and the grand averages were calculated for graphical display. Figures 5.1 to 5.4 are movement-locked, which means that 0 equals the time of the action or reaction.

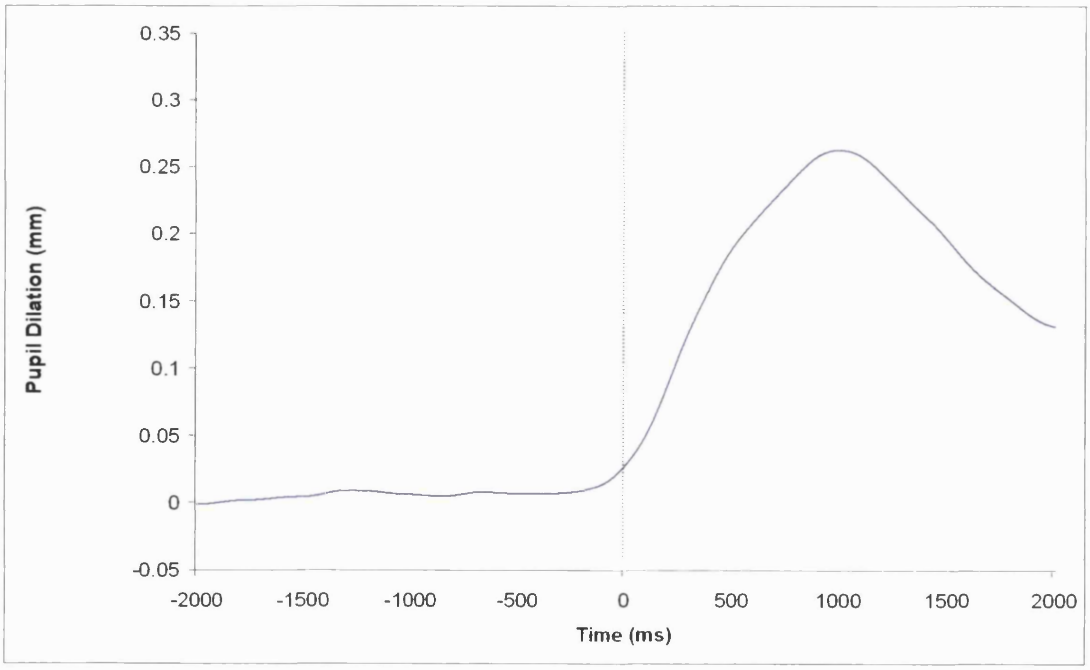
Figure 5.1, the SRT graph, shows a similar pattern of dilation as seen in the previous experiment (section 4.3.2, Figure 4.3), with almost no pre-movement mean dilation (0.01 mm), and peak dilation occurring at approximately 1000 ms post-movement.

Figure 5.1. SRT condition: movement-locked. 0 = time of movement.



The shape of the 50% SRT trials pupillogram, as shown in Figure 5.2, is similar to the SRT pupillogram, shown in Figure 5.1, with no pre-movement mean dilation, and larger peak dilation.

Figure 5.2. 50% SRT condition, reactive trials (50% SRT), movement-locked. 0 = time of movement.



In Figures 5.3 and 5.4, the TIN and TRT pupillograms resemble those from chapter 4 (section 4.3.2, Figures 4.6 and 4.5), with clear pre-movement mean dilation in both instances, and a steep increase at approximately -400 ms in TRT where the stimulus has been presented and the subject is reacting.

Figure 5.3. Truncation condition, intentional action trials (TIN), movement-locked. 0 = time of movement.

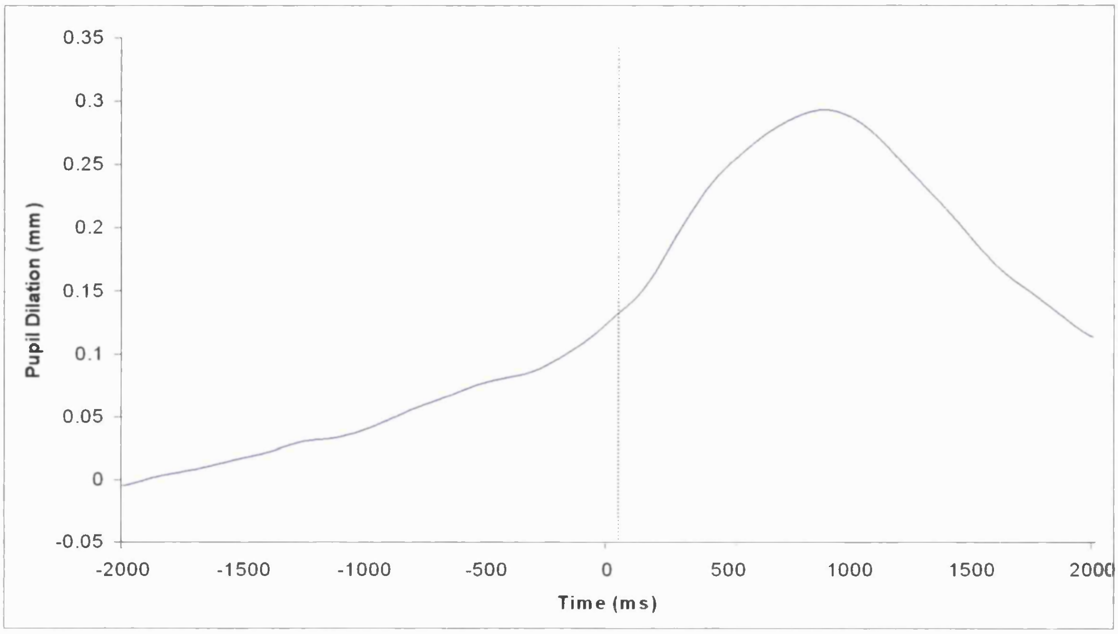


Figure 5.4. Truncation condition, reactive trials (TRT), movement-locked. 0 = time of movement.

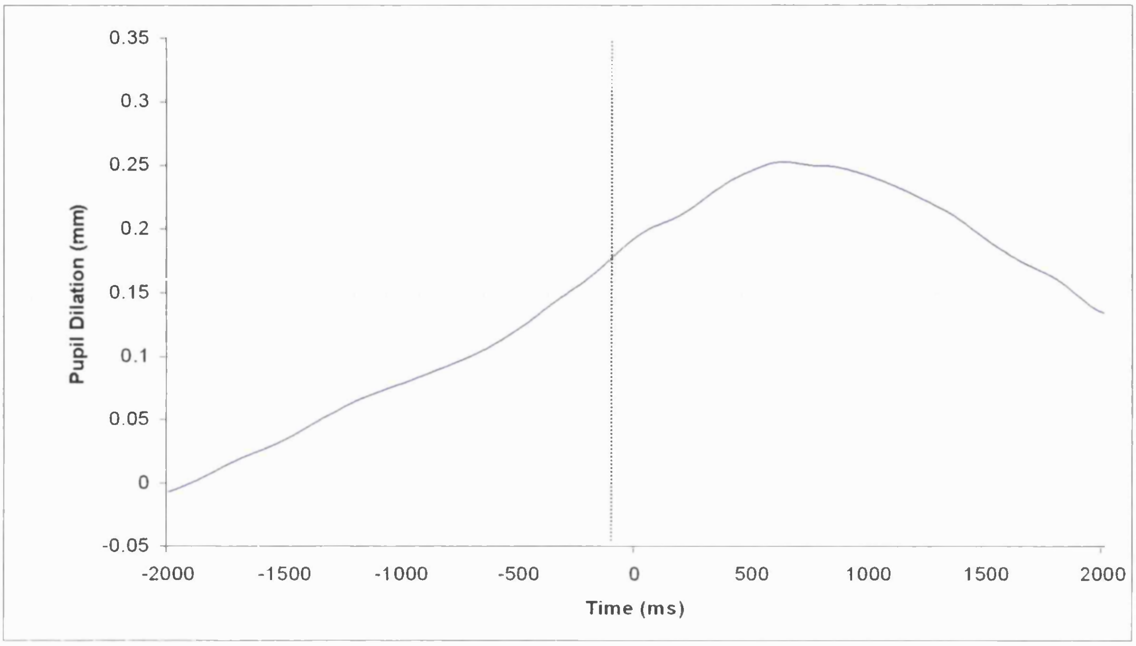


Table 5.2. The means (s.d.) of the peak, latency of peak and pre-movement mean dilation for the SRT, 50% SRT, truncated reactive trials (TRT) and truncated intentional trials (TIN).

CONDITIONS	PEAK (MM)	LATENCY (MS)	PMMD (MM)
SRT	0.23 (0.08)	925 (219)	0.02 (0.03)
50% SRT	0.29 (0.11)	953 (215)	0.01 (0.02)
TRT	0.34 (0.13)	870 (213)	0.06 (0.04)
TIN	0.29 (0.11)	918 (323)	0.08 (0.04)

The following sections (5.3.2.1 to 5.3.2.4) include the results and brief discussion of the four planned comparisons: SRT versus TRT, SRT versus 50% SRT, 50% SRT versus TRT and TRT versus TIN for three features of comparison: peak dilation, latency of peak dilation and the pre-movement mean dilation, which are presented in Table 5.2. Chapter 4, section 4.3.2 describes reasons for features of analyses.

5.3.2.1 SRT versus TRT

A significant difference was found between the peak dilations of the SRT and TRT conditions ($t_{(11)} = 5.34$, $p = 0.0002$, uncorrected), similar to the experiment in chapter 4 (section 4.3.2.1). This suggests that it is more effortful to react, following intentional preparation, compared with simply reacting alone. Again, a non significant difference was found between the latency of the peak dilations ($t_{(11)} = 0.88$,

$p = 0.40$, uncorrected). However, the earlier latency of 870 ms was found in the TRT, not in the SRT, implying that the stimulus is not processed significantly more slowly in the TRT compared with the SRT. A significantly larger pre-movement mean dilation was found in the TRT compared with the SRT ($t_{(11)} = 2.87$, $p = 0.015$, uncorrected), supporting the finding from the experiment in chapter 4 that subjects did prepare an intentional action at the start of each truncation trial. This finding was expected and the pre-movement mean dilation in TRT reflects the smeared preparations for the interrupted intentional actions.

5.3.2.2 SRT versus 50% SRT

The only significant difference found between SRT and 50% SRT was in the peak dilations ($t_{(11)} = 3.04$, $p = 0.0112$, uncorrected). The larger peak dilation in 50% SRT suggests that uncertainty over stimulus presentation, that is reduced stimulus expectancy, affects the amplitude of the dilation, presumably because the stimulus is more surprising in the 50% SRT condition. However, the non significant differences found between SRT and 50% SRT in latency and pre-movement mean dilation,($t_{(11)} = 0.52$, $p = 0.61$, uncorrected and $t_{(11)} = 1.01$, $p = 0.33$, uncorrected, respectively) imply that reduced stimulus expectancy affects neither the timing of the stimulus-driven processes nor the pre-movement processes.

5.3.2.3 TRT versus 50% SRT

The peak and pre-movement mean dilations were both significantly larger in the TRT than in the 50% SRT ($t_{(11)} = 2.54$, $p = 0.027$, uncorrected and $t_{(11)} = 3.49$, $p = 0.0051$, uncorrected, respectively). The larger pre-movement mean dilation in TRT was expected (as in section 5.3.2.1). The higher peak dilation in TRT implies that the effect of switching from intention to reaction in the truncation condition involves an additional cognitive process over and above processing an unexpected stimulus. Therefore, the pre-movement mean dilation is unlikely to be due to expectation, but rather due to intention, and the peak amplitude is more likely to be due to switching between movements rather than processing an unexpected stimulus. The latencies of the peak dilations were non significant ($t_{(11)} = 1.34$, $p = 0.21$, uncorrected) suggesting that timing of the stimulus driven processes are similar.

5.3.2.4 TRT versus TIN

There were non significant differences in peak and latency of the peak dilations between the TRT and the TIN ($t_{(11)} = 1.35$, $p = 0.20$, uncorrected and $t_{(11)} = 0.54$, $p = 0.60$, uncorrected, respectively). This finding differs from experiment 4 (chapter 4, section 4.3.2.4) whereby a significant difference was found between the peak dilations of TRT and TIN. However, the peak dilation was larger in TRT, and therefore, the trend was expected. The pattern of the latency of the peak dilation was opposite to that found in chapter 4 where the peak dilation was earlier in TIN. The highly significant difference found between TRT and TIN in pre-movement mean dilation ($t_{(11)} = 4.35$, $p = 0.0012$, uncorrected) suggests that the subject switches from intentional action preparation to reaction in TRT, which results in the dilation stopping as the subject reacts.

5.3.3 Stimulus-locked Analyses

The trials were re-averaged, locking the trials to the stimulus, rather than the movement, that is 0 equals the stimulus, following the same procedure detailed in chapter 4 (section 4.3.2) and noted in section 5.3.2. Stimulus-locked analyses were carried out to see if there were any specific effects due to stimulus processing. Figures 5.5, 5.6 and 5.8 are grand average traces locked to the time of the stimulus (in each trial). Figure 5.7 displays the grand average of the 50% SRT condition trials in which no imperative stimulus occurred and no reaction occurred. These trials were, therefore, locked to the middle of the foreperiod (6000 ms), that is, the median time that the stimulus would have occurred, had it occurred.

The stimulus-locked Figures 5.5, 5.6 and 5.8, all resemble the movement-locked Figures from the previous section (5.3.2), shifted to the right by the mean RT (overall approximately 330 ms).

Figure 5.5. SRT condition, stimulus-locked. 0 = imperative auditory stimulus onset.

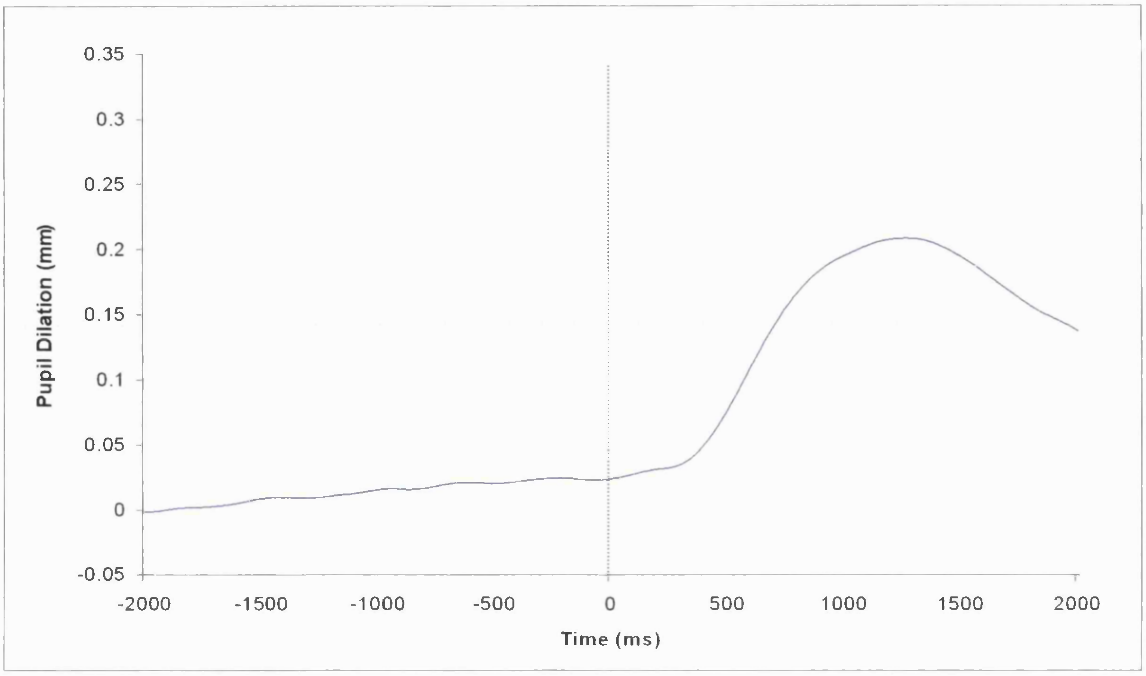


Figure 5.6. 50% SRT condition, reactive trials, (50% SRT), stimulus-locked. 0 = imperative auditory stimulus onset.

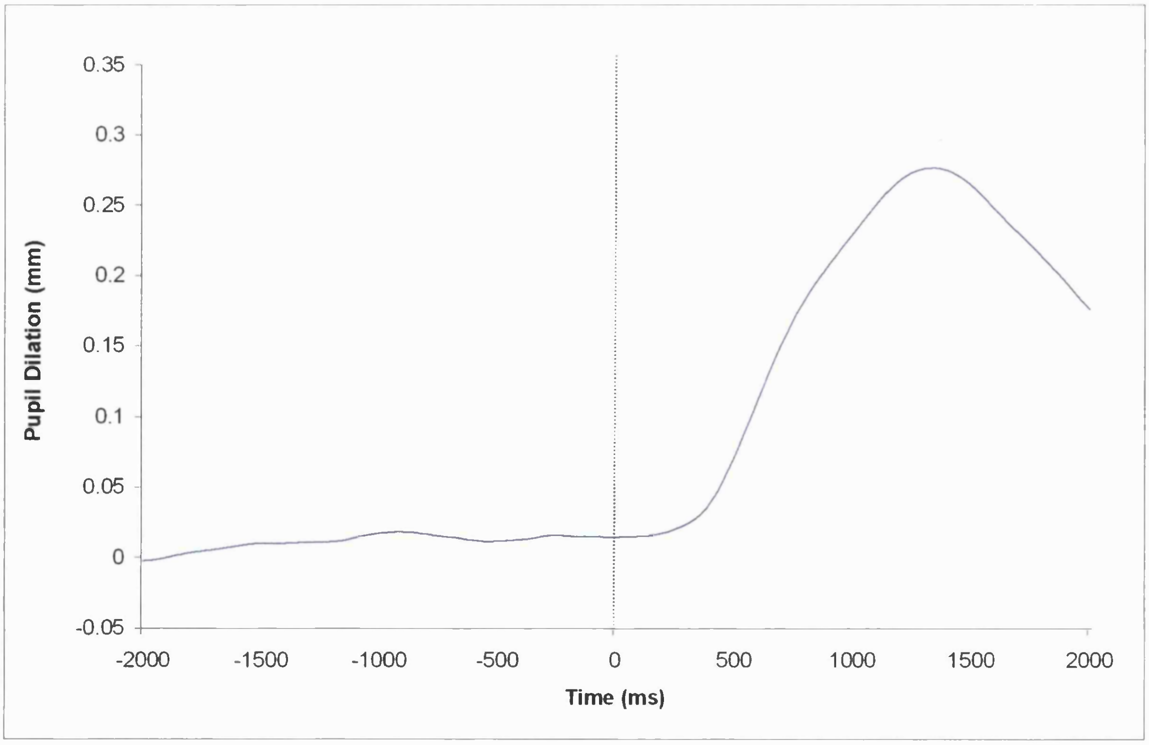


Figure 5.7. 50% SRT condition, no stimulus or movement trials (50% no SRT), median foreperiod-locked. 0 = median foreperiod.

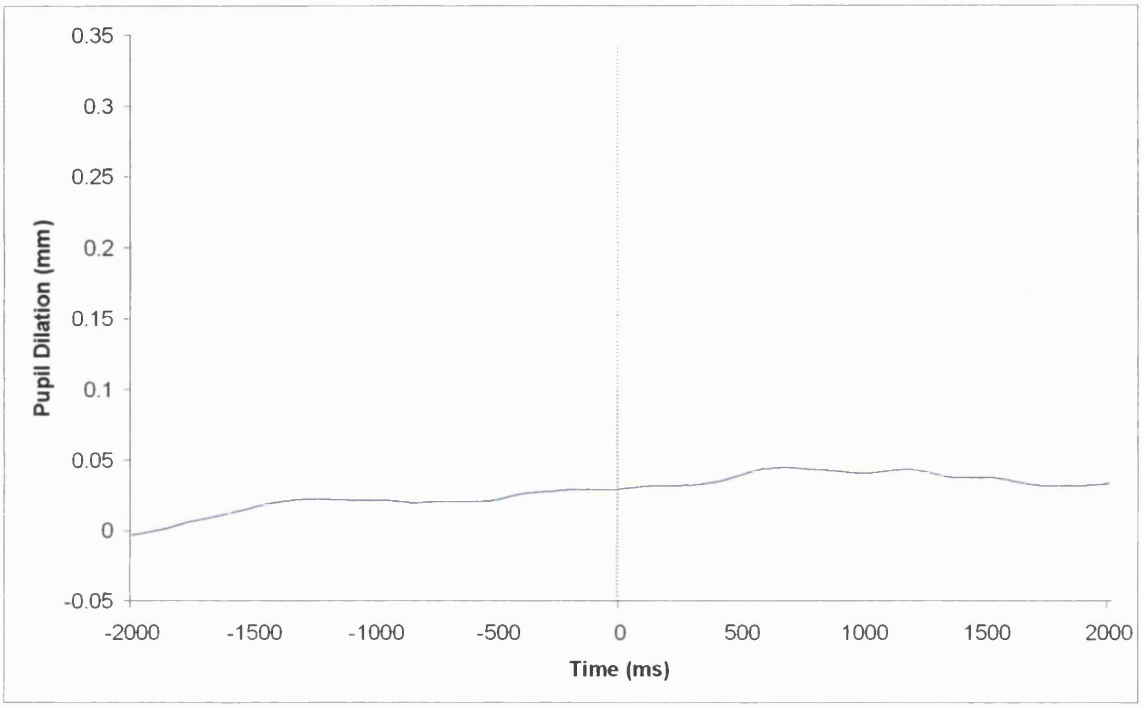


Figure 5.8. Truncation condition, reactive trials (TRT), stimulus-locked. 0 = imperative auditory stimulus onset.

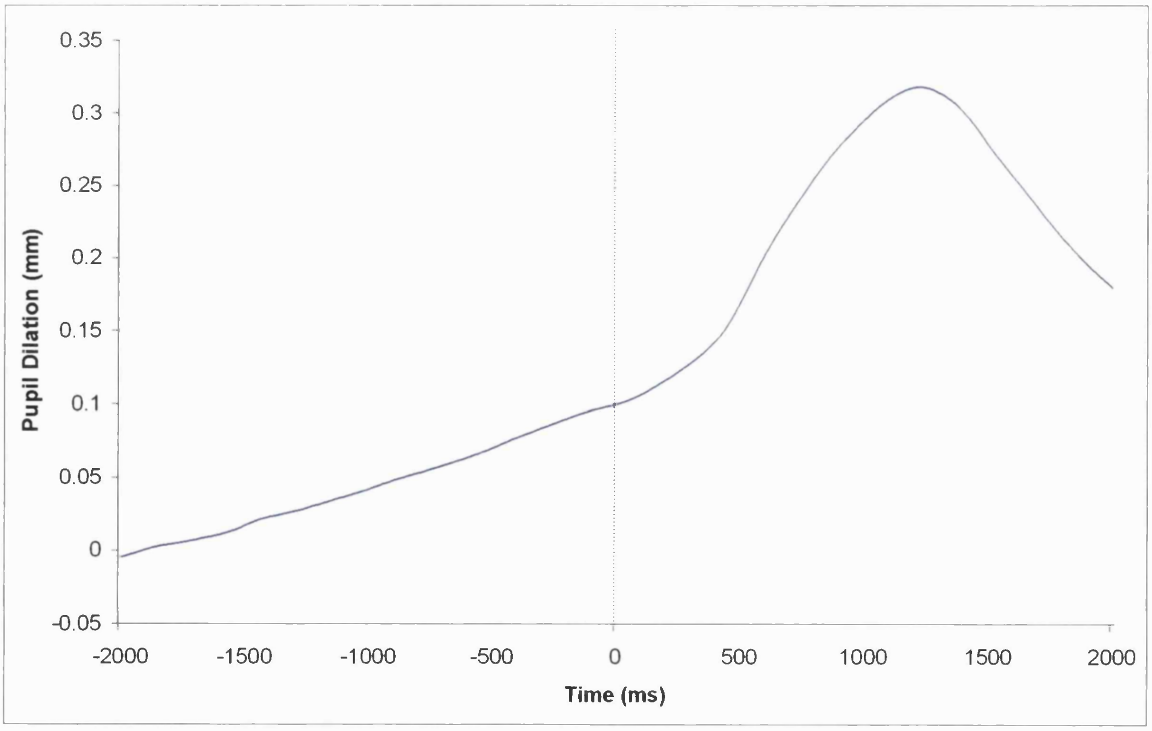


Figure 5.7 (50% no SRT, demonstrates that when there was no stimulus, there was no dilation. This is markedly different from Figure 5.6, 50% SRT, which showed the grand averages for the other type of trial that arose in that condition. That is, when subjects might have to make a reaction to a stimulus and do not, there is no dilation. Therefore, based on the lack of marked pre-movement dilation in SRT and no dilation in 50% no SRT, it seems unlikely that stimulus expectancy affects pupil dilation.

The means and standard deviations of the peak, latency of the peak and the pre-stimulus mean dilations are tabulated below for SRT, 50% SRT and TRT. The planned comparisons between SRT and TRT, SRT and 50% SRT, and TRT and 50% SRT for the three calculated features of the data are presented in sections 5.3.3.1 to 5.3.3.3.

Table 5.3. The means (s.d.) of the peak, latency of the peak and pre-stimulus mean dilation (PSMD) for SRT, 50% SRT and TRT.

CONDITIONS	PEAK (MM^2)	LATENCY (MS)	PSMD (MM^2)
SRT	0.23 (0.08)	1230 (208)	0.02 (0.03)
50% SRT	0.29 (0.11)	1273 (181)	0.01 (0.02)
TRT	0.34 (0.13)	1198 (192)	0.06 (0.04)

5.3.3.1 SRT versus TRT

The pattern of significance between SRT and TRT for peak, latency of peak and pre-stimulus mean dilation was identical to that found in the movement-locked analyses; significant differences in peak ($t_{(11)} = 6.05$, $p < 0.0001$, uncorrected) and in pre-stimulus mean dilation ($t_{(11)} = 3.90$, $p = 0.0025$, uncorrected) and a non significant difference in latency ($t_{(11)} = 0.53$, $p = 0.61$, uncorrected).

5.3.3.2 SRT versus 50% SRT

The significant difference between SRT and 50% SRT in peak dilation ($t_{(11)} = 3.36$, $p = 0.0063$, uncorrected) and the non significant differences in latency of the peak and pre-stimulus mean dilation ($t_{(11)} = 0.69$, $p = 0.51$, uncorrected and $t_{(11)} = 0.49$, $p = 0.63$, uncorrected, respectively) mirrors the movement-locked analyses.

5.3.3.3 TRT versus 50% SRT

As in sections 5.3.3.1 and 5.3.3.2, the pattern of significant differences in peak dilation ($t_{(11)} = 2.87$, $p = 0.015$, uncorrected) and pre-stimulus mean dilation ($t_{(11)} = 4.06$, $p = 0.0019$, uncorrected) and non significant difference in latency of peak dilation ($t_{(11)} = 1.34$, $p = 0.21$, uncorrected) was the same as that found in the movement-locked analyses.

TIN and 50% no SRT were not considered in these analyses because in neither case could the trials be locked to a stimulus.

5.4 DISCUSSION

5.4.1 Stimulus Expectancy and Pupil Dilation

The grand average pupillogram of 50% no SRT (Figure 5.7) demonstrates that when subjects expect to hear a stimulus, but do not, changes in the pupil dilation are minimal. This suggests that expectation is not responsible for pre-movement dilation in the truncation condition. It would seem likely that the pre-movement dilation demonstrated in this experiment is due to intention.

The statistics also lend support to the suggestion that intention, not expectation is responsible for the dilation. If subjects were highly expectant, then it might be expected that they would react quickly to the stimulus. However, subjects react faster in the truncation condition than in the 50% reactive trials condition, suggesting that the subjects were possibly paying less attention to the stimulus in the 50% SRT condition than in the truncation condition, which would imply that, in the truncation condition, subjects are maintaining a vigilant awareness of the external environment so that when a stimulus occurs they react relatively quickly. In conclusion, therefore, the pre-movement dilation observed in the truncation condition (both TIN and TRT) is unlikely to be due to expectation and is probably the result of intentional preparation.

5.4.2 Stimulus Expectancy and RT cost of Intention

Decreased expectancy increases RT, as demonstrated by the significantly longer RT found in 50% SRT compared with SRT. However, it is not clear how the requirement for making an intentional action in the truncation condition modulates the subjective expectancy of the stimulus. In one sense, the subjective expectancy of the imperative stimulus in the truncation condition is higher than that in the 50% SRT condition. This is because the *a priori* probability of the stimulus occurring when a truncation trial starts is 1. The stimulus is programmed to occur on every trial and would do so, if the subject's intentional action did not result in the termination of a proportion of the trials before the stimulus occurred. The relationship between stimulus probability and RT has been extensively studied and modelled (e.g. Welford, 1968). However, these models are not directly applicable to the truncation condition where the imperative stimulus occurrence is under the control of the subject. That is, the occurrence of the imperative stimulus is contingent upon whether or not the subject makes an intentional action. Future research might examine this situation.

The RT cost of intention (28 ms) in this experiment was lower that in previous experiments, and did not reach the conventional level of significance. Interestingly, the 28 ms RT cost of intention was actually lower that the RT cost of low stimulus expectancy (50% SRT - SRT = 42 ms) in this experiment. This implies that the RT cost of intention is not simply reflecting some change in signal detection parameters resulting from subjects observing that the *a posteriori* probability of the stimulus occurring in TRT is less than 100% (and is probably closer to ½[1]). That is, if the RT cost of intention was simply a cost of stimulus expectancy, then two factors which delay RTs should be introduced in the truncation condition; these are (i) the reduced expectancy of the imperative stimulus; and (ii) the prior intention to make the intentional action. The 50% SRT condition, in contrast, would only incur the stimulus expectancy cost (and not the intention cost), and would therefore produce faster RTs than in the truncation condition, but slower than the conventional SRT condition. This was not found to be the case — the 50% RT condition had *slower* RTs than the

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[1] The *a posteriori* probability is ½ because at the end of each trial one of two events occurred: either the intentional action or the truncated reaction.

truncation condition. This finding is incompatible with the proposal that the RT cost of intention is an artefact of stimulus expectancy.

In conclusion, therefore, the RT cost of intention is probably attributable to the processes occurring when a subject switches from the internally-generated to the externally-triggered motor system, and is not an artefact of stimulus expectancy.

The next chapter in this thesis utilises electrophysiological measures to examine the difference in stimulus processing between SRT and TRT, in an attempt to qualitatively define the processes contributing to the RT cost of intention.

Chapter 6

IS THE STIMULUS PROCESSING DELAYED IN THE TRUNCATION CONDITION? FURTHER EXAMINATION OF THE COMPONENTS OF THE TRUNCATION CONDITION AND CONTRIBUTORS TO THE RT COST OF INTENTION.

6.1 INTRODUCTION

The previous experiments in this thesis indicated that subjects react more slowly to the truncating stimulus than to the same auditory or visual stimulus in a simple reaction time condition. It has been suggested that this delay is due to intention; the intentional preparation interferes with the reaction to the truncating stimulus, thus an RT cost of intention is incurred. However, the delay in reacting to the truncating stimulus might be due to delayed processing of the imperative stimulus. Previous analyses of pupil dilation data found little evidence for this view, but the time resolution of pupil dilation is relatively slow, and may therefore be inefficient to address the question. This experiment aims to investigate whether the longer RT in the truncation condition might be due to slower stimulus processing.

An independent measure of the speed of stimulus processing, over and above RT, might shed some light on this issue. An effective methodology to examine the time course of stimulus processing and to compare it between conditions is electroencephalography (EEG). EEG measures the electrical activity and the event-related potentials (ERP) from the scalp via electrodes. In a task such as truncation, both movement-related and stimulus-related components can be measured.

The most relevant motor potential is the bereitschaftspotential (BP). The BP is a slow negative potential, which begins up to 2 seconds prior to an intentional action (chapter 1, section 1.5.1). The most relevant stimulus potential is the auditory-evoked potential. This chapter focuses primarily on the stimulus-related potentials due to the main hypothesis being concerned with stimulus processing in the truncation condition.

EEG as a technique has good temporal resolution, which means that it is highly suited to researching the timing aspects of the truncation condition. The ERP approach also allows the investigation of the processing of stimuli that do not require any overt behavioural response (Schröger and Eimer, 1997).

There are a number of different waveform features that are associated with the processing of auditory stimuli, three of which are of interest in this experiment. The first major auditory-evoked potential is the first *negative* potential (N1). Attended auditory stimuli elicit: (i) an enhanced negativity at around 100-200 ms after the stimulus has occurred, which has been called processing negativity (PN), (Schröger, 1993); and (ii) a positive wave at approximately 90-100 ms, (Näätänen and Picton, 1987). Both the PN and the positive wave have been considered to be part of the N1 (Näätänen and Picton, 1987).

There is some controversy over whether the PN (or negative difference, Nd; a waveform of the difference between the attended and unattended stimuli) is in fact a distinct process or is the result of increased activity of the cerebral sources responsible for generating the N1 (Näätänen, 1988). The PN appears to reflect modality-specific processing (Näätänen, 1982) or a process of matching the sensory input and the neuronal representation of the relevant stimulus (an "attentional trace"), (Näätänen, 1982, 1985). However, Näätänen (1988) observed that it is problematic to interpret this enhancement in terms of qualitatively or quantitatively improved information processing.

The first two peaks of interest in this chapter are the P1, which will be identified in this chapter as the P80 (where 80 = time in ms), based on Schröger and Eimer (1993), and Näätänen and Picton (1987); and the N1, which will be called the N150 (where 150 = time in ms, post-stimulus onset), based on Spencer and Polich (1999); and Schröger (1993).

The third peak of interest is the P300 waveform, which generally peaks around 250-400 ms (Spencer and Polich, 1999). The P300 is influenced by attention, task requirement and target stimulus probability (Spencer and Polich, 1999). These factors are all relevant to this experiment, because: (i) the truncation condition (and others to be introduced) has a dual-task nature (chapter 4, section 4.1.3), (ii) the requirements of each task vary with some requiring a reaction or an action whilst others, require no movement at all; and (iii) the varied probability of the stimulus presentation in the truncation condition (chapter 5, section 5.4.2).

6.1.1 Introduction of New Experimental Conditions

A number of features make up the truncation condition: an intention, a possible truncating stimulus, and a movement that is a response to the truncating stimulus. To investigate the processing of a stimulus, it is important to vary these features, to try to establish the influence of each on the cause of the RT cost of intention. Fundamentally, is delayed stimulus processing or intentional preparation the reason for the longer RT found in the truncation condition?

The first logical condition to examine is one in which only a stimulus occurs. This condition, called *listen*, requires subjects to simply fixate on the fixation point and *listen* to the auditory stimulus. The stimulus in this condition is therefore task-irrelevant; subjects are not required to make any response to it.

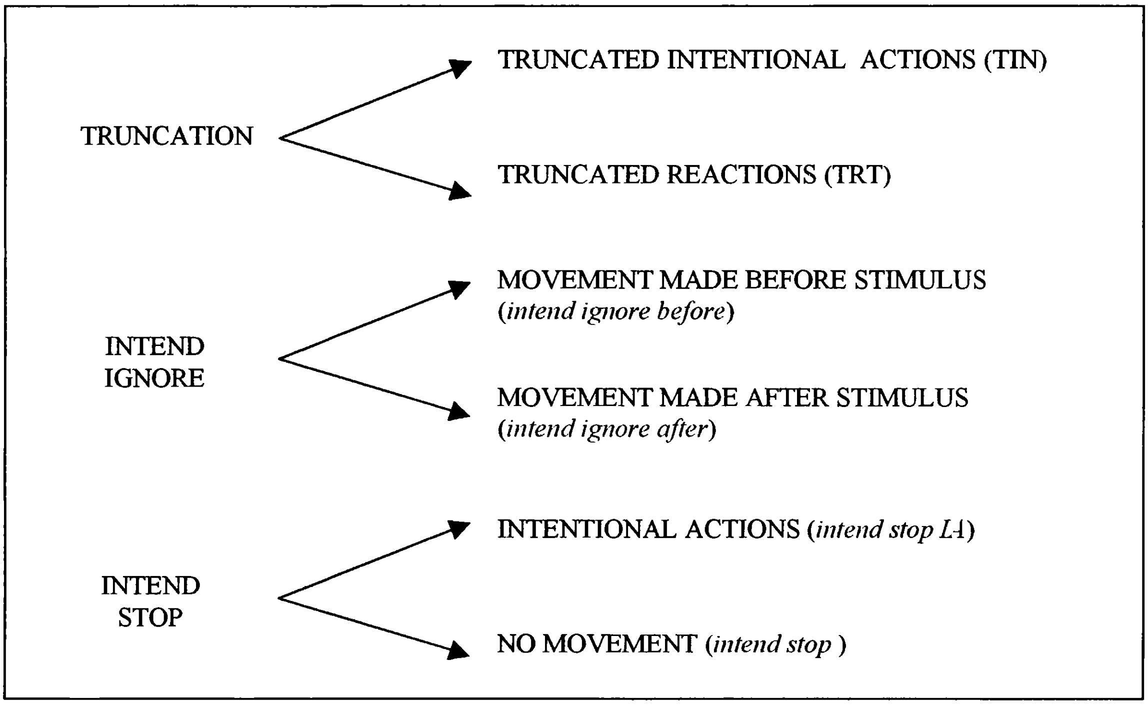
The second condition has featured in previous experiments and involves a stimulus and a reactive movement, the simple reaction time condition (SRT). The subject is randomly presented with a stimulus during the variable foreperiod and required to react immediately with their right hand. The SRT condition is predominantly used as a comparison for the truncation condition so that the effect of intentional preparation can be compared with the situation where no preparation occurs.

The next four conditions all include intention, and all require the subject to begin the trial by preparing an intentional action. The aim of these conditions is to manipulate what is intended and therefore, how intention interacts with other task components.

The third condition, the *intend* condition, requires subjects to prepare to make an intentional action at the time of their own choosing. This condition therefore, includes intention and a movement.

The next three conditions are schematised in Figure 6.1.

Figure 6.1. Schematic to show the forking of the Truncation, the *intend stop* and the *intend ignore* conditions and their names.



The truncation condition is the fourth condition to be used in this experiment and has been explained in previous chapters (e.g. section 2.1.3). Briefly, the subjects start by preparing an intentional action. Two possible outcomes may occur, either an intentional action, consisting of an intention and a movement (but no reaction), or a truncated reaction (TRT), consisting of an intention, a stimulus and a reactive movement. The truncation condition remains the main focus of interest; the other conditions are designed to contain subsets of the processes occurring in truncation.

The fifth condition includes a possible stimulus, an intention and a movement. The subject prepares an intentional action and makes a movement. If a random stimulus occurs, the subject is instructed to ignore it and continue with the planned intentional action. Two possible trial outcomes can occur in this condition, either the subject makes an intentional action before the stimulus occurred, or the subject makes the intentional action after, but not in response to, the stimulus. This condition, called *intend ignore*, therefore, modulates the stimulus processing by not requiring subjects to produce a response, overt or otherwise, to the stimulus. This condition also serves as an attentional control, in that, if intention attenuates stimulus processing, then *intend ignore* ERPs should be smaller and/or later than *listen*.

The sixth condition requires the subject to start the trial by preparing an intentional action. Either the subject makes the planned intentional action, in which case the outcome includes intention and movement, or a stimulus occurs. If a stimulus occurs, the subject is requested not to make the intentional action, that is, to suppress it, in which case the trial outcome includes intention (and suppression). Therefore, the subject does not react overtly to the stimulus. This condition partly resembles the truncation condition, at least if a switching account of truncation is assumed. If the RT cost of intention reflects the time to switch from intention to reaction, then *intend stop* resembles the switching off of the intention without the switching on of the reaction. The truncation condition ERPs will be compared with this condition to see if suppressing an intentional action, and then activating a reaction is similar to simply suppressing the intention. The *intend stop* condition can also be compared with the *listen* condition to investigate the effect of intention on processing a task-irrelevant stimulus.

6.1.2 Switching or Inhibition

The data produced in this experiment can be analysed to further clarify the two hypotheses that have been proposed as the possible cause of the RT cost of intention. In the experiments in chapters 2, 3, 4 and 5 it was shown that facilitation, unitary systems and competition for resources were unlikely to be the cause of the RT cost of intention. However, it was not ascertained whether switching or inhibition was the most likely case.

The muscular activity of the first dorsal interosseous (FDI), the muscle responsible for a right index finger button press, will be measured. The electromyogram (EMG) data produced will provide a detailed profile of the movements. The SRT and *intend* EMGs will then be compared with TRT to ascertain whether the motor parameters of an intended but truncated intentional action are carried over into the reaction (TRT) or whether the planned intentional action is stopped, switched off and replaced by a reactive movement with quite different motor parameters. The former finding would rule out a switching hypothesis, since switching predicts that the motor parameters of TRT movements should be exactly like those of SRT movements. That is, reacting is the same regardless of whether it is in response to a stimulus or whether it is in response to a truncating stimulus.

The EMG data can only test a motor- or effector-based site of the inter-relation between the two hypothesised motor systems. However, previous experiments in this thesis have suggested that any interaction between the two motor systems is occurring at the action or brain level of the motor hierarchy. However, if the inhibitory hypothesis is to be supported by the EMG data, it would predict that the TRT would be smaller, or certainly no larger, than in SRT due to the hypothesised inhibition of the externally-triggered motor system by the internally-generated system.

6.1.3 Aims and Hypotheses

i. To ascertain whether the stimulus is processed more slowly in the truncation condition compared with the SRT condition, providing a possible explanation for the RT cost of intention.
ii. To ascertain the effect of listening to a stimulus compared to reacting to a stimulus, that is, the difference between task-relevant and task-irrelevant stimuli.
iii. To further examine processes that are occurring in truncation, by comparing *intend stop* with truncation. In both cases, the subject starts by preparing an intentional action and on hearing the stimulus, suppresses the intention or switches from intention to reaction. Therefore, if truncation first involves suppression of the intentional preparation and second activation of the reactive motor system, it might be expected that the truncation ERPs would be larger compared with *intend stop*, particularly in the later components which might reflect the reactivation of the externally-triggered motor system.
iv. To compare *listen* and *intend ignore after*, to ascertain the effect of intention on processing a task-irrelevant stimulus.
v. To examine the EMG data to try to decide between inhibition and switching as possible causes of the RT cost of intention.

6.2 METHOD

6.2.1 Subjects

All subjects were given an information sheet to read which made it clear that they could leave the experiment at any point if they wished. They were then asked to sign a consent form. Five male and seven female right-handed subjects participated in this experiment. The mean age of the twelve subjects was 23.83 years (s.d. 3.01). None of the subjects had any known neurological problems.

6.2.2 Apparatus

Two computers were used, one to run the behavioural tasks and collect the RT and trial information data and the other to collect the electrophysiological data. Subjects were seated in a comfortable chair that supported their neck to restrict movement and reduce muscle tension in the neck. They were instructed to fixate on a 3 cm cross approximately 60 cm from their eyes, to hold a response box in their lap with their right index finger resting above the button, and to remain totally still during each block.

Eight electrodes were attached to the subjects' scalps at 8 sites: F3, Fz, F4, C3, Cz, C4, P3 and P4 where F = frontal, C = central, P = parietal, even numbers (e.g. 3) = left side, z = central and odd numbers (e.g. 4) = right side. Two electrodes were attached to the right hand to record EMGs (the first dorsal interosseous muscle and the knuckle). Two electrodes were attached around the right eye to record electrooculograms (EOGs) so that trials with blinks could be removed from the data at the analysis stage. A reference electrode on the nose and a ground electrode on the left cheek were also attached. The EEG, EMG and EOG signals were calibrated, amplified and recorded continuously.

The subject's skin was cleaned with surgical spirit and cotton buds. The electrodes on the face and hand were attached with double-sided circular electrode stickers and the conducting electrode cream. The electrodes on the scalp were attached with adhesive conducting electrode cream.

Auditory stimuli were delivered binaurally from speakers situated symmetrically behind the subject's chair such that they were presented without lateralisation.

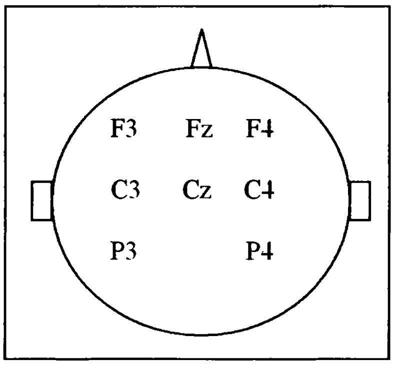
6.2.3 Procedure

The bipolar EMG electrodes were attached first because they take approximately 30 minutes to achieve sufficient connection to produce clear signals. The EMG of the first dorsal interosseous (FDI) muscle of the right hand was measured between an electrode over the belly of the muscle and a second one over the knuckle.

Eight silver-silver chloride electrodes were attached to the subjects' scalps using the 10-20 system (Figure 6.2). The eight scalp electrodes were referenced to the nose. The electrodes for measuring the EOG were attached diagonally across the right eye, which results in a combined horizontal and vertical EOG signal.

The bandwidth of the amplifiers was set to 0.03 - 40 Hz. The sampling rate was 208.33 Hz. Trials in which subjects blinked between 0.5 seconds before and 2 seconds after the response or the stimulus were not included in the analysis. Impedence for EEG electrodes was always below 5 KHz.

Figure 6.2. Schematic of the electrode sites.



6.2.4 Conditions

There were six conditions, which were ordered such that conditions with strongly conflicting instructions were not performed consecutively. Thus, the subjects never performed the truncation, *intend ignore* and *intend stop* conditions consecutively since the auditory stimulus required a totally different response in each of these conditions. The main reasoning for this is that the meaning of the beep could otherwise transfer between conditions and affect stimulus processing.

All conditions required subjects to be seated comfortably with their heads and necks stable. The response button was held in the lap. Subjects fixated on the cross. Each trial began with a pre-recorded version of the experimenter's voice saying "ready". In all trials including a stimulus, the pure tone (100 ms duration, 1KHz) occurred at random within a variable foreperiod of 2-10 seconds duration after the trial had begun. The next trial began 2 seconds after the completion of the previous one.

6.2.4.1 *Listen* condition

This condition was included for the purpose of collecting simple auditory ERPs. It provides a baseline condition to observe the passive brain processing of an auditory stimulus. Subjects were instructed to fixate on the cross and make no overt response to the stimulus. One block of 40 trials was run.

6.2.4.2 SRT condition

In this condition, the warning stimulus ("ready") signalled the start of the new trial. Subjects were instructed to react to the imperative stimulus, which occurred at random between 2-10 seconds after the trial onset, by pressing the button as fast as possible. One block consisting of 40 trials was performed.

6.2.4.3 *Intend* condition

In this condition, subjects were instructed to make intentional right keypresses, as and when they felt like it, after the warning stimulus had occurred. No imperative stimuli occurred in this block. Forty trials were carried out.

6.2.4.4 Truncation

This was similar to previous experiments. Subjects were instructed to wait for the warning stimulus, then to start to prepare an intentional right keypress at the time of their choosing. They were told that a beep might occur, during this preparational period, to which they must react as fast and as accurately as possible with the same movement as they were preparing. This should in principle result in approximately 50% of the trials being intentional actions (TIN) and 50% being reactions (TRT). Two consecutive blocks of 40 trials were performed.

6.2.4.5 *Intend ignore* condition

This condition required subjects to start preparing a right intentional button press as and when they felt like it, after the warning stimulus. If the stimulus occurred they were instructed to ignore it and continue with their planned right intentional key press. Two consecutive blocks of 40 trials were performed. Two types of trial arise, with an approximately 50-50% distribution: *intend ignore before*, where the subject moved before the stimulus and *intend ignore after*, where the subject moved after, but not in response to, the stimulus. These trials will be analysed separately.

6.2.4.6 *Intend stop* condition

Subjects were instructed to start preparing an intentional right button press as and when they felt like it, after the warning stimulus. However, if the beep occurred, they were to stop preparing the movement altogether and were not to press the response button. This condition, therefore, looked at the effort required to stop the movement, in the preparational stage. Eighty trials, in two consecutive blocks of 40 were carried out. Approximately 50% of the trials were intentional action trials (*intend stop IA*) and 50% should be stopped intentional actions (*intend stop*), where the stimulus had occurred.

6.3 RESULTS

6.3.1 Reaction Time Data

Following the trimming criterion and removal of trials based on the ERP criteria (sections 6.3.2.1 and 6.3.2.2), the mean (s.d.) reaction time for the SRT condition was 354 (100.50) ms and 417 (143.82) ms for the reactive trials from the truncation condition. These values were significantly different: $t_{(11)} = 3.45$, $p = 0.0062$, uncorrected. The RT cost of intention was, therefore, equal to 417-354 = 63 ms. These are similar findings to the previous experiments; subjects react more quickly when they have not been preparing an intentional action. 38% of the remaining trials were reactive (TRT).

6.3.2 EEG Data

The EEG data was processed in a number of stages, following established procedures.

6.3.2.1 First stage processing

There were three stages in this processing:

i. The audio channel containing the imperative stimulus and the EEG channel containing the subjects' response keypress were first analysed in a waveform editor (Spike 2, version 3; CED). The exact time of each auditory stimulus onset and of each keypress was calculated, producing stimulus-locked and movement-locked data.
ii. The EOG waveform data was examined to determine the amplitude of the EOG during typical blinks for each subject. These amplitudes were used to define upper and lower thresholds for rejecting data on EEG channels, to eliminate the possibility of blink artefacts. A conservative estimate was chosen, based on "small" blink traces. Artefact rejection was repeated for those conditions that had movements and stimuli, once locked to the movement and once locked to the stimulus (SRT, truncation, *intend ignore* and *intend stop*) and once for those conditions that had only movements (*intend*) and those which only had stimuli (*listen*). This stage of processing segmented the data into epochs of 'clean' ERP data around each auditory stimulus and around each movement.
iii. Erroneous trials involving subject error were manually deleted by placing cursors around the event and then deleting them. These trials had been marked during the experiment by the experimenter, for example when subjects reacted to the stimulus in the *intend stop* condition or the RT was outside of the range 150-1000 ms.

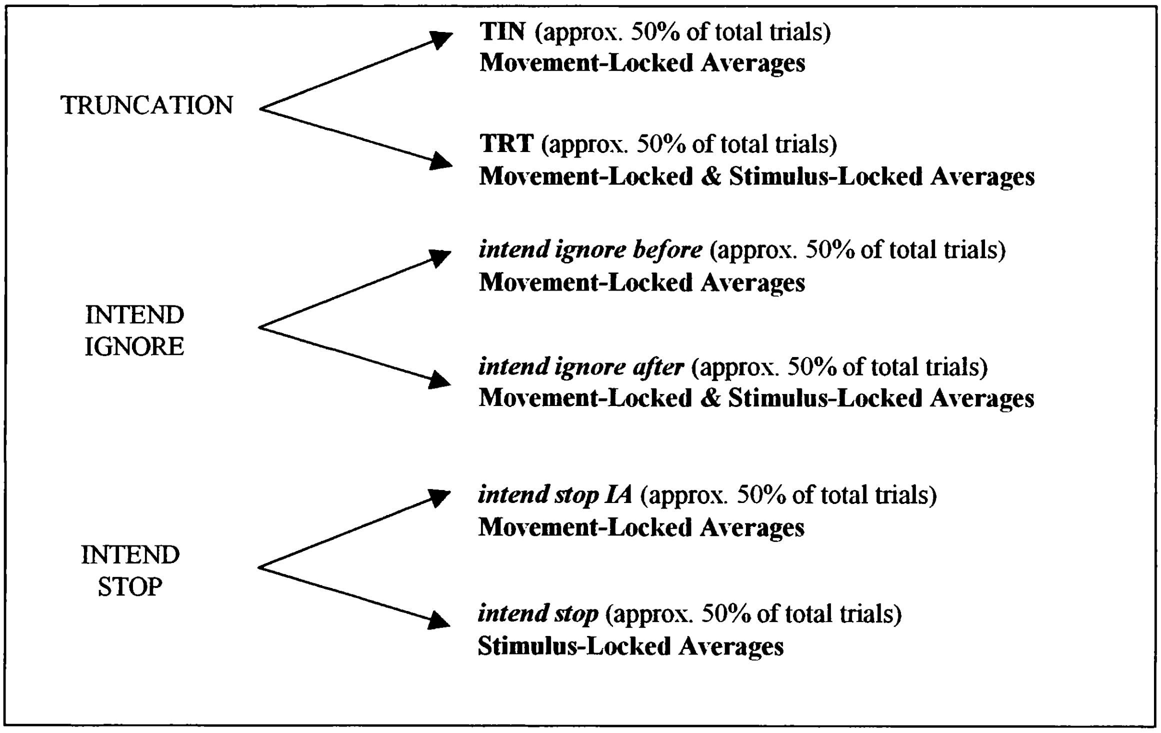
Further processing was performed in a vector manipulation software package (MATLAB).

6.3.2.2 MATLAB processing

In MATLAB, the data were subjected to further artefact rejection, called 'clipping'. Clipping occurs when the EEG wave goes outside of the -5 to 5 voltage range supported by the amplifier and is, therefore, not recording valid information. The data were then baseline-corrected and averaged twice, once with respect to the movement (movement-locked) and once with respect to the stimulus (stimulus-locked).

Movement-locked trials were averaged over a period of 1500 ms, -1000 ms before the movement and 500 ms after the movement, where 0 equals the time of the movement. These epochs were baseline-corrected (i.e. large fluctuations in overall EEG level were removed) by subtracting the mean value of the signal from 1000 to 800 ms before movement onset. The stimulus-locked trials were averaged over a 500 ms period, -100 ms pre-movement to 400 ms post-movement. These were baseline-corrected from -100 to 0 ms (where 0 equals the time of the imperative stimulus onset). This was done for each subject, for each electrode and for each relevant condition and its manipulations. Thus, conditions such as truncation and *intend stop*, which had two possible outcomes, were forked to produce averages of each trial type (Figure 6.3).

Figure 6.3. Schematic of forked outcomes for the truncation, *intend stop* and *intend ignore* conditions, indicating trial names and whether the trials produced are movement-locked and/or stimulus-locked.



The subjects' averages were then averaged to produce grand averages of all electrodes for all conditions and their manipulations. These are displayed below as electrode montages. 18.7% of the trials were rejected in total.

6.3.2.3 Stimulus-locked grand average montages

Figures 6.4 to 6.8 are stimulus-locked montages, which means 0 equals the time of the stimulus. Each Figure includes the EEG data from the eight scalp electrodes. The montages are presented in the hierarchical order as presented in the introduction (section 6.1.1), in which the action significance of the stimulus gradually increases, in the following order: *listen*, SRT, TRT, *intend ignore after*, *intend stop*. Inspection of Figures 6.4 to 6.8 shows that the general form and distribution of the ERPs is fairly consistent both across conditions and electrodes. The traces are nevertheless described in general terms first, with specific analyses of established components following later.

Figure 6.4. The grand average montage of the *listen* condition. Task-irrelevant or passive stimulus processing. 0 = imperative auditory stimulus onset.

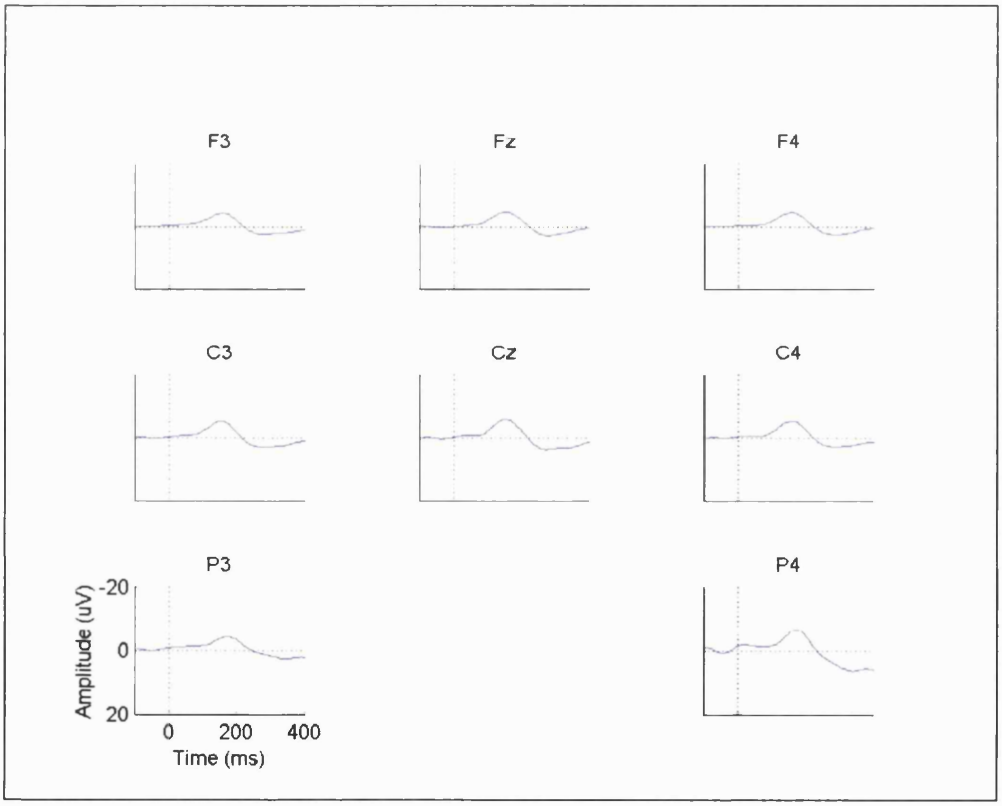


Figure 6.4 shows the grand average montages of the listen condition. The P80 waveforms are all very small in this condition. The N150 is largest at Cz. The P300 waveforms in this condition are also very small because there is no movement or other meaningful processing of the stimulus and therefore, no corresponding electrical activity. Figure 6.5 has three arrows to the three main waveforms.

Figure 6.5. The grand average montage of the SRT condition. Task-relevant or active stimulus processing, requiring a response. 0 = imperative auditory stimulus onset.

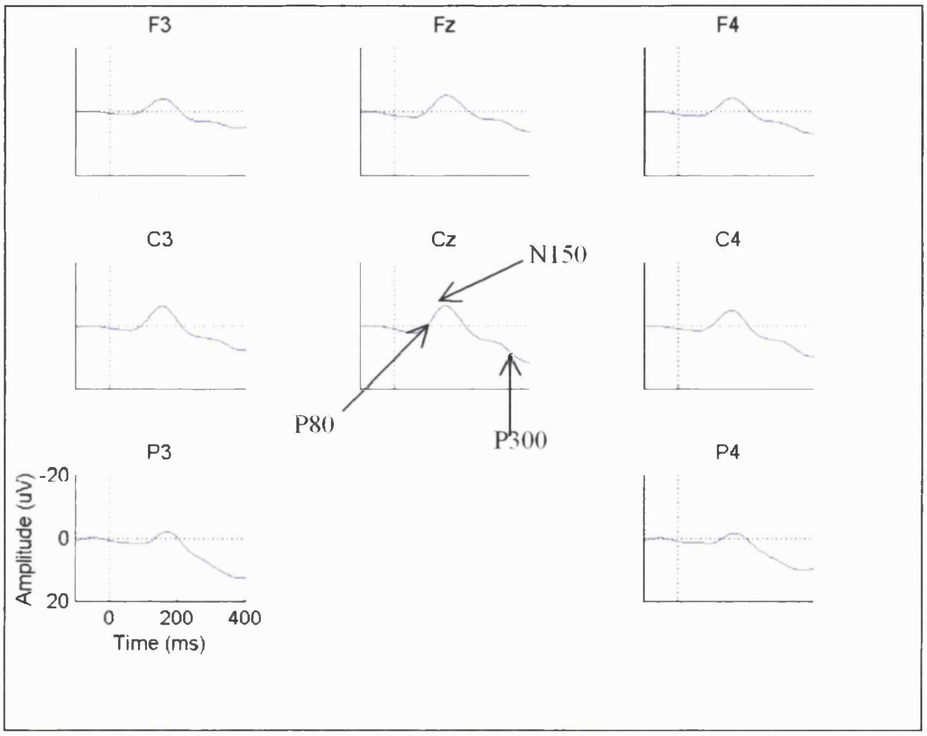


Figure 6.5 shows the grand average montages of the SRT condition. Overall, the ERPs are very similar in SRT to those found in the *listen* condition. However, the P80 is much more prominent, particularly at the central electrodes. The N150 is comparable to those found in *listen*. The P300 is clearly much larger and longer lasting (still continuing at 400 ms in most electrodes), which is probably due to the movement and possibly results in the larger post-movement positivity. The P80, N150 and P300 are all largest at the most central electrode, Cz.

Figure 6.6. The grand average montage of TRT. Task-relevant or active stimulus processing, requiring a response. 0 = imperative auditory stimulus onset.

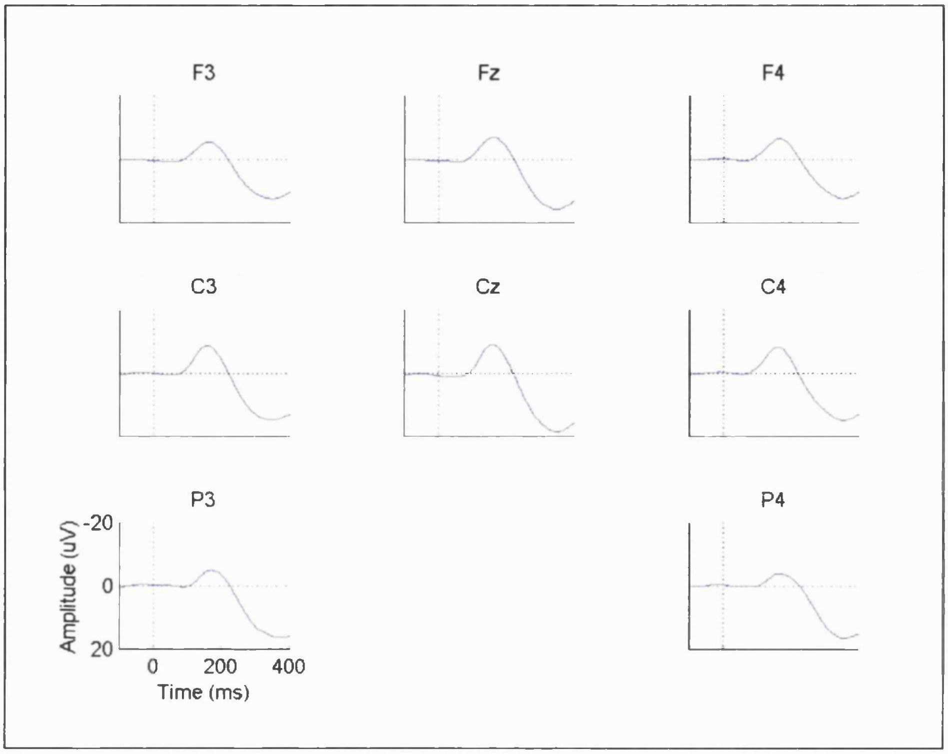


Figure 6.6 shows the grand average montages of the TRT condition. Overall the ERPs are quite similar to those found in SRT, although the P80 is clearly less visible in TRT. The N150 and P300 are much larger in TRT. The P300 seems to have finished by 400 ms in TRT, unlike SRT, where it is still occurring. The largest peak waveforms are seen in the central electrodes, particularly the P300 waveforms and the smallest are seen in the parietal electrodes. This marked difference in the size of the later waveforms (N150 and P300) suggests that reacting to a stimulus is affected by whether the subject is intending when the stimulus is presented, and that the effect is not manifested in the attentional stages of the stimulus processing.

Figure 6.7. The grand average montage of *intend ignore after*. Task-irrelevant stimulus, requiring a movement, but no overt response. 0 = imperative auditory stimulus onset. N.B. No subject 2 data included in P4 grand average and no subject 6 data for the Cz, due to electrode failure.

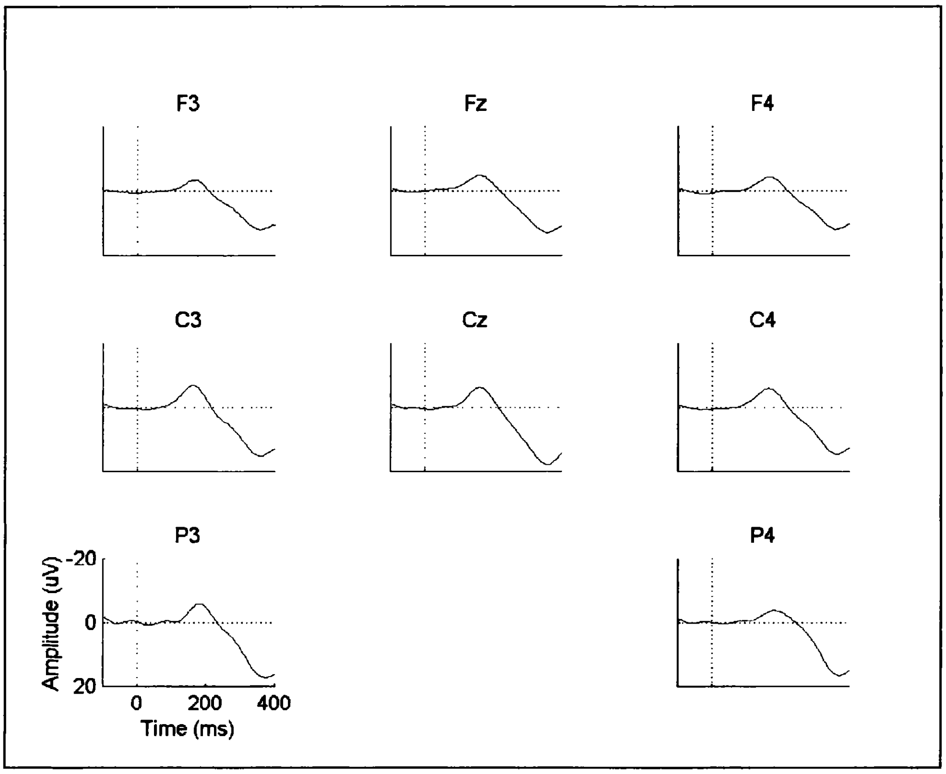


Figure 6.7 shows the grand average montages of the intend ignore after condition. Overall these ERPs are similar to those found in the *listen* condition, particularly the small P80 and comparable medium-sized N150 waveforms. The P300 waveforms are, however, much larger in this condition, particularly in the central and parietal electrodes, which is probably due to the movement. The P300 waveforms appear to be finished by 400 ms, similar to those found in the TRT ERPs. The ERPs are much larger for all waveforms at Cz.

Figure 6.8. The grand average montage of *intend stop*. Task-relevant stimulus, requiring no overt response. 0 = imperative auditory stimulus onset.

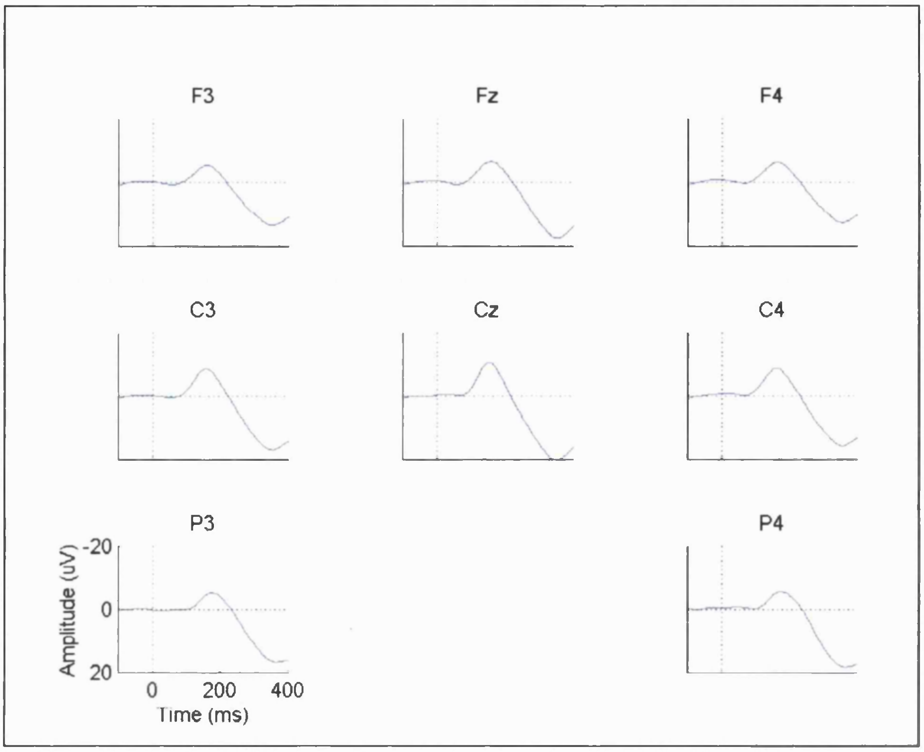


Figure 6.8 shows the grand average montages of the intend stop condition. Again these ERPs are similar to those found in the *listen* condition, particularly with the small P80 waveforms at all electrodes. The N150 waveforms are much larger than in *listen*, as are the P300. Similar to TRT and *intend ignore after*, the P300 waveforms are large and appear to be finishing by 400 ms. However, unlike TRT and *intend ignore after*, no overt response was required in *intend stop*; the occurrence of the stimulus necessitated a suppression of the intentional action. That is, suppressing an action in response to a stimulus is effortful, seemingly as effortful as reacting.

6.3.3 Statistical Analyses of Features of ERPs

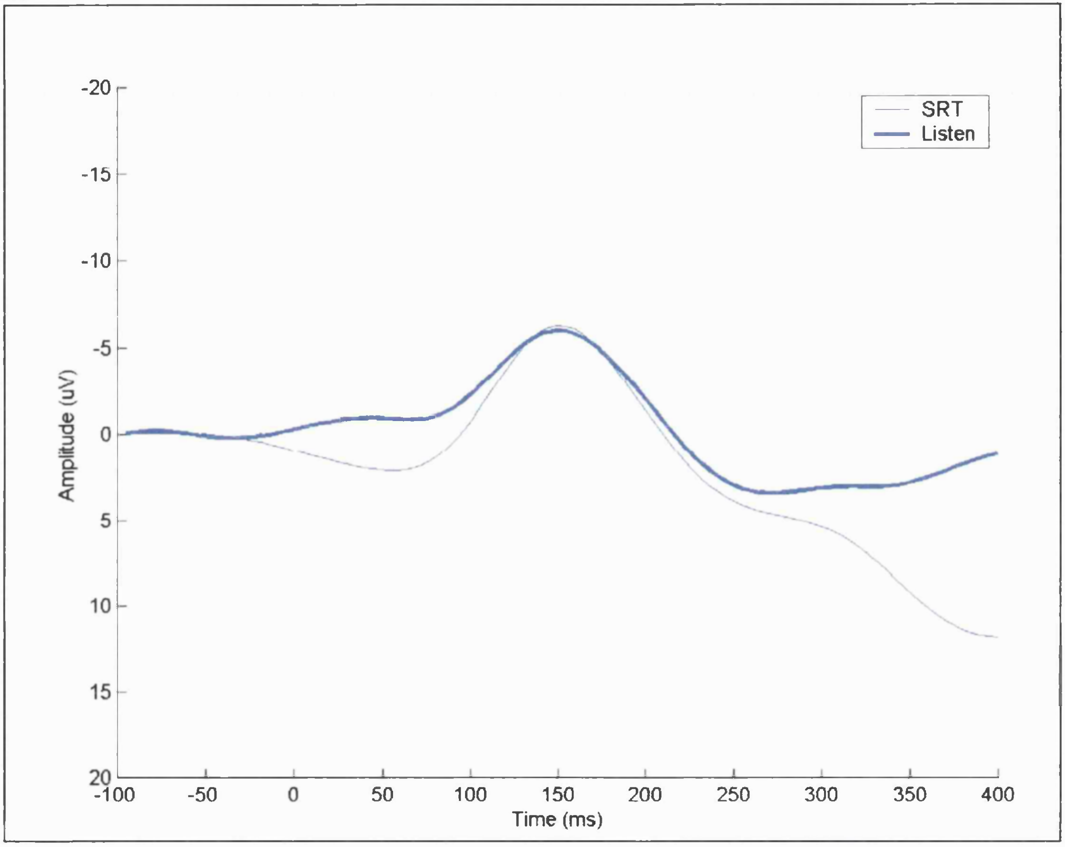
The ERP data was analysed by planned comparisons driven by the hypotheses in the introduction. Since montage plots did not show large differences between electrodes, and since the auditory ERP is conventionally measured at Cz (Shröger and Eimer, 1993) only the Cz traces were used for statistical analysis. The conventional time windows were also used to analyse distinct established waveform components, taking window locations from Schröger and Eimer (1997). Paired t-tests of the peak amplitude (maximum: positive or minimum: negative, dependent on waveform), the latency of the peak amplitude and the mean amplitude within specific time windows were performed. By analysing these three aspects of the data within delineated time windows, the effect of experimenter bias in subjectively locating the relevant ERP peaks of interest was eliminated. The time windows were used because each included the waveform component of interest, as discussed in the introduction (section 6.1). The first time window, 0-100 ms, includes a positive peak that is approximately the P80; the second time window, 100-250 ms, includes a negative peak that is approximately the N150; and the third time window 250-400 ms, includes a positive peak that is approximately the P300.

The conditions were compared in stimulus-locked averaged, due to the stimulus processing differences being of interest. Graphical plots of the compared conditions, plotted on top of each other ('overplot'), tabulated values and t-test results for the four comparisons detailed in the introduction (section 6.1.3), at the Cz electrode are presented for: (i) SRT versus *listen* (Figure 6.9, Table 6.1); (ii) SRT versus TRT (Figure 6.10, Table 6.2); (iii) *listen* versus *intend ignore after*[1] (Figure 6.11, Table 6.3); and (iv) TRT versus *intend stop* (Figure 6.12, Table 6.4).

6.3.3.1 SRT versus *listen*

Figure 6.9 shows an overplot of the grand average ERPs for the SRT and Listen conditions. T-tests for relevant features of the plots are shown in Table 6.1. The commentary following the table explains the referenced superscripted letters.

Figure 6.9. The overplot of grand average ERPs for SRT and *listen*. 0 = imperative auditory stimulus onset.



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[1] The *intend ignore before* data is not presented in this chapter, henceforth the *intend ignore after* trials will be called *intend ignore*, for simplicity.

Table 6.1. T-tests between SRT and *listen* of the peak amplitude, latency of peak amplitude and the mean amplitude, in three different time windows. The following commentary explains the referenced superscripted letters. All t-tests are uncorrected. * denotes significance.

CONDITION	MEASUREMENT	0 TO ≤ 100 MS. Approximating P80 wave	> 100 TO ≤ 250 MS. Approximating N150 wave	250 TO ≤ 400 MS. Approximating P300 wave
SRT	Peak amplitude (µV)	3.21	-11.94	13.63
	Latency of peak (ms)	61	164	348
	Mean amplitude (µV)	1.58	-3.11	7.56
LISTEN	Peak amplitude (µV)	1.36	-11.12	7.01
	Latency of peak (ms)	50	160	294
	Mean amplitude (µV)	-0.83	-2.81	2.76
t-test probabilities	Peak amplitude (µV)	p = 0.17	p = 0.57	p = 0.039 *[b]
	Latency of peak (ms)	p = 0.45	p = 0.70	p = 0.006 *[c]
	Mean amplitude (µV)	p = 0.033 *[a]	p = 0.43	p = 0.072

COMMENTARY

[a] The mean amplitude is positive, that is, the P wave in the SRT condition and negative, that is, the N wave in the *listen* condition, thus, they are significantly different when compared.

[b] The maximum peak amplitude (P300) in the SRT condition is almost twice the size of the *listen* condition. This suggests that a difference between these two conditions occur in the period when subjects actually react. The SRT RT was 354 ms, which is around the time of the P300. It might be that the larger P300 in SRT is due to the amalgamation of the relevancy of the stimulus and the motor response.

[c] The time of the maximum peak (P300) is much later in the SRT condition (55 ms) than in the *listen* condition, which suggests that the *listen* condition finishes earlier, due to the reasons posited above.

The non significant differences found between SRT and *listen* at the N150 waveform imply that this component is not specifically associated with response. That is, the N150 appears not to be response relevant, otherwise the SRT would be larger than the *listen* peak, which it clearly is not.

6.3.3.2 SRT versus TRT

Figure 6.10 shows an overplot of the grand average ERPs for the SRT and TRT conditions. T-tests for relevant features of the plots are shown in Table 6.2. The commentary following the table explains the referenced superscripted letters.

Figure 6.10. The overplot of grand average ERPs for SRT and TRT. 0 = imperative auditory stimulus onset.

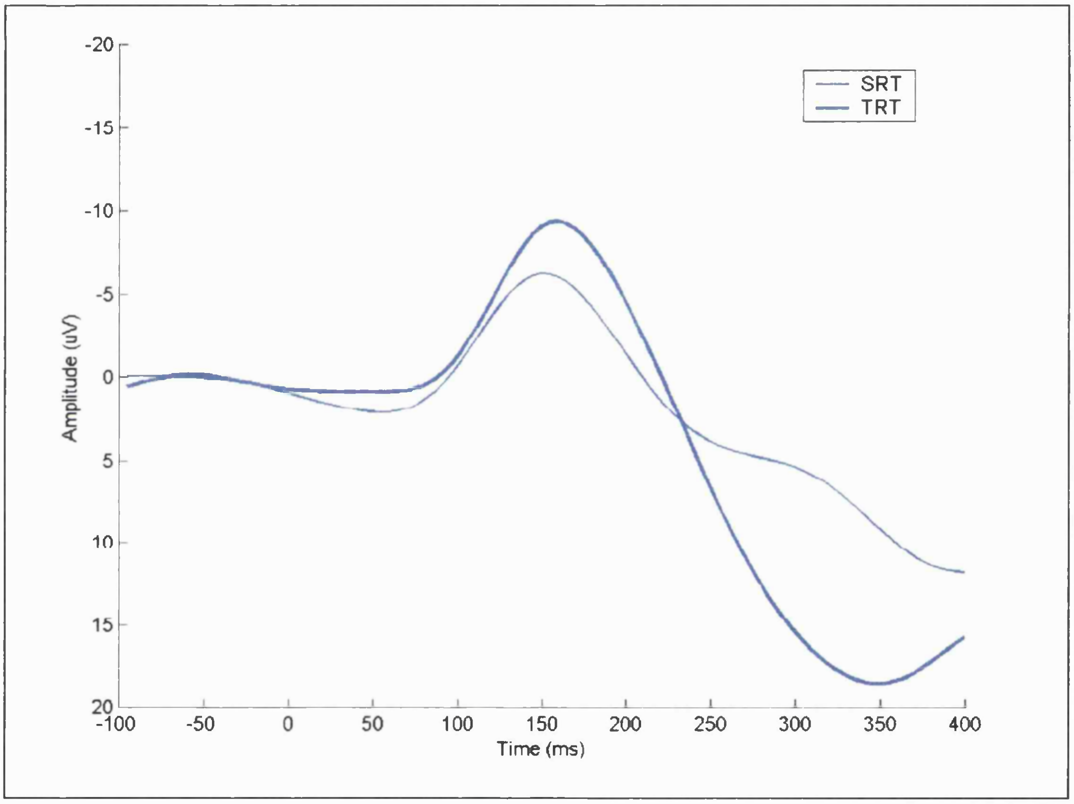


Table 6.2. T-tests between SRT and TRT of the peak amplitude, latency of peak amplitude and the mean amplitude, in three different time windows. The following commentary explains the referenced superscripted letters. All t-tests are uncorrected. * denotes significance.

CONDITION	MEASUREMENT	0 TO ≤ 100 MS. Approximating P80 wave	> 100 TO ≤ 250 MS. Approximating N150 wave	250 TO ≤ 400 MS. Approximating P300 wave
SRT	Peak amplitude (μV)	3.21	-11.94	13.63
	Latency of peak (ms)	61	164	348
	Mean amplitude (μV)	1.58	-3.11	7.56
TRT	Peak amplitude (μV)	3.20	-16.81	23.20
	Latency of peak (ms)	39	172	342
	Mean amplitude (μV)	0.65	-5.45	15.46
t-test probabilities	Peak amplitude (μV)	p = 1.00	p = 0.029 *[b]	p = 0.003 *[e]
	Latency of peak (ms)	p = 0.078 *[a]	p = 0.007 *[c]	p = 0.75
	Mean amplitude (μV)	p = 0.49	p = 0.029 *[d]	p = 0.002 *[f]

COMMENTARY

[a] There is a clear difference between SRT and TRT in the timing of the first post-stimulus positive peak, however the values were found not to be significantly different. Notably, the difference between the timings of the first peak was in the opposite direction predicted by delayed stimulus processing. That is, the TRT peak is *earlier* than the SRT peak, suggesting that the first stages of the stimulus processing are, if anything, faster in the truncation condition. This finding supports the suggestion that the stimulus processing is not significantly delayed in truncation.

[b] The amplitude of the negative peak (above the 0) is larger in truncation, as expected, and is clearly seen in the graphical overplot in Figure 6.9.

[c] The time of this N peak is earlier in SRT, which is the opposite to the prediction. This suggests that the stimulus is processed faster in the SRT condition, in this time window, which would explain some of the RT cost of intention. However, the difference is only 8 ms and the RT cost of intention is 63 ms, so this can only explain part of the difference. Also, there are no significant differences between the SRT and TRT in the first time window, that is, the early stimulus processing is not delayed in TRT.

[d] The mean amplitude is larger in the truncation condition, which is as expected and is clearly visible in Figure 6.9. The larger amplitude in TRT undermines the idea that stimulus processing is weaker in TRT (even if it is 8 ms later).

[e] the maximum positive amplitude, that is, the P300 peak, is larger in the truncation condition in this time frame, suggesting that the differences between SRT and truncation occur in the later stages of stimulus processing, and are probably related to the increased effort required to react to the truncating stimulus.

[f] the mean amplitude in the truncation condition is almost twice the size of the mean amplitude in the SRT condition, which is probably a function of the much larger amplitudes found in TRT.

b, c, d, e and f suggest that the differences between the SRT and truncation conditions occur largely between 100-400 ms, that is, in the period where the subjects react, and not in the earliest stimulus processing stages. Therefore, the early (0-≤ 100 ms) stimulus processing is not delayed in TRT. The early stimulus processing is roughly similar in SRT and TRT, but its impact is much larger in TRT. In the later stages, the difference between the conditions is that, in SRT, the subject only reacts, having been waiting for and thus able to prepare the response for the stimulus; and in truncation the subject has to stop preparing the intentional movement (*suppression*) and then has to activate a reactive movement.

Observation of the comparison in section 6.3.3.1, between SRT and *listen* (Figure 6.9, and the related statistics in Table 6.1), allows for the identification of the response-relevant stimulus-locked components. The SRT condition produces a significantly larger P80 and P300 than *listen*. These components are therefore related to the significance of the tone, that is whether it demands a response or not. Neither of these components are significantly delayed or reduced in TRT, which would be expected if the stimulus was processed more slowly. In fact, the TRT has a significantly larger P300, which suggests that the processing required to react to the tone is greater than that required to react in SRT. Thus, although there is a significant difference in the minimum latency between SRT and TRT in the middle window, this difference is very small and is not accompanied by a reduction in ERP amplitude, but by an increase. Moreover, the main difference between SRT and TRT is not at the stimulus processing stage, but later. This, therefore, supports the view that delayed stimulus processing does not satisfactorily explain the significant difference in RT between SRT and TRT.

6.3.3.3 Listen versus *intend ignore*

Figure 6.11 shows an overplot of the grand average ERPs for the Listen and Intend Ignore conditions. T-tests for relevant features of the plots are shown in Table 6.3. The commentary following the table explains the referenced superscripted letters.

Figure 6.11. The overplot of grand average ERPs for *listen* and *intend ignore*. 0 = imperative auditory stimulus onset.

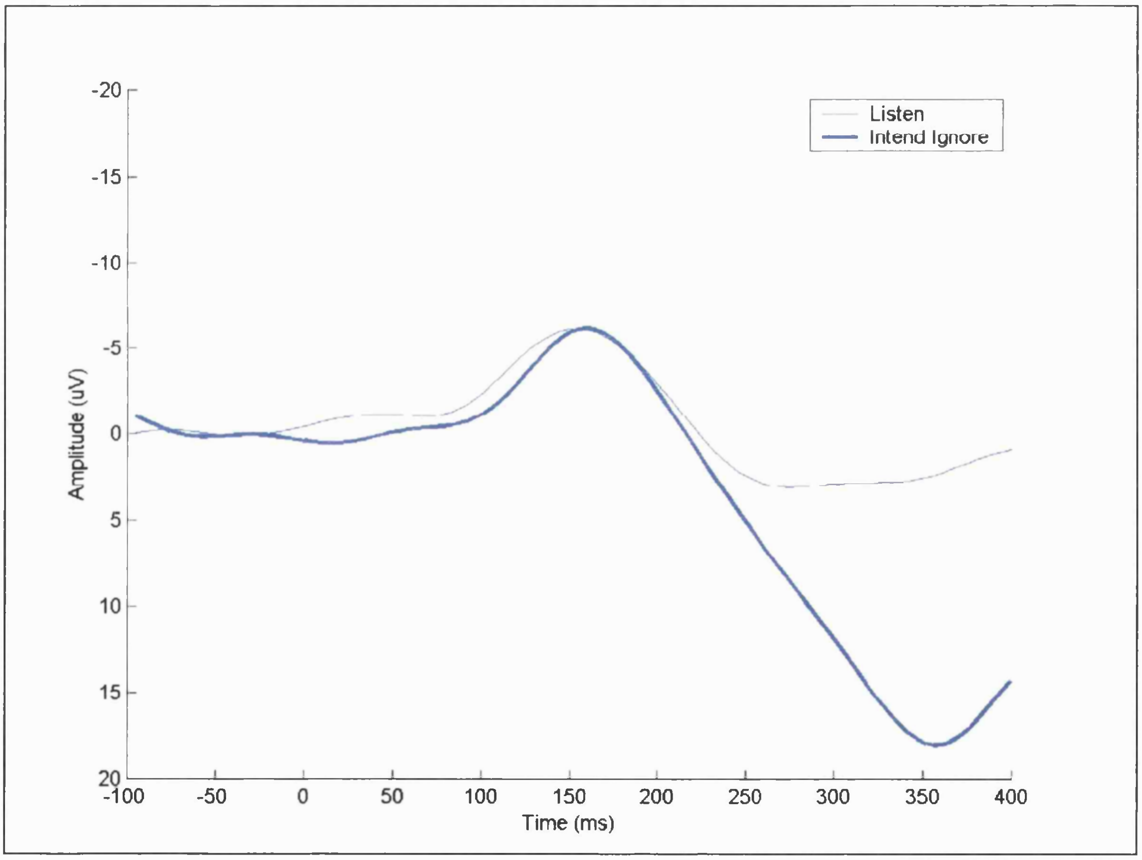


Table 6.3. T-tests between *listen* and *intend ignore after* of the peak amplitude, latency of peak amplitude and the mean amplitude, in three different time windows. NB. Only 11 subjects were compared here because one subject did not have a Cz average for *intend ignore* due to electrode failure. The following commentary explains the referenced superscripted letters. All t-tests are uncorrected. * denotes significance.

CONDITION	**MEASUREMENT**	**0 TO ≤ 100 MS.** **Approximating P80 wave**	**> 100 TO ≤ 250 MS. Approximating N150 wave**	**250 TO ≤ 400 MS. Approximating P300 wave**
LISTEN	Peak amplitude (µV)	1.31	-11.61	6.88
	Latency of peak (ms)	47	162	298
	Mean amplitude (µV)	-1.06	-3.29	2.46
INTEND IGNORE	Peak amplitude (µV)	2.98	-13.11	22.34
	Latency of peak (ms)	35	170	343
	Mean amplitude (µV)	0.02	-2.43	13.50
t-test probabilities	Peak amplitude (µV)	p = 0.21	p = 0.60	P < 0.0001 *[a]
	Latency of peak (ms)	p = 0.34	p = 0.63	P = 0.040 *[b]
	Mean amplitude (µV)	p = 0.40	p = 0.72	P < 0.0001 *[c]

COMMENTARY

[a] The peak positive amplitude, the P300 wave is much larger in the *intend ignore* condition. This is clearly seen in the graphical overplot (Figure 6.11).

[b] The time of the peak amplitude, the P300, is much later in the *intend ignore* condition.

[c] The mean amplitude of the *intend ignore* condition is more than five times that of the *listen* condition.

These differences all occur in the late stages (>250 and ≤ 400 ms) of the ERP. The lack of P80 and N150 effects show that merely intending does not reduce early stimulus processing, for example by dividing attention. The delayed N150 in the SRT-TRT comparison (section 6.3.3.2) therefore, seems unlikely to be just a consequence of intention.

The P300 wave is much larger in the *intend ignore* condition as can be seen in the grand average overplot. It may be that ignoring the beep actually requires a huge amount of resources. Perhaps, despite the instruction to ignore the stimulus the subjects need to not react to it, since at least some of the subjects will have reacted to the same stimulus in the previous blocks, this account is plausible. This large P300 might, therefore indicate the suppression of a reaction. It could be interesting to know if the intentional actions following an ignored beep resemble those before the beep, but that is a topic for further research.

6.3.3.4 TRT vs *intend stop*

Figure 6.12 shows an overplot of the grand average ERPs for the TRT and Intend Stop conditions. T-tests for relevant features of the plots are shown in Table 6.4. The commentary following the table explains the referenced superscripted letters.

Figure 6.12. The overplot of grand average ERPs for TRT and *intend stop*. 0 = imperative auditory stimulus onset.

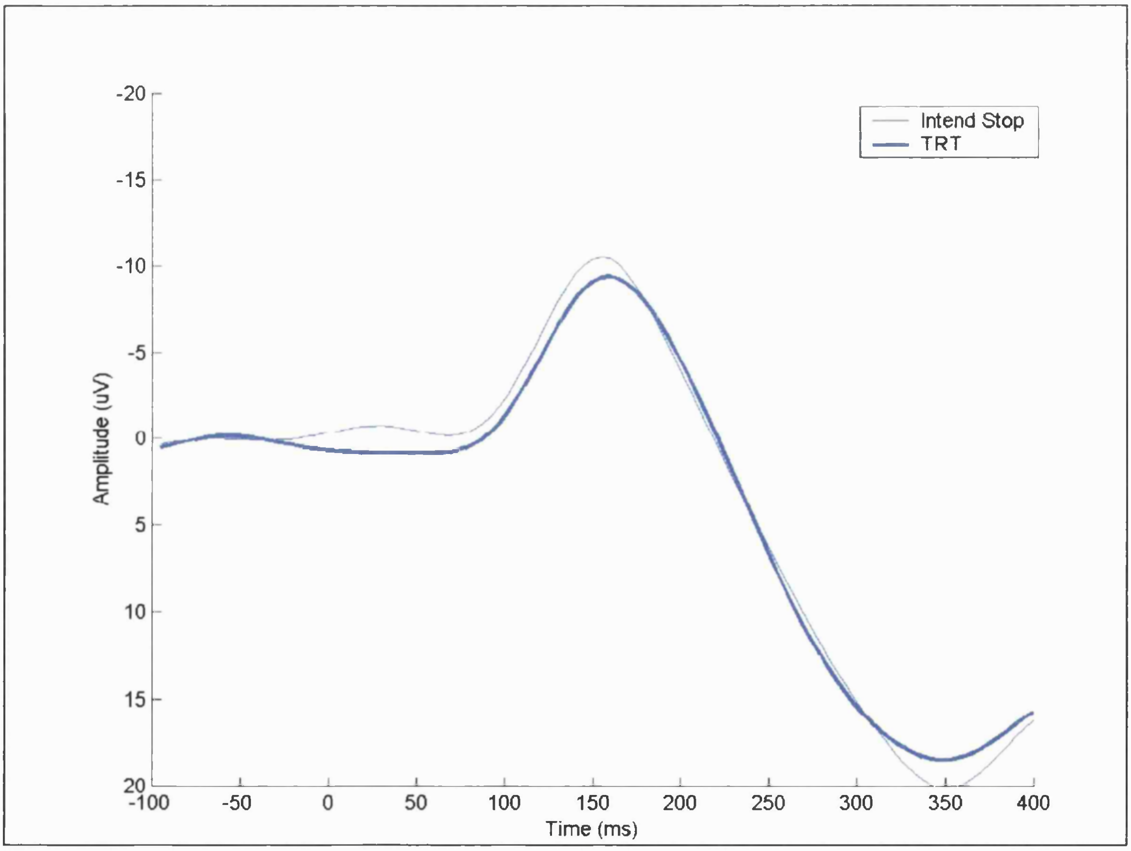


Table 6.4. T-tests between TRT and *intend stop* of the peak amplitude, latency of peak amplitude and the mean amplitude, in three different time windows. All t-tests are uncorrected.

CONDITION	MEASUREMENT	0 TO ≤ 100 MS. Approximating P80 wave	> 100 TO ≤ 250 MS. Approximating N150 wave	250 TO ≤ 400 MS. Approximating P300 wave
TRT	Peak amplitude (μV)	3.20	-16.81	23.20
	Latency of peak (ms)	39	172	342
	Mean amplitude (μV)	0.65	-4.29	15.46
INTEND STOP	Peak amplitude (μV)	1.68	-16.05	22.63
	Latency of peak (ms)	47	170	338
	Mean amplitude (μV)	-0.60	-4.69	15.82
t-test probabilities	Peak amplitude (μV)	p = 0.39	p = 0.65	p = 0.81
	Latency of peak (ms)	p = 0.57	p = 0.51	p = 0.69
	Mean amplitude (μV)	p = 0.48	p = 0.80	p = 0.86

COMMENTARY

The overplot, Figure 6.12 and the non significant t-tests imply that all the major ERP features of truncation are seen in the *intend stop* condition. This suggests that the effect of suppressing an intentional action involves the same processes as switching from an intentional action to a reactive action and is consistent with the suggestion that truncation involves stopping the intentional action prior to responding.

If, in TRT, the intentional action was completely suppressed before the reactive action was initiated, then the ERP (particularly at P300) should be larger because there is a movement in TRT and none in *intend stop*. This would be expected because the difference between SRT and *listen* indicated that a response is more effortful than listening, particularly in the latter stages (P300). The fact that the P300 is *not* larger in TRT, suggests that the intentional action being suppressed and then the reactive action being activated is equal to simply suppressing an intentional action. This implies that the main portion of the RT cost of intention is due to this first stage, that is, the suppression of the intentional action, rather than the activation of the reactive action.

6.3.5 Further Examination of the Switching and Inhibitory Hypotheses

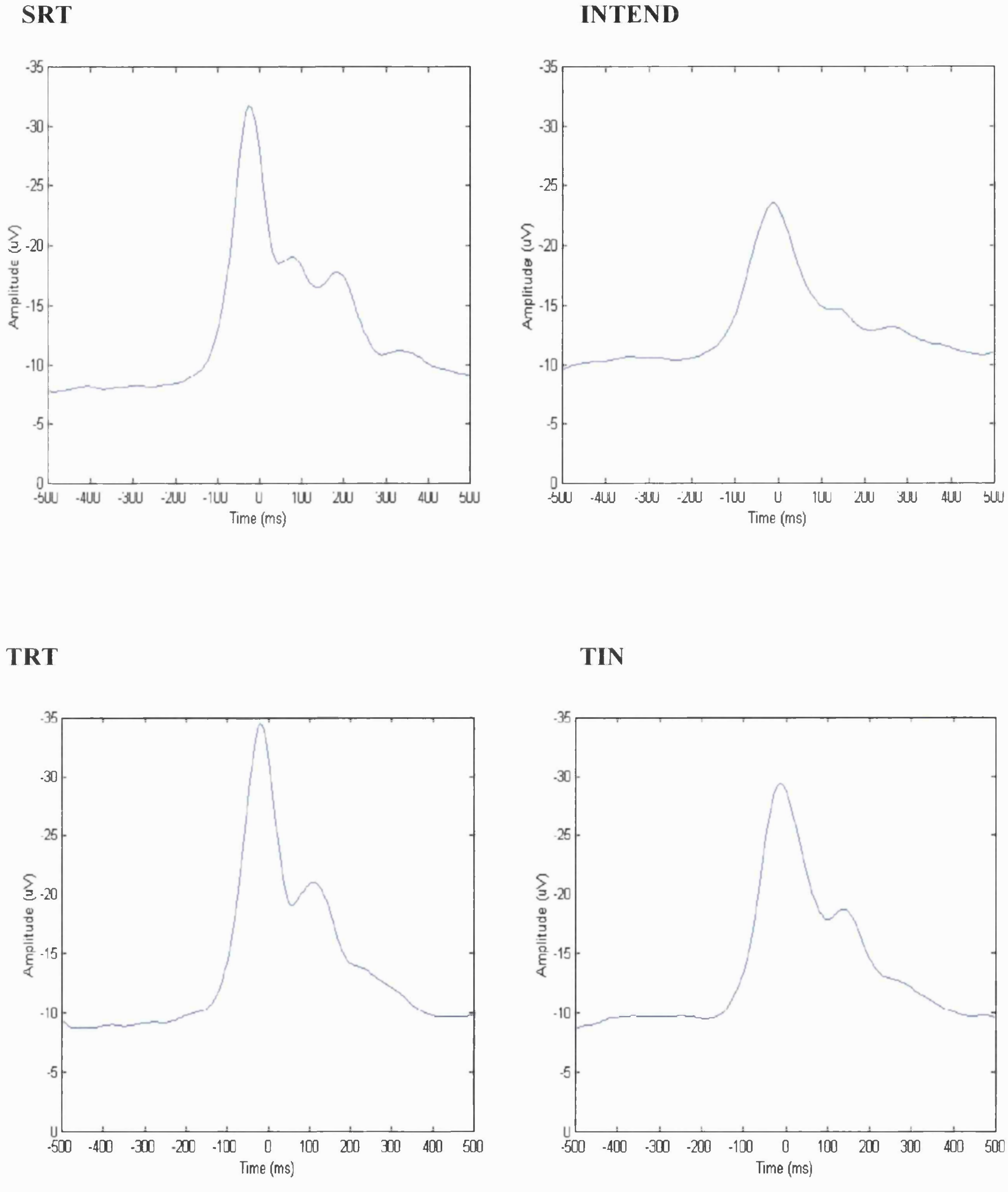
6.3.5.1 Comparing EMG in TRT, TIN, SRT and *intend* trials

The EMG data was processed using the same techniques as the EEG data. Grand averages were computed for the truncated intentional trials (TIN), the truncated reaction trials (TRT), the *intend* condition and the SRT condition. These four waveforms were compared in order to further examine the processes that occur when subjects react to the truncating stimulus.

The predictions were made in the introduction (section 6.1.2). Briefly, if the switching hypothesis is to be supported, it would be expected that the TRT EMG would be the same as SRT. Statistically it would be expected that the main effect of action type would be significant, the main effect of truncation non significant and the interaction, non significant.

If the inhibitory hypothesis is to be supported, then it would be expected that the TRT EMG would be smaller than the SRT, due to the inhibitory effect of the internally-generated system on the externally-triggered reaction to the truncating system. Statistically, the interaction between truncation (yes or no) and action type (reactive or intentional) would be significant. The peak EMG would be significantly larger in SRT than in TRT.

Figure 6.13. The grand average EMGs of the four conditions, SRT, *intend*, TRT and TIN.



All the EMGs are similar, especially at the beginning, although the SRT EMG is slightly lower, suggesting that there is less pre-movement muscle activity associated with waiting for a stimulus, than preparing for an intentional action (Table 6.5). The largest pre-movement EMG activity is seen in *intend*, which is the only condition in which a purely intentional action is occurring. That is, in TRT and TIN, there is a dual task nature in that the possibility of reaction perhaps results in slightly less muscle preparation. TIN, TRT and SRT all steeply increase at approximately 150 ms prior to the action; the slope is less steep in *intend*. The four conditions all peak at approximately 0 ms (i.e. at the time of the action) with TRT having the highest peak, followed by TIN, SRT and finally *intend*. All the EMGs have a second smaller peak in the middle time window, which is most prominent in SRT and TRT. This is probably associated with the release of the button. Around 250 ms after the action has occurred, all the EMGs return to the same level.

Table 6.5. Mean (s.d.) amplitude, in (μV) of SRT, *intend*, TRT (truncated reactive trials) and TIN (truncated intentional trials), in three time windows.

Time Window	SRT	*INTEND*	TRT	TIN
-500 to -200 ms	8.07 (6.50)	10.37 (8.77)	9.01 (7.68)	9.49 (7.97)
-200 to 200 ms	17.85 (15.10)	16.05 (12.17)	19.39 (16.34)	18.34 (16.17)
200 to 500 ms	11.25 (9.78)	11.94 (11.19)	11.29 (9.08)	11.26 (9.47)

Three 2 (truncation: yes or no) x 2 (action type: intentional or reactive) ANOVAs were performed on the mean amplitude (Table 6.5) in three time windows of the grand averages of the EMG. The time windows were decided post hoc based on observation of the figures. Prior to -200 ms all EMGs were flat, as no movement occurred. The first time window was chosen to be -500 to -200 ms. The second time window includes all the main movement-related activity and was delineated as -200 to 200 ms. The third time window includes the later post-movement stages as the muscle activity returned to normal and was chosen as 200-500 ms.

In all time windows the main effect of truncation was non significant: $F_{(1,11)} = 0.001$, $p = 0.98$ (-500 to -200 ms), $F_{(1,11)} = 1.17$, $p = 0.30$ (-200 to 200 ms) and $F_{(1,11)} = 0.055$, $p = 0.82$ (200 to 500 ms). In all the time windows the effect of action type was non significant, $F_{(1,11)} = 1.97$, $p = 0.19$, $F_{(1,11)} = 1.26$, $p = 0.29$, and $F_{(1,11)} = 0.16$, $p =$

0.70. The interactions were also all non significant ($F_{(1,11)}$ =1.23, p = 0.29, $F_{(1,11)}$ = 0.13, p = 0.72 and $F_{(1,11)}$ = 0.19, p = 0.67).

The non significant main effect of truncation and the non significant interaction would not have occurred if the hypothesised motor systems were related in an inhibitory manner. The lack of supportive data for an inhibitory relationship does not necessarily imply that the data supports a switching hypothesis. However, the data is *consistent* with the switching hypothesis.

Table 6.6. The mean (s.d.) peak amplitude and latency of the peak amplitude in the -200 to 200 ms time window of SRT, *intend*, TRT and TIN.

MEASUREMENT	SRT	*INTEND*	TRT	TIN
Peak amplitude (µV)	46.05 (46.76)	30.88 (26.01)	52.97 (48.73)	40.75 (36.44)
Latency of peak (ms)	0.80 (61.74)	-7.60 (57.33)	-7.20 (49.54)	-8.00 (57.33)

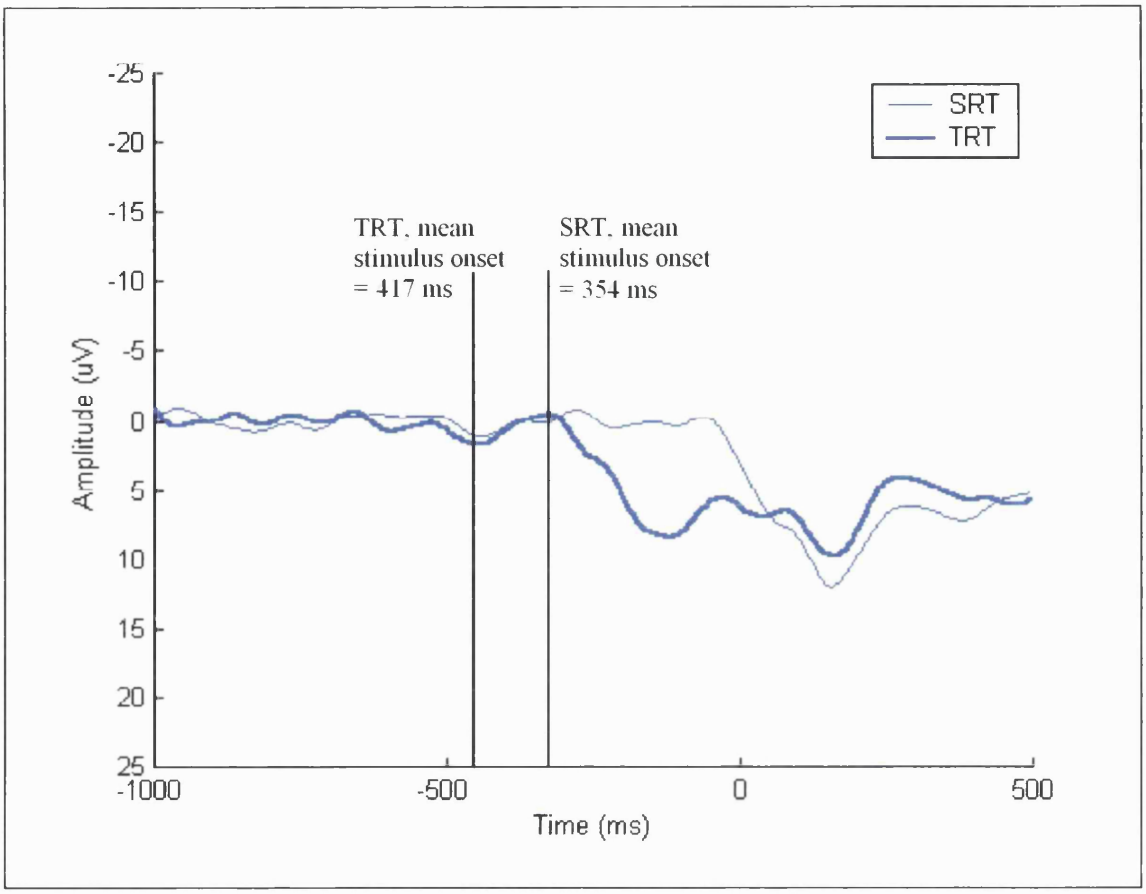
Interestingly, the times of the peak amplitudes are similar to those found in the main pupil experiment (chapter 4), in which the peak dilation was earlier in conditions containing an intentional action (*intend*, TRT and TIN), and later in SRT. That is, the action is completed motorically earlier in conditions generated by the internally-generated system (*intend* and TIN), and by those in which the internally-generated system is active prior to the externally-triggered system (TRT), even though the externally-triggered system is responsible for the final motoric output. There is no support for the inhibitory hypothesis because the SRT peak is smaller than the TRT peak. The latency of the peak is not later in TRT, which implies that the timing of the switch process is not altered; only the amplitude and mean amplitude are later, although neither are significant. These findings refute the inhibitory hypothesis and provide no support either way for the switch hypothesis, although the earlier peak in TRT suggests that if a switch does occur, it does not manifest in delaying the electrophysiological measures but only significantly delays the RT.

Two 2 (truncation: yes or no) x 2 (action type: reactive or intentional) ANOVAs were performed, with the dependent variables peak amplitude and latency of peak amplitude. The main effect of truncation was non significant for both peak and time of peak ($F_{(1,11)} = 2.90$, $p = 0.12$; and $F_{(1,11)} = 0.42$, $p = 0.53$, respectively). The main effect of action type indicates that the difference between reactive and intentional actions peak amplitude approaches significance ($F_{(1,11)} = 3.34$, $p = 0.095$), but is clearly non significant when comparing the time of the peak ($F_{(1,11)} = 0.14$, $p = 0.71$). The interactions are both non significant: $F_{(1,11)} = 0.40$, $p = 0.54$; and $F_{(1,11)} = 0.27$, $p = 0.61$. The slightly larger overall peak amplitudes found in the reactive actions (overall mean of SRT and TRT = 49.51) compared with the intentional conditions (overall mean of *intend* and TIN = 35.82) is the probable cause of the main effect of action type approaching significance. The fact that the reactive actions have a slightly larger peak than the intentional actions suggests that the reactive actions result in subjects pressing the response button more vigorously.

6.3.5.2 SRT versus TRT movement-locked analysis

Another analysis was performed to try and clarify the processes responsible for the RT cost of intention. The SRT and TRT EEGs were plotted on the same graph, locked to the movement, in order to examine the reaction processes. If the process of reaction is inhibited in truncation, then it would be expected that there would be less activity immediately after the stimulus has been presented, and before the movement. This should be in the -500 to 0 ms region shown in Figure 6.14. However, this does not appear to be the case; in fact, there is more activity in the TRT condition than in the SRT condition, immediately prior to the movement. The mean amplitudes were compared, by t-test to verify this prediction.

Figure 6.14. Grand average overplot of SRT and TRT, at electrode Cz. 0 = movement onset.



The data was compared in three different time windows, chosen post hoc and based on observation of the overplot (Figure 6.14). The peak amplitude and time of peak amplitude were not examined due to the lack of clear peaks in both SRT and TRT in the -500 to 0 ms time window. The t-test for the first window, -1000 to -500 ms, was non significant ($t_{(11)} = -0.13$, $p = 0.90$, uncorrected). The t-test for the middle window, -500 to 0 ms, was significant ($t_{(11)} = -3.09$, $p = 0.01$, uncorrected) and the t-test for the final window, 0 - 500 ms, was non significant ($t_{(11)} = 0.439$, $p = 0.67$, uncorrected). The significant difference in the middle section is probably due to the difference in P300, the large positive stimulus-locked waveform demonstrated in Figure 6.10 and Table 6.2, which was much larger in TRT. This result contradicts the suggestion that the internally-generated and externally-triggered motor systems have an inhibitory relationship, because there is clearly more activity in the TRT waveform in the post-stimulus pre-movement time window (-500 - 0 ms).

The comparison of movement-locked SRT and TRT and the EMG analyses lend support to the idea that these systems do not have an inhibitory relationship, but that switching from the intentional motor system to the reactive motor system incurs a switch cost which is responsible for the RT cost of intention.

6.4 DISCUSSION

6.4.1 Reaction Time Data

The RT for the TRT condition is significantly longer than the RT for the SRT condition, which follows the results of previous experiments in this thesis. The RT cost of intention, the posited reason for the delayed RT in TRT is 63 ms. This data replicates earlier findings.

6.4.2 ERP Data: Montages

6.4.2.1 SRT versus TRT

There were no significant differences between the SRT and TRT ERPs in the first 100 ms after the stimulus, although the differences were approaching significance. The difference was in the opposite direction to that predicted by delayed stimulus processing in TRT. The first waveform occurred at 39 ms in TRT and 61 ms in SRT, indicating that the early stages in TRT are not affected by delayed stimulus processing.

Differences can be observed in the graph and the t-tests in the middle period, where the negative peak is larger and later in the TRT. The delayed peak in the TRT is, however, only 8 ms slower than the SRT peak. The RT cost of intention is 63 ms in this case, so delayed stimulus processing cannot explain all of this value. The TRT also has a larger positive amplitude at N150 and P300, which suggest that stimulus processing is not attenuated by intentional preparation.

When the stimulus arrives, its implications are greater in TRT than in SRT. This is perhaps because it engages the two processes of switching and reacting rather than simply reacting.

6.4.2.2 SRT versus *Listen*

In the early period of the ERP, there are differences in the peak amplitude and the latency of the peak amplitude. The SRT does not have a large negative peak in this early stage, and the *listen* barely enters the positive side. They, therefore, have quite different beginnings; the presentation of the stimulus in SRT requires the subject to activate a response, whereas the *listen* condition only results in the subject observing that the stimulus has occurred.

The middle part of the ERPs are almost identical, peaking at almost exactly the same spot and dropping off from the peak with the same slope.

The final stage of the ERPs differ again, probably due to the resultant motoric output, which is demanded in the SRT but not in the *listen* condition. The large positive deflection seen in the SRT condition can be attributed to this response.

6.4.2.3 TRT versus *intend stop*

As can be seen by the overplot (Figure 6.12), these two ERPs are almost identical. They are practically flat for approximately the first 100 ms, they climb to the same peak point and then decrease with the same slope. This would suggest that it is as effortful to stop a partially prepared action as it is to switch from an intentional action to a response. This stopping process can be considered the first part of a switching process. The second part would be activating the reaction. Since the second part also occurs in SRT (i.e. is common to both SRT and TRT), it is possible that stopping the intentional action in response to a stimulus (the difference between SRT and TRT), may be the main contributor to the RT cost of intention.

Interestingly, the large P300, which was prevalent in conditions, in which an actual movement occurred, and was small in the *listen* condition, was present in *intend stop*. It is possible that the lack of stimulus-relevancy in the *listen* condition resulted in a minimal P300, and that the large P300 found in *intend stop* is associated with task-relevant stimuli that require direct responses. Alternatively, the effort required to suppress the intentional action preparation is as much and seemingly equivalent to the effort required to react. This interpretation would fit with the findings that frontal patients find inhibiting behaviours particularly difficult (e.g. Shallice, 1988).

6.4.2.4 *Listen* versus *intend ignore*

These two ERPs have no significant differences in the first two periods. The *intend ignore* ERP has a very large positive deflection at approximately 350 ms which is highly significantly different from the *listen* condition. This difference is probably due to the motoric output required in *intend ignore*, as seen in the other comparisons of *listen* with conditions, which required movement.

6.4.3 Switching or Inhibition

The EMG and movement locked SRT and TRT comparisons were carried out in order to further examine the hypothesis that the RT cost of intention is due to either switch costs or inhibition between the two motor systems. In brief, if the inhibition was believed to occur at the motor level in the movement hierarchy, it was predicted that the mean amplitude of the TRT EMG would be smaller than SRT due to the inhibition of the externally-triggered action by the internally-generated system. Therefore, the peak amplitude would be larger in SRT. Neither of these predictions was found. The overplot of the movement-locked SRT and TRT ERPs (Figure 6.14) showed more activity immediately pre-movement (and post-stimulus) suggesting that the presentation of the truncating stimulus did not result in inhibition of the externally-triggered action (due to prior activation of the internally-generated motor system).

The results therefore provide no support for the inhibition hypothesis. The EMG analyses predominantly support the switch hypothesis, in that the main effect of truncation and the interaction between action type and truncation was not significant. In conclusion, it seems that the most likely contributor to the RT cost of intention is a switch cost incurred when switching from an intentional to a reactive action, rather than a delay due to the active inhibition of the externally-triggered system by the internally-generated system.

6.4.4 Conclusion

Stimulus processing was largely similar in SRT and TRT. There was no evidence for attenuation of the stimulus processing in TRT. A small, but significant 8 ms delay in the N150 component (i) could not explain the 63 ms RT cost of intention; (ii) was reversed in the first component (P80 waveform); and (iii) was accompanied by an inverse in ERP amplitude rather than the decrease that would be expected if the assumption that intentions attenuated stimulus processing was true. Thus, overall, TRT processing of the stimulus did not appear as a delayed or attenuated version of SRT. Instead TRT processing resembled *intend stop*, suggesting that effortful termination of intentional preparation may explain and perhaps be responsible for the majority of, the RT cost of intention.

The EMG data did not support the inhibitory process occurring at the motor level of the movement hierarchy. Instead, they are consistent with the switch hypothesis, in that the main effects of truncation and the interactions were not significant using mean amplitudes, peak amplitudes and latencies of amplitudes. The fact that the TRT peak amplitude is not later than the SRT amplitude suggests that the difference between them which results in the larger, though non significant peak in TRT and (significantly) longer RT in TRT is not to do with delayed stimulus processing or inhibitory mechanisms between the two systems at the motor level, but is the result of suppressing the intentional action at the action or brain level.

These findings are consistent with Roger and Monsell's (1995) proposal relating to the reconfiguration from one task set to another (chapter 2, section 2.4.8). Endogenous control is initiated by subjects before the stimulus occurs, allowing them to prepare for the action; thus, by the time the stimulus arrives, they have done some of the reorganisation of cognitive and motor resources required for the new task. Exogenous control ('stimulus-driven' control) is needed to complete the reconfiguring process and can only occur once the stimulus is presented. The fact that SRT does not produce earlier EMGs than TRT suggests that the difference between them is at the endogenous level of control, therefore the switch from the internally-generated to externally-triggered motor system occurs at the action level of the motor hierarchy, rather than the motor level.

The SRT and TRT overplot and analyses suggest that the differences between the two conditions is due to the probably P300 which is larger in TRT; it is certainly more effortful to react in TRT than in SRT. However, the non significant differences at the other two time windows provide no support for an inhibitory relationship between the two motor systems.

In conclusion, the results of this experiment support the switch hypothesis, which suggests that the RT cost of intention is incurred by a switch between the hypothesised internally-generated and externally-triggered motor systems.

The next part of this thesis examines the subjective experience of intentional and reactive actions. Chapter 7 introduces the main areas of research into subjective reports of intentional and reactive actions. Two experiments are presented, which examine the subjective perception of reactions, intentional actions and truncated reactions (first experiment) and stimuli (second experiment). These two experiments will be presented and evaluated in an attempt to ascertain (i) whether subjects are aware of the RT cost of intention; and (ii) where in the motor hierarchy it might occur. This thesis concludes with summaries of the findings, wider implications and possible further research in chapter 8.

Chapter 7

SUBJECTIVE ASPECTS OF INTENTION AND REACTIVITY

7.1 INTRODUCTION

The second part of this thesis is concerned with the subjective elements of intention and reactivity. The particular aspects of subjective experience studied in this section, namely the conscious awareness of action and stimuli, require certain concepts and theories, for example conscious awareness and prior entry, to be explained and reviewed. These concepts and theories are discussed in the following introductory sections.

7.1.1 Conscious Awareness

To be able to veridically report the occurrence of an action requires accurate perception via introspection and the sensory modalities, including proprioception. People must be able to access (i) the outcome of their actions and possibly (ii) their intentions to reach a desired state (goal-directed behaviour). These processes rely on internal and external monitoring. For example, the outcome of the action, for example, a right index finger flexion pressing a key, can be proprioceptively experienced via the muscle receptors (internal monitoring), or in terms of achieving the desired state, such as when a key being pressed results in the start of the next trial (external monitoring).

Almost twenty years ago, the influential work of Libet et al (1983), sparked an interest in the psychological study of conscious awareness of intentions and actions. The interest was primarily due to their highly contentious results, which implied that when we make intentional actions, our brains are active prior to our conscious awareness of the intention to act. Moreover, the delay between the onset of brain electrical activity (the bereitschaftspotential), and the related conscious awareness of intention was approximately 300 ms. The experiment is summarised below.

The experimental design involved the collecting of ERPs, and subjective reports (i) of when the subjects felt the “the urge to move”; and (ii) when they thought they had moved. Subjects were seated facing a cathode ray oscilloscope (CRO). The CRO "spot of light" rotated near the circumference, starting at the 12 -o'clock position and took 2560 ms for one revolution. A scale with numbers at each 5-second position mounted on the CRO, provided the subjects with a judgement marker. Subjects were instructed to allow one complete revolution of the CRO to occur before making their movement.

In the first two conditions, subjects were instructed to "let the urge to act appear on its own at any time without any preplanning or concentration on when to act" (Libet et al, 1983). In the first condition, subjects were asked to report where the hand on the clock was when they felt the "urge to move" (called the 'W judgement'). In the second condition, subjects reported the position of the clock hand when they thought they had actually moved (called the 'M judgement'). The spot continued to rotate for a random amount of time (500 to 800 ms) after the event had occurred in order to remove any judgement cues. It must be acknowledged that a problem with this method, particularly in the case of intentional actions, is that subjects might decide a clock position prior to moving and then synchronise their action to it.

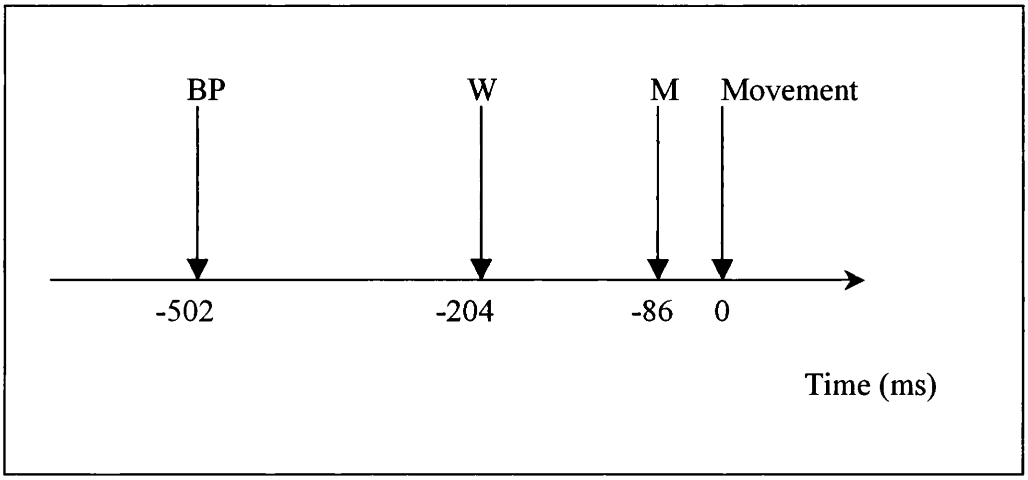
The results indicated that on average:

i. The BP began 502 ms prior to the intentional movement.

ii. Subjects reported the "urge to move" (which Libet et al called W) 204 ms prior to the movement.

iii. Subjects reported making the movement (which Libet et al called M) 86 ms before they actually did (i.e. before any EMG activity) [Figure 7.1].

Figure 7.1. A schematic based on Libet et al (1983) to demonstrate the temporal relationship between the BP, the urge to move (W), the reported awareness of the movement (M) and the actual movement (Movement).



The first finding is as expected: the BP always occurs well before, and indeed up to 1500 ms prior to the movement. The second finding was surprising in the context of the first finding in that the neural activity preceded the intention (W awareness), the "urge to move". That is, one's intention does not precede and therefore, cannot cause the neural firing that is responsible for the action.

The finding that subjects perceive themselves to have moved 86 ms before they actually do suggests that subjects were possibly reporting the cerebral output (efference copy) and not the muscular contractions. This would support the feeling of innervation.

The feeling of innervation as defined by James is the "... special current of energy going out from the brain into the appropriate muscles during the act; and this outgoing current ... must have in each particular case a feeling *sui generis* attached to it." Libet et al's data imply that we are capable of feeling this innervation prior to a willed action. Recent researchers have reached similar conclusions (e.g. Haggard, Aschersleben, Gerhke and Prinz, in press). Moreover, it is possible to localise specific neural or informational processes as occurring before or after awareness of action. These studies are reviewed later.

7.1.1.1 A brief overview of abnormalities in the perception of action awareness

There are cases where the action is not consciously perceived and where the awareness of action is abnormal. An example of the former includes an experiment in which subjects performed a visually-guided aiming task. Subjects were able to make swift error corrections based on the difference between the anticipated hand position (the target jump was not perceived) and the desired hand position (Goodale, Pélisson and Prablanc, 1986). Examples of the latter include utilisation behaviour (chapter 1, section 1.8.2) where the patient does not perceive any inconsistency between his/her intention and the resultant action; and certain schizophrenic patients who experience delusions of control (chapter 1, section 1.8.4).

Frith, Blakemore and Wolpert (2000) employed disorders such as utilisation behaviour, evidence from research on normal subjects and established models of normal motor control (e.g. Wolpert, 1997) to derive a model of motor control that accounted for abnormalities in the perception and control of action. Their model suggests that three states of the motor control system: the current, the desired and the predicted state, are separately represented in the brain. Certain disorders result in inefficient balancing between these states, for example, in utilisation behaviour a lesion occurs where the goal and desired state occur (Figure 5, Frith et al, 2000). Therefore, no intention arises with which the predicted state can be compared – that is, the patient has no representation of their intention and therefore, does not select an action. The excessive reactivity to environmental stimuli is not inhibited as in normal people, who inhibit responses until the development of an intention. Frith et al (2000) propose that the system responsible for developing intentions is also responsible for inhibiting inappropriate stimulus-driven responses.

7.1.1.2 The conscious awareness of intention

Measuring the conscious awareness of intentions is incredibly difficult due to the fact that intentions are not discrete events. Firstly, an intention, by nature 'builds up' over time and therefore, has no clear starting point. Secondly, there are subjective differences in defining when this 'build-up' starts and therefore, at what point it can be called an intention. For these reasons, it has been decided to avoid the direct study of the conscious awareness of intention. Instead, this chapter, which consists of two related experiments, is concerned with (i) the effects of intentional preparation on judgements about actions and stimuli; these are both discrete, objective events; (ii) the localisation of the RT cost of intention with respect to actions; and (iii) the attentional components, resulting from requiring subjects to focus on and report the perceived time of either actions or stimuli.

The rest of the introduction will review and discuss the main contributions to the study of awareness of action, the awareness of stimuli, and the way that the percepts of stimuli and actions are bound together.

7.1.2 Awareness of Action

In order to quantify the awareness of action, an objective event, the action itself (e.g. a keypress or the EMG) has to be compared with a subjective event, namely the subject's percept. The subjective event is 'captured' by the subject making judgements. In the tradition followed here, the subject judges when the action occurred. In the case of Libet et al (1983), subjects observed a clock with one hand rotating at a speed of 2560 ms/rotation, (section 7.1.1) and simply reported the position of the clock hand at the time of their action.

An alternative method of 'capturing' the subjective event, used by McCloskey, Colebatch, Potter and Burke (1983), required subjects to report whether their voluntary action occurred before or after a tactile reference stimulus, that is, subjects made temporal order judgements. The inter-onset interval is adjusted to find the exact point of subjective simultaneity. The timing of the conscious awareness of action can, therefore, be calculated by the difference between the actual and the subjective event, which is needed for them to appear simultaneous to the subject. However, this method is not really designed to calculate absolute values of the timings of conscious awareness, and, although frequently used in tests of the prior entry phenomenon (Sternberg and Knoll, 1973) and attention, is not really appropriate for measuring the awareness of action and stimuli, due to the reference stimulus acting as an additional attentional cue (Spence and Driver, 1994).

7.1.2.1 Judgements and localisation of intentional actions

To recapitulate, Libet et al's data implied that subjects' conscious awareness of intentional action was anticipated. The fact that their subjects demonstrated an 86 ms difference between their percept and the EMG activity suggested that they were not reporting the relevant muscular contractions. This lead to the conclusion that subjects were reporting some pre-motor event, perhaps the efferent output from the brain to the muscles.

Haggard (1999) extended Libet et al's original experiment in order to examine the replicability of the anticipatory findings and to control for the temporal biases introduced by the necessary cross-modal matching inherent within Libet et al's paradigm. Using a computerised Libet-style clock with a rotating hand (rather than a CRO spot), subjects reported the time of their action awareness. Haggard used pressure pads rather than EMG to measure the time of the action. The control conditions used a freely-rotating, horizontally-fixed car steering wheel over a marked scale, similar to that on the Libet-style clock, with a pressure pad. Subjects either moved and reported the time of release of the pressure pad or moved and then, after a specified time, returned to the point at which they had released the pressure pad. An anticipatory awareness of 56 ms was found in the first condition. The values for the other two conditions were statistically similar. It can, therefore be concluded that Libet et al's paradigm was not fatally flawed by the problems of cross-modal matching.

The robustness of this anticipatory action awareness was tested again by Haggard, Newman and Magno (1999), who attempted to localise the time of awareness of the first in a sequence of movements, within a specific model of action generation postulated by Sternberg, Monsell, Knoll and Wright (1978). Briefly, Sternberg et al (1978) found that the longer the sequence of letters to type was, the longer the delay was between the 'go' signal and the first letter typed (a positive linear relationship). This was interpreted in terms of a serial search buffer within which the letter strings were stored: the longer the string, the more searching was required.

Using similar conditions to Sternberg et al (1978), Haggard et al (1999) included three intentional conditions, which involved subjects typing nonsense letter strings of one, three or five letters at 'a time of their own choosing'. They reported the position of the hand on the Libet-style clock of the time of their first keypress. The reactive conditions utilised the same one, three or five nonsense letter strings, but the subjects had to start preparing to type when the first visual stimulus appeared, and to start typing when the third visual stimulus was presented. The first two signals were green, and if the third signal was green, this indicated 'go'. Eighty percent of the trials were 'go' trials. Twenty percent of the trials were catch trials indicated by a red signal. This prevented subjects starting to type, prior to the presentation of the final stimulus.

The authors replicated the anticipatory awareness of intentional actions; subjects perceived themselves to have moved on average 96 ms before they actually did. A similar finding was found in this experiment, even though the time of the action in was taken to be the first keypress and not the EMG. Haggard et al believed that the keypress was more "functionally relevant to the goal of the action" than the onset of EMG. Moreover, they also found that as the sequence length increased, so did both the RT and the anticipatory awareness of the *first* keypress: the times of action awareness were -52, -110 and -126 ms for word-string lengths of one, three and five respectively. This suggests that the motor awareness is generated *after* the buffer search stage, and *before* the assembly and dispatch of the motor command.
Attempts to relate the awareness of actions (and intentions) with brain potentials have been carried out using the lateralised readiness potential (LRP). Eimer (1998), amongst others, notes that the LRP, by providing a measure of the contralateral negativity in addition to the bereitschaftstpotential (BP) in the ipsilateral cortex, gives a more precise dimension for quantifying motor preparation. Specifically, the LRP onset indicates that the stage of response selection has terminated — the motor system has actively 'decided' to produce a left or right response.

Haggard and Eimer (1999), using the Libet-style clock, required subjects to make fixed or free movements with their index fingers and to judge their awareness of their intention or action. The data was split into those trials with early awareness and those with late awareness of intention. Interestingly, the BP occurred later in those trials with early awareness and vice versa. However, the LRP (calculated by subtracting the activation in electrode C4' from electrode C3', which are approximately left and right SMA) demonstrated the opposite pattern in that the trials with early awareness had significantly earlier LRP activity than late awareness trials, which had later LRP activity.

Haggard and Eimer (1999) suggest that the LRP onset "is not the starting point of the psychological processes that culminate in voluntary movement, but it may be the starting point of conscious awareness of our motor performance." Their data imply that the awareness of intention, like the awareness of action, is intimately linked with the timing of the specific action. That is, one's awareness of initiating a voluntary action is related to the preparation of a specific movement, not an indeterminate state of intending to perform an action of some sort.

7.1.2.2 Judgements and localisation of reactive actions

Using transcranial magnetic stimulation (TMS), Haggard and Magno (1999) suggested that the awareness of reactive actions is localised somewhere between the supplementary motor area (SMA) and the primary motor cortex (M1). Subjects observed a Libet-style clock. A random warning stimulus was presented, followed by a 'go' signal at a fixed time. Subjects were not to respond in the absence of a 'go' signal. Median RTs to the 'go' stimulus were established for each subject. TMS was then applied 75 ms prior to each subject's median RT over the M1, the SMA and the control site V (the visual cortex). The data confirmed previous findings that TMS over M1 delays RT (Day, Rothwell, Thompson, Maertens de Noordhout, Nakashima, Shannon and Marsden, 1989).

However, some of this delay entered conscious awareness when the M1 was stimulated. TMS over SMA produced smaller delays, but a greater part of these small delays entered awareness. This implies that conscious awareness is generated, at least partly, at some time between the activation of the SMA and the M1. That is, when the M1 was stimulated, the conscious awareness had already been produced, so the delays in RT did not fully enter conscious awareness. However, when the SMA was stimulated, the conscious awareness was yet to be produced, resulting in the majority of the delay entering conscious awareness and being reported by the subjects. The effect is, however, partial; some of the M1 delay did enter awareness, and some of the SMA delay did not. This agrees with the proposition by Dennett and Kinsbourne (1992) who suggest that it is unlikely that (i) one area alone is responsible for conscious awareness of action and (ii) conscious awareness is generated at a single instant. Nevertheless, these authors have provided clear evidence that part of the conscious awareness of action is generated between the activation of the SMA and the M1.

7.1.3 Awareness of Stimuli

Experimentally, the conscious awareness of stimuli has generally been used as a control in action awareness studies rather than as an event of interest itself. Libet et al (1983) delivered random tactile stimuli to the back of the same hand that made the voluntary movements. The value for the stimuli awareness was then subtracted from the action awareness, to give " a 'corrected' average" (Libet et al, 1983). Interestingly, subjects reported the stimulus to have occurred 47 ms before it actually did, that is, anticipatory. Therefore, the 'corrected' average was 39 ms, that is, subjects believed they moved 39 ms before they actually did. This method of subtracting the awareness of stimuli from the awareness of action to obtain a real value in time, of the awareness of action, is somewhat dubious. It is clear from the subjective judgements about action that the subjects were reporting some pre-motor event and not muscular activity. However, it is not clear why Libet et al believed that the judging of the timing of an external stimulus could be regarded as a "measure of the way the subject is handling those reporting factors that the S [stimulus awareness] and W [intention awareness] series have in common."

Haggard et al (in press) carried out two experiments examining the perceived time of actions and their concomitant stimuli. In the first experiment, subjects judged the time of the beep, the time of a willed action, the time of a beep to which the subject responded, the time of the response to the beep, the time of a willed operant action, and finally, the time of the beep elicited by a willed operant action. Operant actions were those in which the subjects' action produced a beep — operance is when the beep occurred 200 ms after the keypress. The results of this experiment indicated that when subjects reacted to the stimuli, or caused beeps, the perceived time of these events shifted; they were attracted to each other. Haggard et al (in press) defined this process as efferent binding.

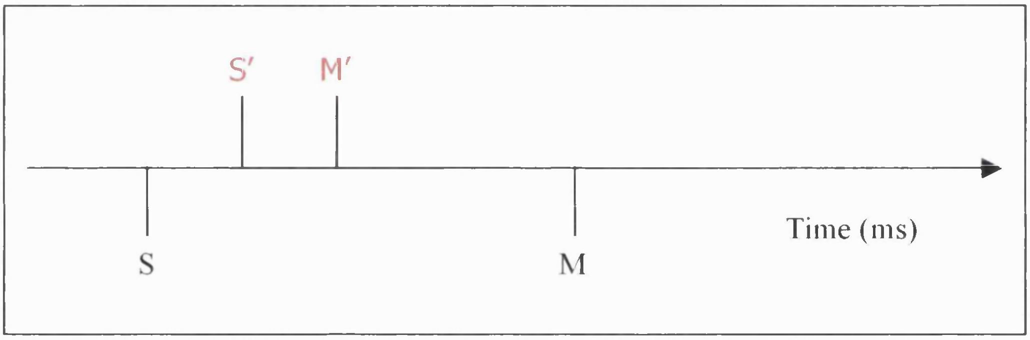
Efferent binding is a hypothetical brain process in which one learns how one's intentions are associated with the representations of one's actions. It is suggested that consciousness plays a key role in constructing the relationship between intention and action and the environmental consequence of the action. Thus, efferent binding is vital in the attribution of agency. Efferent binding is similar to perceptual binding, a process occurring in visual object perception. It is also important for the correct attribution of actions to agents, including the self, that is, efferent binding is important when distinguishing between the consequence of ones own actions, the actions of others and external stimuli.

The second experiment included the six conditions from experiment one, in addition to four new, non-causal conditions. These conditions were: judge the time of the first of two beeps, judge the time of the second of two beeps, judge the first of two keypress actions and judge the time of the second of two keypress actions. These last two conditions involved training subjects to make these actions at an interval of 250 ms. The results of this experiment indicate that perceptual attraction of events does not occur in the non-causal (or sequential context). When subjects' actions are intimately linked with stimuli, the percepts are bound together. When events are temporally but not causally linked, people do not perceive them as being closer together than they actually are. That is, the phenomenon of efferent binding is only applicable to situations in which people have a causal link with their environment, not in general perceptions of time.

In conclusion, these experiments suggest three things, (i) conscious representations of actions and events are integrated by an efferent binding process; (ii) the efferent binding process is not a result of a general perceptual attraction, but is specific to actions; and (iii) efferent binding "forms part of a wider process integrating our actions with their causes and effects in which they occur" (Haggard et al, in press).

Johnson and Haggard (2001) examined the conscious awareness of responses and stimuli in a lateralised cued-attention paradigm (Posner, 1980). Subjects fixated on a central Libet-style clock, in the centre of which the cue (left, <; right, >; or neutral, +) was shown. Eighty percent of the cues were accurate. Subjects then had to react to the left or right light emitting diode (LED) and make judgements about the time of their response or the time of the stimulus. Similar to previous findings, subjects reported anticipatory awareness of their actions (153 ms earlier than the first EMG). However, in opposition to Libet et al (1983), Johnson and Haggard found that subjects perceived the stimuli to occur, on average, 64 ms later than it really did, that is, with a delayed percept. The largest judgement errors were in those trials with invalid cues. If the stimulus (S) and its percept (S′), and the movement (M) and its percept (M′) are represented on a time line (Figure 7.2), it can be seen that the percepts of the stimulus and the action are perceptually attracted to each other. Neither stimulus nor movement judgements were significantly affected by cue validity, therefore, the perceptual binding was not altered.

Figure 7.2. A schematic of the stimulus (S), it's percept (S′), the movement (M) and its percept (M′), based on the results from Johnson and Haggard (2001).



In summary, the experiments reviewed show that the subjective values of conscious awareness of intention and action produced by Libet et al (1983) vary widely from experiment to experiment. However, the differences between the subjective judgements and the actual values do produce robust effects. These processes have been localised with respect to awareness.

7.1.4 Experiments

This chapter contains two experiments on the subjective elements of the truncation task; one requiring subjects to judge their awareness of their actions, and the other requiring them to judge their awareness of stimuli. By comparing judgement errors in different conditions, rather than relying on specific numerical values, the problems with the methods of subjective report and cross-modal mapping are controlled for.

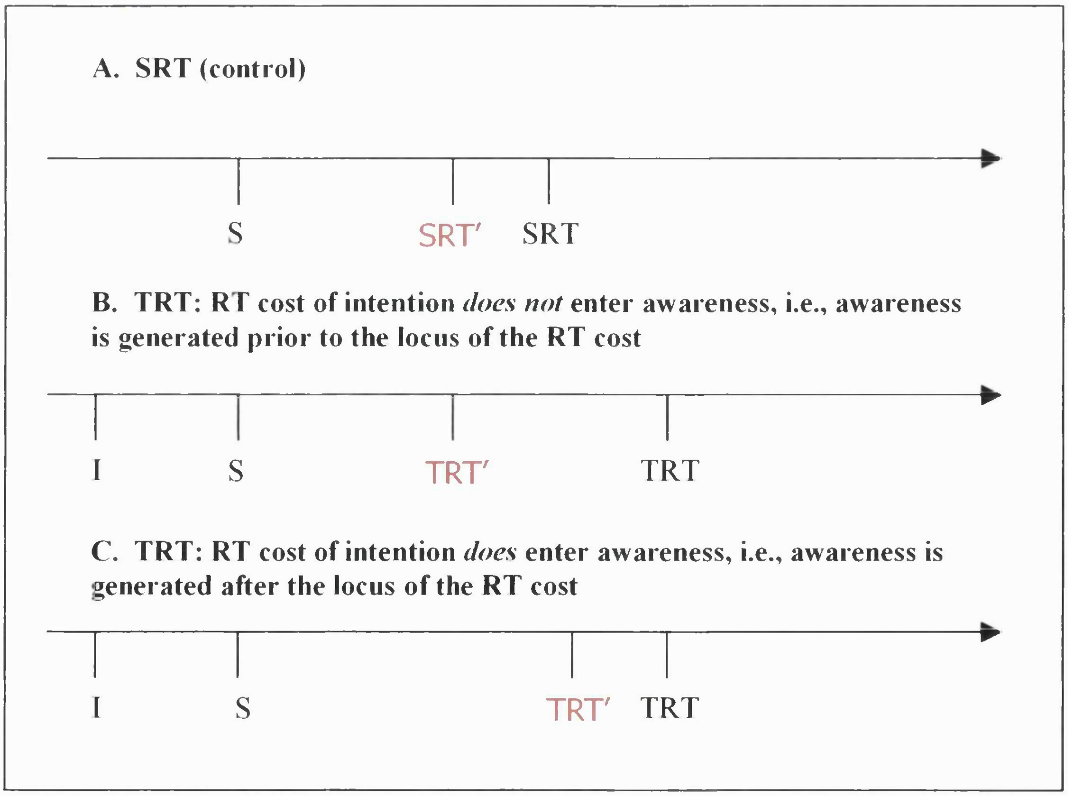
7.1.4.1 Hypotheses/proposals for action awareness experiment

i. It is predicted that intentional preparation will result in altered action judgements.

ii. It is predicted that the RT cost of intention will occur prior to the generation of action awareness.

Figure 7.3 schematises the possible outcomes dependent on whether the action awareness is generated *after* the RT cost of intention, or whether the action awareness is generated *before* the RT cost of intention. Direct comparison of the judgement errors in SRT (where the effect of intention is not present) and TRT (where the effect of intention is present) should provide evidence in support of one or the other prediction.

Figure 7.3. Schematic to show the control condition, SRT (A), the prediction of the RT cost of intention not entering awareness (B), and the prediction of the RT cost of intention entering awareness (C). I = intention, S = stimulus, SRT = simple reaction time, SRT′ = judged SRT, TRT = truncated reaction time, TRT′ = judged truncated reaction time.



The literature reviewed here indicates that action awareness is generally anticipatory. Therefore, it is predicted that the awareness of the reaction in SRT (SRT′) and the awareness of the reaction in TRT (TRT′) will be anticipatory. If the RT cost of intention enters awareness, the percept of TRT will be shifted by a similar amount to that demonstrated in SRT. However, if the RT cost of intention does not enter awareness, the percept of TRT (TRT′) will be shifted by a much larger amount, because the subject will not be aware that they have reacted more slowly.

7.1.4.2 Hypotheses/proposals for stimulus awareness experiment

i. It is predicted that intentional preparation will alter the stimulus judgements, due to some shift of attention away from the stimulus towards the intentional action.

ii. It is predicted that the RT cost of intention will be reduced when subjects report stimulus awareness.

7.2 METHOD

7.2.1 Subjects

Twelve subjects consisting of eight women and four men participated in both experiments. The majority of the students were UCL postgraduate and undergraduate students. Their mean age was 28.25 years (s.d. 7.67). All subjects were right-handed and were not suffering from any known neurological impairments.

7.2.2 Apparatus

In both the action (section 7.2.2.A) and stimuli (7.2.2.S) experiments, subjects were seated approximately 60 cm in front of a computer. Subjects' arms rested on a table in front of the computer monitor. Actions were made via the left button on a conventional mouse with the roller ball removed and judgements and trial activations were made via a keyboard. Two loud speakers were situated directly in front of the subject, such that auditory stimuli were presented ambiently without lateralisation. The experimenter was seated behind the subject.

7.2.2.A Procedure of action experiment

Subjects performed a truncation experiment consisting of three experimental conditions: an intentional action condition, an SRT condition and a TRT condition (similar to the previous experiments). All conditions required subjects to judge the perceived time of their keypress (action). Subjects made their judgements based on the position of the hand on the Libet-style clock (Libet et al, 1983). This clock was presented in the middle of the screen and was approximately 5 cm in diameter. The numbers on the clock were the same as the time in minutes of a conventional clock, at intervals of 5 seconds.

The clock hand rotated at a speed of 2560 ms per rotation. Subjects were instructed to fixate on the clock, but not to follow the clock hand around. Every block consisted of 40 trials. The SRT and intentional action conditions consisted of one block, and the TRT condition consisted of two blocks because the trials were forked in the analyses. Two types of data were recorded and analysed, RT data and judgement errors. Judgement errors were calculated by subtracting the time of the keypress from the subjects' judgement of that event.

In all conditions (i) the clock hand continued to rotate for a random amount of time after the response, to ensure that subjects could not use the stopping of the rotation as a means of calculating when they had pressed the response button; (ii) when the clock stopped, a box appeared saying "please enter the time of the event" to which they were instructed to enter a number between 0-59 on a keyboard to record when they thought they had moved; and (iii) subjects activated the next trial by pressing Enter.

7.2.2.1.A SRT condition (SRT_A)

In the simple reaction time, action judgement condition (SRT_A), subjects waited for the presentation of a beep, which occurred at random within the time window of 2-10 seconds after the activation of each trial. Subjects were instructed to react as quickly as possible to the beep and then to make a judgement about the time of their keypress.

7.2.2.2.A Truncation condition (TRT_A)

The truncated reaction time, action judgement condition (TRT_A) involved the subjects beginning each trial by preparing to make an intentional action. If, however, the stimulus occurred, they were instructed to respond to the beep as quickly as possible. The stimulus occurred at random between 2-10 seconds after the start of the trial. This condition was repeated because approximately half the trials were intentional actions and half the trials were reactions to the stimulus. The required response was the same as for the SRT condition.

7.2.2.3.A Intentional action condition

Subjects were instructed to prepare and make a freely-willed intentional action. No auditory stimuli occurred. Subjects were asked not to use the clock to pre-decide when they should move, but to really prepare an intentional action, at the time of their own choosing, in a non-stereotyped manner, whilst observing the time of its occurrence.

7.2.2.S Procedure of stimulus experiment

Six subjects performed this experiment first, followed by the action experiment. The other six subjects performed the action experiment first, followed by the stimulus experiment. Each subject performed the conditions within each experiment in a different order (six possible orders of three conditions, and six subjects). The stimulus beep differed from that in the action experiment in order to minimise confusion for the subjects over whether they were judging stimulus or action awareness. The beeps were of equal duration (0.01 seconds), but of different frequency (0.5 KHz and 1.0 KHz, respectively). Judgement errors were calculated by subtracting the time of the stimulus from the subject's judgement of that event.

There were three conditions encompassing four blocks: (i) the SRT_S (simple reaction time, stimulus judgement) condition; (ii) the TRT (truncated reaction time, stimulus judgement) condition (with two blocks); and (iii) the *listen* condition. All conditions required subjects to judge the perceived time of the stimulus. Subjects made their judgements as before, based on the position of the hand on the Libet-style clock. RT data and judgements were recorded for analysis.

7.2.2.1.S SRT condition (SRT_S)

In the SRT_S condition, subjects waited for the presentation of a beep, which occurred at random within the time window of 2-10 seconds after the activation of the trial. Subjects were instructed to react as quickly as possible to the beep, with a right index finger keypress on the left button of a conventional mouse, and to note the position of the hand on the clock at the time of the stimulus. Subjects made judgements of stimuli times as in the action experiment.

7.2.2.2.S The truncation condition, stimulus judgement (TRT_S)

The TRT_S condition required the subjects to begin each trial by preparing to make an intentional action. The stimulus was programmed to occur at random between 2-10 seconds after the start of the trial. If the stimulus occurred they were instructed to respond as quickly as possible. This condition was repeated in an additional block because approximately half the trials were intentional actions (TINs) and half the trials were reactions to the truncating stimuli (TRTs).

Subjects were required to give judgements about the time of the perceived stimulus in the trials in which a stimulus occurred. When subjects made an intentional action before the stimulus occurred the trial was not considered for analysis.

7.2.2.3.S Listen

This condition required subjects to listen to the stimulus and report the time they perceived it to have occurred. As before, the stimulus occurred at random between 2-10 seconds after the trial began.

Both the action and stimulus experiments were performed with the same set of subjects to allow for comparisons to be made between the judged awareness of stimuli and actions. Previous experiments, such as Libet et al (1983) and Haggard et al (in press) showed large inter-subject variability. Therefore, it seemed logical to compare stimulus and action judgements within the same set of subjects, to reduce extraneous effects.

7.3 RESULTS

Table 7.1 gives the abbreviations for all the conditions in both the action and the stimulus experiments. The truncation condition produces two types of trials, those in which the subject made their intentional action before the beep occurred, truncated intention trials (TIN) and those in which they reacted to the truncating stimulus, truncated reaction trials (TRT). These are forked at the stage of analysis and considered as two conditions thereafter.

Table 7.1. Conditions and their relevant abbreviations.

JUDGEMENT	TRUNCATION CONDITION	ACTION TYPE	ABBREVIATION CODE
ACTION	No	Intention	Intentional action
	No	Reaction	SRT_A
	Yes	Intention	TIN_A
	Yes	Reaction	TRT_A
STIMULUS	No	No Action	*Listen*
	No	Reaction	SRT_S
	Yes	Intention	TIN_S
	Yes	Reaction	TRT_S

7.3.1 RT Data

The values in Table 7.2, were trimmed to be within 150 -1000 ms, as in previous experiments in this thesis. Observation of the RT data indicated that one subject had RTs that were much larger than the other eleven subjects. This subject's RTs for the four conditions (SRT_A, SRT_S, TRT_A and TRT_S), were between 4 and 8 standard deviations larger than the mean of the other 11 subjects (reported in Table 7.2). For this reason, this subject, who was clearly an outlier, was discarded. 12% of the remaining trials were discarded due to the RT trimming criterion, subject and technical error. 70% of the remaining action judging trials in truncation were truncated reactions (TRTs). Coincidentally, 70% of the remaining stimulus judging trials were truncated reactions (TRTs).

Table 7.2. Mean (s.d.) reaction times for SRT and TRT, action and stimulus judgements conditions (SRT_A, SRT_S, TRT_A and TRT_S).

	CONDITION		
JUDGEMENT	**SRT**	**TRT**	**Mean (s.d.)**
ACTION	278 (45.88) **SRT_A**	360 (35.78) **TRT_A**	322 (26.51)
STIMULUS	279 (43.37) **SRT_S**	305 (83.77) **TRT_S**	288 (51.64)
Mean (s.d.)	278 (41.62)	329 (37.85)	305 (34.92)

The reaction times for the SRT action and stimulus judgement conditions were both faster than those for the TRT conditions, as previously seen in the experiments in chapters 2, 3, 4, 5 and 6. The RTs for both SRT_A and SRT_S were almost identical. However, there was a clear difference (of 55 ms) in RT between the TRT_A and TRT_S. When subjects were required to judge the time of the stimulus in the truncation condition, they reacted much faster than when they were required to judge the time of their action. If the RT in SRT_S was slower than in SRT_A, then the difference in RT between TRT_A and TRT_S might be due to the difference in attentional focus due to the event being judged, rather than intentional preparation. However, the RTs were almost identical in SRT, therefore, intentional preparation seems to have a much more marked effect on reaction when subjects are judging the action.

The RT cost of intention when subjects judge action awareness was 360 - 278 = 82 ms, which was larger than the in other experiments in this thesis. The RT cost of intention when subjects judge stimuli was 305 - 279 = 26 ms, which was smaller than in previous experiments.

A planned t-test between SRT_A and TRT_A indicates that the RT cost of intention (82 ms) was indeed highly significant ($t_{(10)} = -4.35$, $p = 0.001$, uncorrected). However, the planned t-test between SRT_S and TRT_S confirms that the RT cost of intention of only 26 ms, was non significant ($t_{(10)} = -1.36$, $p = 0.20$, uncorrected). The RT cost of intention was therefore increased compared to previous experiments, when subjects focused on judging their actions, and was decreased compared to previous experiments, when they focused on judging the stimulus.

A 2 (condition: SRT or TRT) x 2 (judgement type: action or stimulus) ANOVA with RT as the dependent variable, produced the following results. As expected, there was a significant effect of condition, $F_{(1,10)} = 24.66$, $p < 0.001$ (overall mean RTs are clearly faster in SRT and TRT), a non significant effect of judgement type: $F_{(1,10)} = 3.65$, $p = 0.085$ (the RTs are almost identical in SRT_S and SRT_A) and a non significant interaction ($F_{(1,10)} = 3.27$, $p = 0.10$). The non significant interaction implies that when it comes to reacting, the effects of condition and judgement type were independent. That is, while the attentional focus does modulate the RT cost of intention to some extent, this effect is not statistically reliable.

7.3.1.1 Attentional components of the judgement tasks

As demonstrated above, although judgement type did not significantly affect RT, there was a clear difference in RT between the TRT_A and TRT_S conditions, implying that there may be an effect of attentional focus on RT, particularly in the truncation condition. In order to examine the attentional components in the stimulus judging and action judging truncation tasks, the percentages of truncated intentional trials (TINs) in TIN_A and TIN_S were compared. This is equivalent to studying percentages of TRTs since the number of trials in both TIN and TRT summate to 100% of the total trials in the truncation condition.

The number of TINs could provide some independent evidence about subjects' attentional focus in these tasks. If subjects were focusing most of their attention on the stimulus in the stimulus judgement condition, they may have been attending to the stimulus more than the action, and therefore, failed to devote sufficient attentional resources to making the intentional action. This might predict more TRTs (reactions) than TINs (intentional actions) in the stimulus judgement conditions. Conversely, in the action judging condition, there may be more TINs than TRTs, because subjects were focusing more on their actions, rather than the external environment and therefore, might have made more intentional actions.

The mean (s.d.) percentages of TIN_A and TIN_S were 27.24 (9.14) and 31.89 (17.89), respectively. This is the opposite direction predicted if attentional focus was responsible for the difference in RT. When subjected to a t-test, these values were shown to be non significantly different ($t_{(10)} = -0.66$, $p = 0.53$, uncorrected). This suggests that the difference in attentional focus in the action and stimulus judging conditions does not affect the RTs in the reactive trials in the truncation condition.

The *listen* and intentional action conditions required no reactions. Hence, there was no RT data to analyse for these two conditions.

7.3.2 Awareness Data

Comparisons and conclusions of the absolute values of judgements cannot be clearly attributed because there are large inter- and intra-subjective variations. Hence, the following sections detail the use of *differences* between values (judgement errors), which provide a less biased form for comparison. Judgement errors were calculated by subtracting the *actual* time of the event (action or stimulus) from the *subjective percept* of the time of the event. Table 7.3 reports the judgement errors for the SRT and TRT conditions for both action and stimulus judgement conditions.

Table 7.3. Mean (s.d.) judgement errors for SRT and TRT in action and stimulus judgement conditions (SRT_A, SRT_S, TRT_A and TRT_S).

	CONDITION		
JUDGEMENT	**SRT**	**TRT**	**Mean (s.d.)**
ACTION	-133.48 (104.77) **SRT_A**	-88.92 (128.88) **TRT_A**	-109.74 (115.30)
STIMULUS	45.26 (89.43) **SRT_S**	67.31 (74.70) **TRT_S**	55.39 (77.50)
Mean (s.d.)	-46.97 (92.53)	-20.23 (100.56)	-32.02 (95.80)

The action judgement errors were anticipatory for both SRT and TRT, although more so in SRT. In contrast, the stimulus judgements were delayed in both SRT and TRT. The anticipatory action awareness is in concordance with Libet et al (1983), Haggard (1999) and Haggard et al (1999).

When the action and stimulus means were collated, subjects perceived the event to have occurred 47 ms before it did in SRT and 20 ms before it did in TRT, implying that they were more accurate at perceiving events when preparing an intentional action. Therefore, in both SRT and TRT, subjects experienced events (actions and stimuli) prior to their occurrence.

When the SRT and TRT means were collated to produce means for action and means for stimulus judgement errors, the values produced were similar to findings by Haggard (1999), Haggard et al (1999) and Johnson and Haggard (2001). That is, anticipatory action awareness and delayed stimulus awareness.

A 2 (condition: SRT or TRT) x 2 (judgement type: action or stimulus) ANOVA of judgement errors, produced the following results. A significant effect of condition,

($F_{(1,10)} = 21.52$, $p = 0.001$), a significant effect of judgement type ($F_{(1,10)} = 97.90$, $p < 0.0001$) and a non significant interaction ($F_{(1,10)} = 0.60$, $p = 0.46$). The significant main effect of condition suggests that, overall, people judge awareness more accurately in the TRT conditions, than in the SRT conditions. The significant effect of judgement type suggests that subjects judge stimuli to occur later than actions. The non significant interaction suggests that condition and judgement type do not influence each other, that is, they are independent effects.

7.3.2.1 Action awareness data

The judgement errors of all conditions in which both reactive and intentional actions were made and judged are analysed and discussed in this section. This partially represents the action judgement data from 7.3 in addition to whether the perceived time of intentional actions and reactive actions differ. Table 7.4 presents the means and standard deviations of the intentional action, SRT_A, TRT_A and TIN_A conditions.

Table 7.4. Mean (s.d.) judgement errors for SRT_A, TRT_A, TIN_A and intentional action conditions.

	TRUNCATION	
ACTION	**NO**	**YES**
INTENTIONAL	-3 (56.40) **Intentional action**	-11 (76.32) **TIN**
REACTIVE	-133 (104.77) **SRT_A**	-89 (128.88) **TRT_A**
Mean (s.d.)	-46.97 (92.53)	-20.23 (100.56)

A 2 x 2 ANOVA of judgement errors on truncation (yes or no) and action type (intentional or reactive) was carried out. The conditions compared were, in order: TRT_A (truncation: yes, action type: reactive), TIN_A (truncation: yes, action type: intentional), SRT_A (truncation: no, action type: reactive) and intentional action (truncation: no, action type: intentional). The effect of truncation was non significant, $F_{(1,10)} = 1.53$, $p = 0.24$ (the truncation judgements did not differ significantly from the SRT judgements). The effect of action type was, however, significant, $F_{(1,10)} = 23.26$, $p = 0.001$ (judgements were less anticipatory when subjects made intentional rather than reactive actions), as was the interaction, $F_{(1,10)} = 17.76$, $p = 0.002$. The significant interaction implies that the effect of truncation on perceived time was dependent on the type of action made. That is, anticipatory awareness of reactions was more pronounced in SRT than in TRT.

The difference between reaction and intentional actions could be due to the event 'finishing' earlier when it is intentional, therefore, the subjects judge the event more accurately. In the pupil dilation experiment detailed in chapter 4, it was found that the latency of the peak dilations were earlier in the intentional action (707 ms) and TIN (637 ms) conditions, than the SRT (901 ms) and TRT (800 ms) conditions. This implied that the whole event (making the action) finished earlier when subjects made intentional actions, rather than reactions. This 'prior knowledge' component of the intentional action conditions, namely the intention, may have led subjects to be more accurate at judging the times of their actions in the two conditions in which they made intentional actions (intentional action and TIN). However, this interpretation is only tentatively suggested due to it being based on subjective percepts, which fluctuate from trial-to-trial and from subject-to-subject.

This difference between the reactive and intentional conditions could, alternatively, be explained by efferent binding (Haggard et al, in press). In the reactive conditions, a stimulus occurred and in the intentional conditions, subjects made an action at a time of their own choosing, *without responding to a stimulus*. The percepts of the actions in the reactive conditions were large and anticipatory and this was greater in the SRT where no intentional preparation occurred. It might be, therefore, that the percept of the action was attracted to the stimulus, biasing the accuracy of the subjects' judgements, resulting in negative percepts. In the TRT condition the effect of efferent binding between the stimulus and the action was less pronounced, perhaps due to the influence of the intentional preparation. This issue also arose in the stimulus judging conditions and is statistically approached in section 7.3.3.3.

In previous experiments, for example Haggard (1999), large inter- and intra-subject variability was found in judgement tasks. For this reason, subjects' means and standard deviations of their judgement errors for SRT_A and TRT_A have been provided, along with the total means and standard deviations (Table 7.5).

Table 7.5. Mean (s.d.) judgement errors for the SRT_A and TRT_A conditions (and the differences) in which subjects judge stimulus time, in ms.

SUBJECT	SRT_A	TRT_A	DIFFERENCE (TRT_A - SRT_A)
1	-188.89 (81.58)	-185.17 (109.42)	3.72
2	-15.53 (68.55)	-52.82 (77.44)	-37.29
3	-49.98 (81.35)	27.57 (62.47)	77.55
4	29.19 (145.75)	108.66 (105.18)	79.47
5	-137.06 (96.56)	-78.94 (125.4)	58.12
6	-45.44 (85.96)	-48.38 (83.66)	-2.94
7	-145.47 (863.62)	-71.48 (97.23)	73.99
8	-307.09 (150.19)	-383.04 (175.42)	-75.95
9	-213.46 (192.51)	-100.97 (181.78)	112.49
10	-255.48 (82.77)	-180.76 (126.76)	74.72
11	-139.09 (155.72)	-12.81 (136.55)	126.28
Mean (s.d.)	-133.48 (104.77)	-88.92 (128.88)	44.56 (63.80)

As can be seen from Table 7.5, there is no clear pattern. All the judgement errors are negative except three: both action and stimulus judgement errors for subject 4 and the action judgement error for subject 3. For seven of the eleven subjects, the TRT_A judgement error is smaller, and therefore, closer to the actual time of the action. The difference between the SRT_A and TRT_A judgement errors by each subject ranges from -2.94 ms for subject 6 to 126.28 ms for subject 11. However, most judgement errors are different by approximately 70 ms (in both directions), although the mean difference is 44.56 ms.

A t-test of the judgement errors in SRT_A and TRT_A indicate that there was a significant difference between them: $t_{(10)} = -2.32$, $p = 0.043$, uncorrected. This suggests that the percept of the action was bound more closely to the action in TRT_A, that is when subjects have previously been intending. Conversely, when the subjects simply wait for the stimulus, as in the case of SRT_A, their percept of the action was bound more closely to the stimulus.

To conclude, observation of Figure 7.3 in light of the judgement errors, indicates that the subjects are aware of their delayed reaction in the truncation condition. The event responsible for the RT cost of intention, therefore, seems to occur prior to the generation of action awareness.

This observation coheres with an executive function locus of the process that occurs when subjects change from intentional action preparation to reaction (postulated to be a 'switch process'). Furthermore, previous research (e.g. Haggard and Magno, 1999) suggests that conscious awareness of action occurs *after* the activation of the frontal motor areas, between the activation of the SMA and the M1. The present result, combined with Haggard and Magno (1999) implies that for subjects to be consciously aware of the RT cost of intention, it must be generated prior to the activation of the frontal motor areas.

Table 7.6 shows the Pearson correlation coefficient (r), the regression equation for judgement error and RT and the ANOVA results for the regression line, by subject, and the mean (s.d.) correlations, slopes and one-sample t-tests on the slopes for SRT_A and TRT_A.

Table 7.6. The Pearson correlation coefficient, r, the regression equation for judgement error (JE) and reaction time (RT), the ANOVA results for the regression line, by subject, and the mean (s.d.) correlations, slopes and one-sample t-tests of slopes, for SRT and TRT action awareness judgements.

	SIMPLE REACTION TIME, ACTION JUDGEMENTS (SRT_A)				TRUNCATED REACTION TIME, ACTION JUDGEMENTS (TRT_A)			
Subject Number	Correlation Coefficient, r	Regression Equation for Judgment Error	F-value of Regression	p-value for Regression	Correlation Coefficient, r	Regression Equation for Judgment Error	F-value of Regression	p-value for Regression
1	-0.29	-0.71RT-22.68	3.23	0.081	0.60	0.28RT-295.66	23.87	< 0.001*
2	-0.042	-0.064RT+0.95	0.06	0.81	0.11	0.040RT-67.57	0.48	0.49
3	-0.32	-0.41RT+50.69	3.88	0.057	0.07	0.024RT+20.81	0.21	0.65
4	-0.0024	-0.0040RT+30.24	< 0.01	0.99	-0.05	-0.032RT+119.03	0.11	0.75
5	0.068	0.36RT-209.52	0.17	0.68	0.35	0.20RT-157.18	5.29	0.027*
6	0.44	0.84RT-256.07	8.76	0.0054*	0.37	0.16RT-113.61	6.71	0.013*
7	-0.095	-0.21RT-75.80	0.32	0.58	-0.01	-0.00641RT-69.04	< 0.01	0.96
8	-0.61	-1.1RT+47.28	22.09	< 0.001*	0.24	0.21RT-461.91	3.73	0.058
9	-0.39	-0.72RT+26.11	6.13	0.018*	0.25	0.25RT-191.93	3.53	0.066
10	-0.52	-0.98RT+28.57	13.39	< 0.001*	0.20	0.18RT-248.15	2.20	0.14
11	-0.57	-0.64RT+68.89	15.16	< 0.001*	-0.06	-0.049RT+3.74	0.21	0.65
Mean (s.d.)	-0.21 (0.32)	-0.33 (0.59) [mean (s.d.) of slope]	$t_{(10)} = -1.87$ p = 0.091 [one-sample t-test of slopes]		0.19 (0.32)	0.12 (0.12) [mean (s.d.) of slope]	$t_{(10)} = 3.15$ p = 0.010 [one-sample t-test of slopes]	

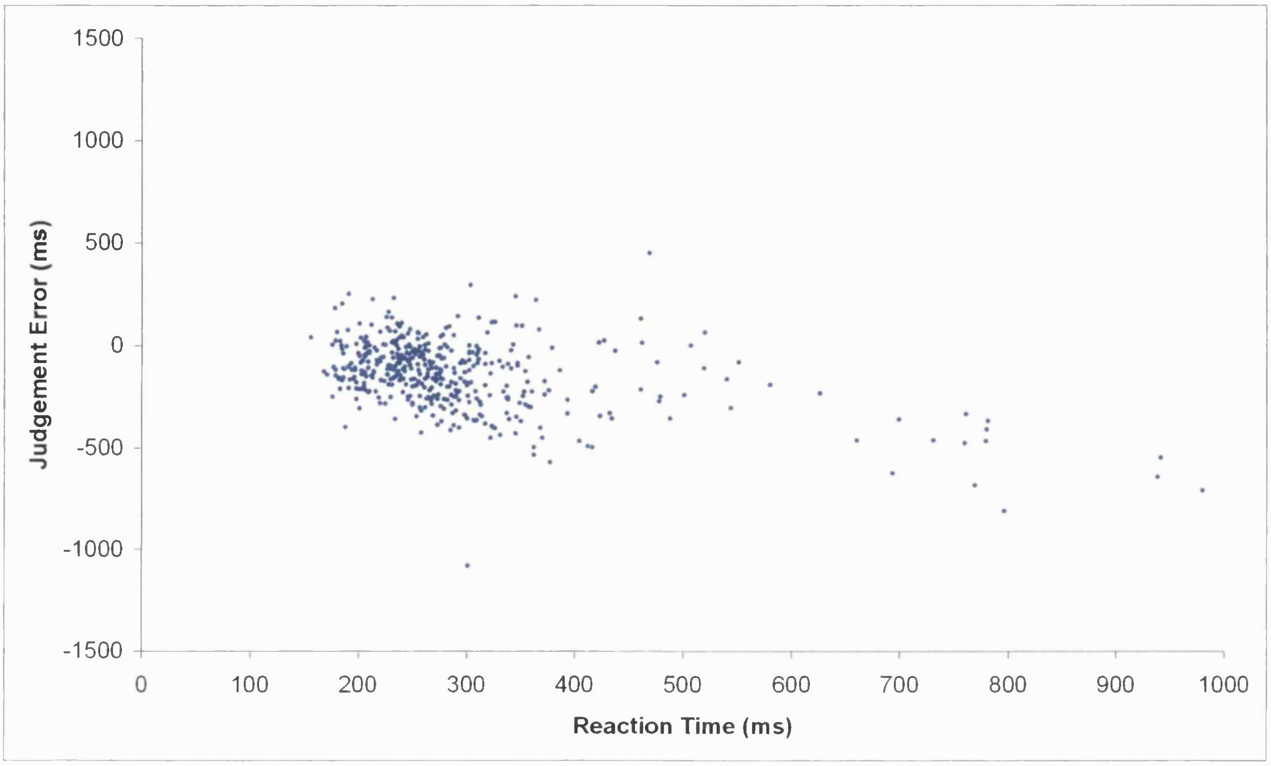
* denotes significance

Similar to the mean judgement errors in Table 7.5, there was no clear pattern. The correlations were a mixture of positive and negative values; nine were negative in SRT and three in TRT. The mean correlation was negative in SRT, and positive in TRT, but of equal size.

Five of the SRT regression lines were significantly different from zero, and three of the TRT regression lines were significantly different from zero. Subject 6 was the only subject who had significant regression lines for both SRT and TRT. A clear pattern regarding the significance of the regression lines in SRT and TRT does not emerge when observed subject by subject.

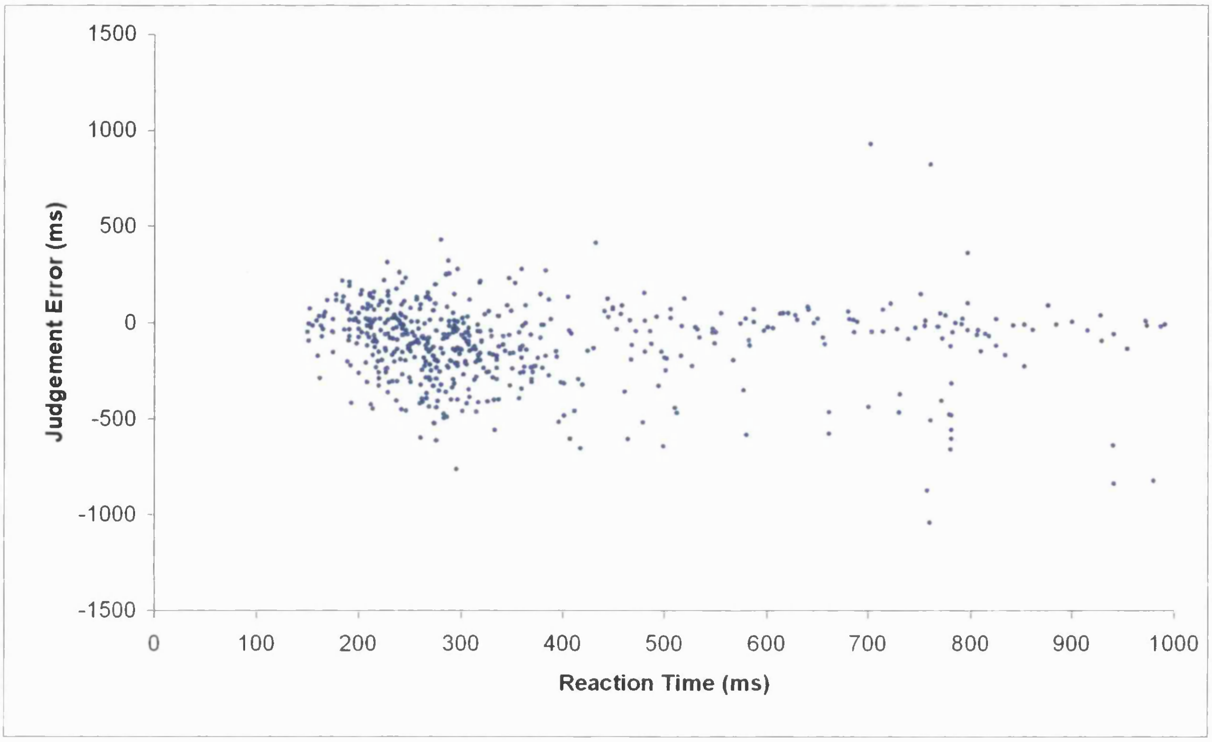
The total means of the slopes of the regression equations (-0.33 (0.59) for SRT and 0.12 (0.12) for TRT) indicate that there was a trend, with a stronger negative slope in SRT (Figure 7.4) and a weaker, positive slope in TRT (Figure 7.5). Notably the variance was much larger in SRT than in TRT. A t-test on the slopes was significant ($t_{(10)} = -2.37$, $p = 0.039$, uncorrected), suggesting that the relationship between RT and judgement error was different in SRT and TRT. The one-sample t-test on the slopes for SRT indicated that when intra-subjective variability is removed, the judgement error could not be predicted from the RT, that is, there was no significant relationship between RT and judgement error. These data show that longer RTs result in *more* anticipatory judgement errors in SRT. That is, people are unaware of a random lengthening of RT and report awareness of a ‘typical’ or ‘average’ RT. There is regression to the mean. However, it is not significant. In contrast, longer RTs produce *less* anticipatory judgements. Thus, people are aware of random trial-to-trial variations in their RTs.

Figure 7.4. Graph of judgement error regressed on to reaction time (RT) in ms for the SRT action judgement condition (SRT_A).



Meanwhile, the judgement error appears to be dependent on the RT in the truncation condition (significant one-sample t-test) implying that action awareness is generated *after* the main source of variation in TRT_A. Figure 7.5 also supports this suggestion because it shows the trials to be less densely clustered in TRT_A than in SRT_A, implying that subjects judged their actions based on their RTs in TRT. However, the mean slope is almost flat (0.12) indicating that although there is a significant pattern of small positive slopes found across subjects, the relationship between judgement error and RT is small; that is, although larger RT predicts larger judgement error, the increment in judgement error is small. It might be conjectured that there is an additional processing stage in TRT, which is absent in SRT, namely the switch process. This process contributes an additional source of randomness to TRTs. However, it appears that action awareness is generated after the putative switch process, which therefore, allows subjects to weakly track this random noise. Taken together, theses analyses support the hypothesis of an executive switch process causing the RT cost of intention.

Figure 7.5. Graph of judgement error regressed on to reaction time (RT) in ms, for the TRT action judgement condition (TRT_A).



7.3.2.2 Stimulus awareness data

The mean judgement errors in Table 7.7 show that subjects were most accurate when judging a stimulus that they did not react to (*listen*), and were least accurate when they had to react to the stimulus after they had been intending (TRT_S). That is, it appears that as task complexity increased, judgement error increased. However, a 1 x 3 ANOVA on these stimulus judging conditions showed that there were no significant differences between these conditions ($F_{(2,20)} = 2.10$, $p = 0.15$).

Table 7.7. Mean (s.d.) judgement errors for *listen*, SRT_S and TRT_S conditions.

CONDITION	*Listen*	SRT_S	TRT_S
Mean	34.17	45.26	67.31
(s.d.)	(92.68)	(89.43)	(74.70)

Table 7.8 presents each subject's mean (s.d.) judgement errors for the SRT_S and TRT_S conditions, in which they were judging the time of the stimulus.

Table 7.8. Mean (s.d.) judgement errors for the SRT_S and TRT_S conditions (and the differences) in which subjects judge stimulus time, in ms.

SUBJECT	SRT_S	TRT_S	DIFFERENCE (TRT_S - SRT_S)
1	-8.83 (145.41)	56.44 (134.86)	65.27
2	66.64 (110.18)	99.50 (87.78)	32.86
3	91.84 (134.56)	81.28 (78.70)	-10.56
4	176.53 (121.83)	220.55 (146.46)	44.02
5	27.54 (186.61)	33.79 (268.60)	6.25
6	81.70 (79.80)	81.38 (46.21)	-0.32
7	41.54 (83.64)	86.38 (160.27)	44.84
8	-180.24 (117.87)	-86.97 (167.08)	93.27
9	96.80 (148.48)	114.12 (234.82)	17.32
10	21.08 (66.27)	31.78 (86.47)	10.70
11	83.21 (244.98)	22.21 (102.06)	-61.00
Mean (s.d.)	45.26 (89.43)	67.31 (74.70)	22.06 (41.14)

As with the action judgements in Table 7.4, there was no clear pattern of judgements and high inter-subject variability in SRT_S and TRT_S. Subject 8 gave anticipatory judgements for SRT and TRT, with larger anticipatory judgements in SRT, and subject 1 gave a mean anticipatory answer for the stimulus awareness. The other nine subjects reported perceiving the stimuli to be delayed in both the SRT and TRT conditions, that is, later than they actually occurred.

A t-test of the SRT_S and TRT_S values shows them to be non significantly different ($t_{(10)} = -1.78$, $p = 0.11$, uncorrected). This is the reverse of the finding for SRT_A and TRT_A. It seems that when subjects are judging their actions, intentional preparation aids their judgement accuracy, but when they are judging stimuli, the intentional preparation slightly hinders, but does not significantly delay, judgement accuracy. The non significant difference suggests that stimulus processing was not seriously delayed in the truncation condition because the delay was seen in both SRT and TRT. In particular, the RT cost of intention cannot be explained by delayed conscious detection of the stimulus in the truncation conditions. This provides subjective evidence pointing to the same conclusion reached on the basis on objective ERP evidence in chapter 6.

Table 7.9 shows the Pearson correlation coefficient (r), the regression equation for judgement error and RT and the ANOVA results for the regression line, by subject; and the mean (s.d.) correlations, slopes and one-sample t-tests on the slopes for SRT_S and TRT_S.

Table 7.9. The Pearson correlation coefficient, r, the regression equation for judgement error (JE) and reaction time (RT), the ANOVA results for the regression line, by subject, and the mean (s.d.) correlations, slopes and one-sample t-tests of slopes, for SRT and TRT stimulus awareness judgements.

	SIMPLE REACTION TIME, STIMULUS JUDGEMENTS (SRT_S)				TRUNCATED REACTION TIME, STIMULUS JUDGEMENTS (TRT_S)			
Subject Number	Correlation Coefficient, r	Regression Equation for Judgement Error	F-value of Regression	p-value of Regression	Correlation Coefficient, r	Regression Equation for Judgement Error	F-value of Regression	p-value of Regression
1	-0.033	-0.092RT+10.92	0.04	0.84	0.80	1.01RT-199.16	71.35	< 0.001*
2	-0.066	-0.088RT+92.20	0.15	0.70	-0.32	-0.33RT+187.01	2.45	0.13
3	0.53	1.95RT-325.48	12.90	< 0.001*	0.19	0.36RT+3.87	1.59	0.21
4	0.16	0.13RT+137.78	0.90	0.35	0.36	0.38RT+111.37	6.67	0.013*
5	0.29	0.47RT-86.64	3.11	0.087	0.16	0.87RT-171.68	1.83	0.18
6	0.31	0.80RT-113.01	3.75	0.061	0.16	0.12RT+26.56	0.77	0.39
7	0.098	0.16RT-2.25	0.36	0.55	0.020	0.32RT+75.52	0.012	0.92
8	0.14	0.15RT-229.40	0.72	0.40	0.11	0.27RT-160.12	0.62	0.43
9	-0.069	-0.11RT-134.44	0.16	0.69	0.23	0.35RT-65.98	0.86	0.37
10	-0.24	-0.14RT+64.93	1.70	0.20	0.020	0.022RT+24.39	0.018	0.89
11	0.014	0.047RT+68.95	0.005	0.94	0.31	0.40RT-112.59	4.22	0.047*
Mean (s.d.)	0.10 (0.22)	0.30 (0.62) [mean (s.d.) of slope]	$t_{(10)} = 1.60$ p = 0.14 [one-sample t-test of slopes]		0.19 (0.27)	0.34 (0.37) [mean (s.d.) of slope]	$t_{(10)} = 3.11$ p = 0.011 [one-sample t-test of slopes]	

* denotes significance

The correlations were a mixture of positive and negative in SRT_S (four were negative) and were mainly positive in TRT_S (ten of eleven were positive). They were generally larger in TRT_S, as can be seen by the mean correlation, which was nearly twice the size.

The mean slope for SRT_S was positive (0.30 [0.62]), as was the mean slope for TRT, which was slightly larger, but similar (0.34 [0.37]). As in the action experiment, the SRT variance was almost twice the size of the TRT variance. A t-test on the slope shows that there was no clear difference between SRT_S and TRT_S ($t_{(10)} = -0.21$, $p = 0.84$, uncorrected). This implies that there was no difference in the relationship between the stimulus judgement errors and RT in SRT and TRT.

The pattern of significance of the regression lines in TRT, was similar to that found in the action analyses. The majority of the regression lines were non significant in both the TRT_S (eight of eleven subjects) and the SRT_S (ten of eleven subjects) conditions. That is, the regression lines in both SRT and TRT were not significantly different from zero for the majority, which means that the stimulus judgement error could not generally be predicted from the RT in the SRT and TRT condition. The non significant one-sample t-test found in SRT_S verifies this claim.

Unexpectedly, the one-sample t-test on the slopes for TRT_S was significant which contradicts the majority of the subjects, that is, the slopes *were* significantly different from zero. This suggests that the judgement error increases as the RT increases, which might imply that when subjects reacted very slowly, they perceived the stimulus to have also occurred more slowly. This again raises the possibility that delayed conscious detection of the stimulus might explain the RT cost of intention. However, the same positive slope was also found in the SRT condition, implying that this finding was not specific to truncation.

Figure 7.6. Graph of judgement error regressed on to reaction time (RT) in ms, for the SRT stimulus judgement condition (SRT_S).

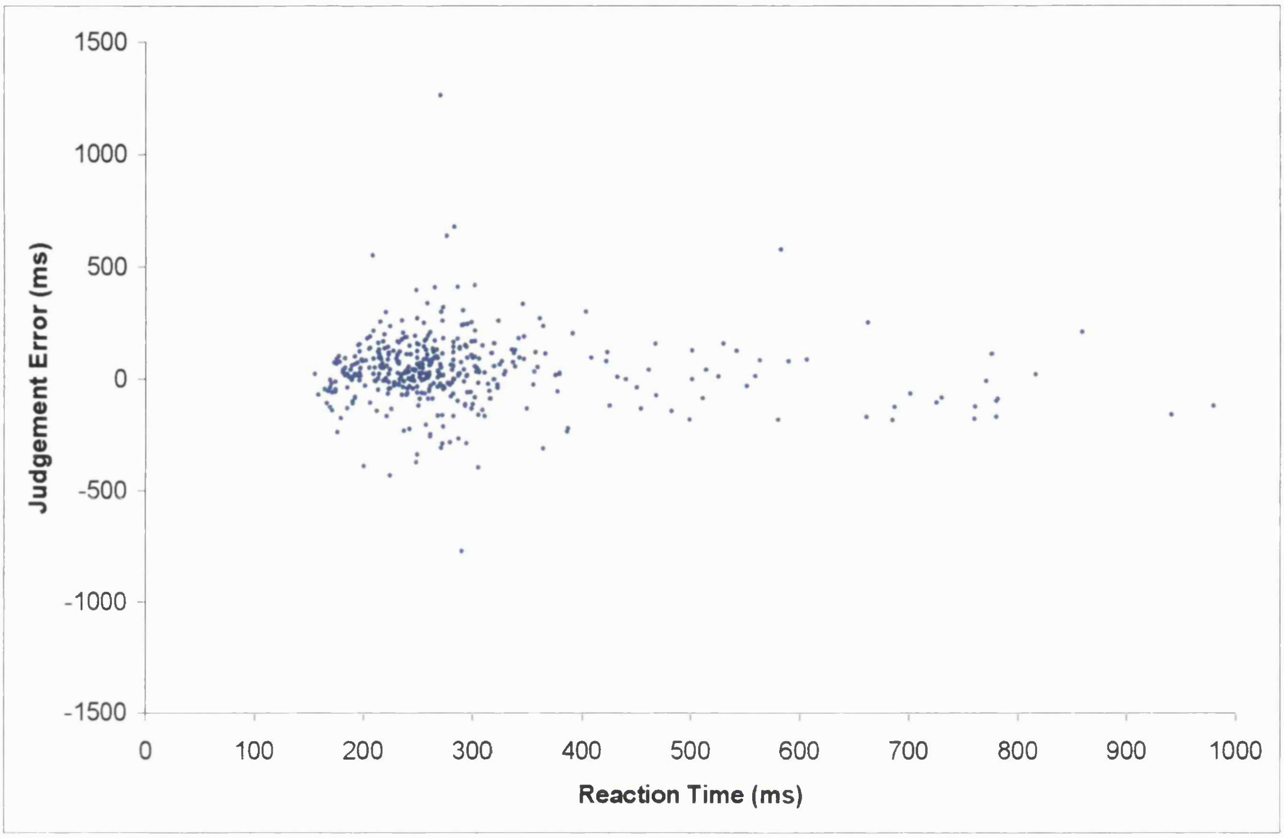


Figure 7.6 shows that the majority of the trials were mainly clustered between the judgement errors of -100 to 300 ms, and were mostly positive and densely packed.

Figure 7.7. Graph of judgement error regressed on to reaction time (RT) in ms, for the TRT stimulus judgement condition (TRT_S).

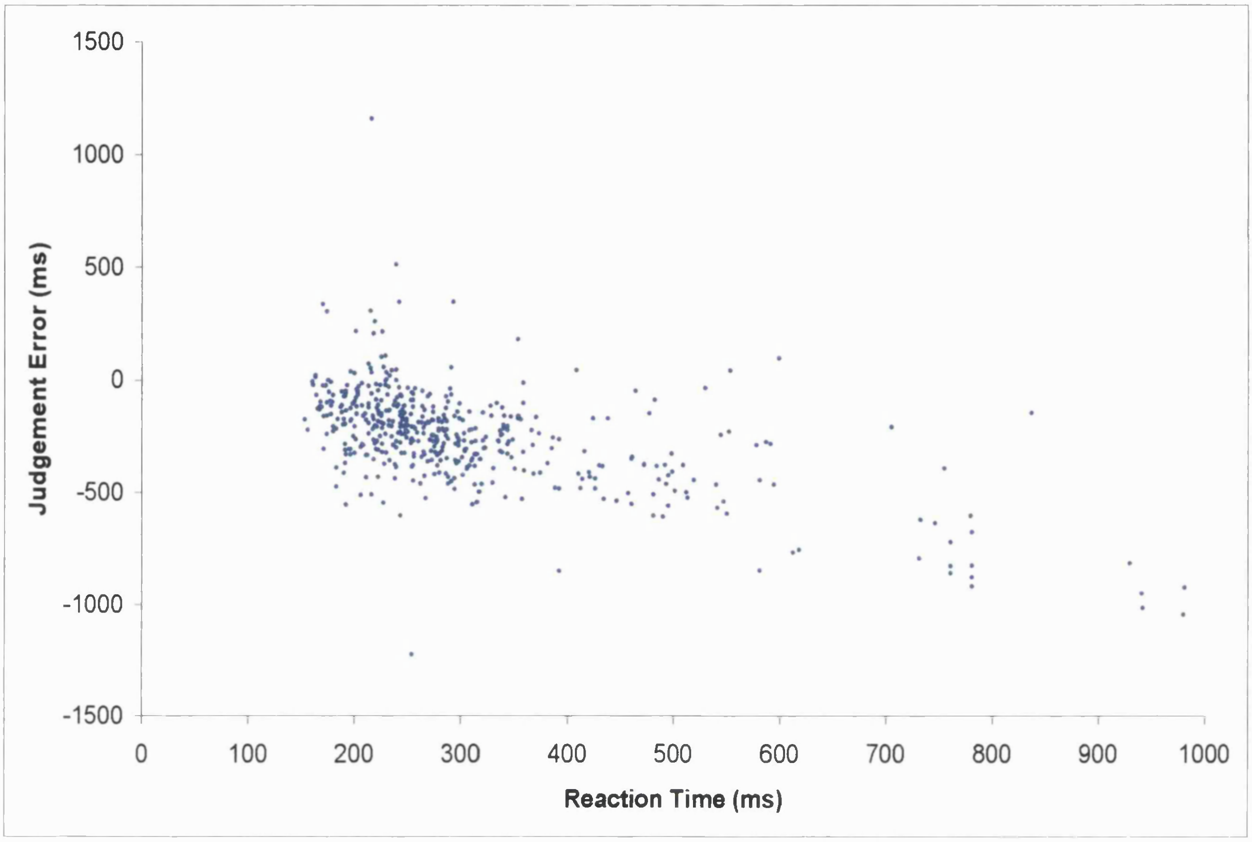


Figure 7.7, similar to Figure 7.5 is less densely clustered than the SRT Figures (7.4 and 7.6). However, both Figures 7.6 and 7.7 (stimulus judgement conditions) differed from the action judgement conditions (Figures 7.4 and 7.5) in that the majority of the trials have positive, rather than negative judgement errors. Moreover, observation of Figures 7.6 and 7.7 indicate that the trials were more densely clustered, but that the overall relationship between judgement error and RT appears to be less pronounced than it was in the action awareness data (Figures 7.4 and 7.5). Conclusions drawn from these figures are tentative due to their not accounting for the varied influence of each subject. The varied influence of each subject is important when using a measure such as judgement error, which has large inter- and intra-subjective variability.

7.4 DISCUSSION

7.4.1 Brief Summary of Results

i. Subjects reacted more quickly in SRT compared with TRT, again producing an RT cost of intention. The main effect of judgement type (action or stimulus) on RT, and the interaction, were found to be non significant.

ii. A significant RT cost of intention (51 ms) was found when the RT data from action and stimulus judgements were collated. However, the RT cost of intention was significant in the action awareness data (82 ms) and non significant in the stimulus awareness data (26 ms).

iii. The analysis of the attentional components implied that focusing on the stimulus or action did not differentially effect the RTs in the truncation conditions. This attentional modulation of the RT cost of intention was not statistically reliable.

iv. When judging action awareness, there was a significant effect of condition, implying that the dual task nature of truncation or the intentional preparation improved the subjective ability to judge the action percept (compare Figure 7.8 and Figure 7.3 B and C). The significant effect of action type indicated that subjects were more accurate at judging action awareness when they did not react.

v. The mean action judgement error was found to be smaller in TRT compared with SRT, which implied that the RT cost of intention occurs prior to the generation of action awareness. Therefore, subjects are probably consciously aware of the RT cost of intention.

vi. The judgement error was significantly larger in SRT_A than in TRT_A implying that the percept of the action was more strongly bound to the stimulus in SRT (Figure 7.8).

vii. The judgement task (action or stimuli) and the context within which the judgement was made significantly modulated the judgement errors; the judgements were more anticipatory in the action awareness data and were attracted more strongly to the stimulus (Figure 7.8).

7.4.1.1 Hypotheses

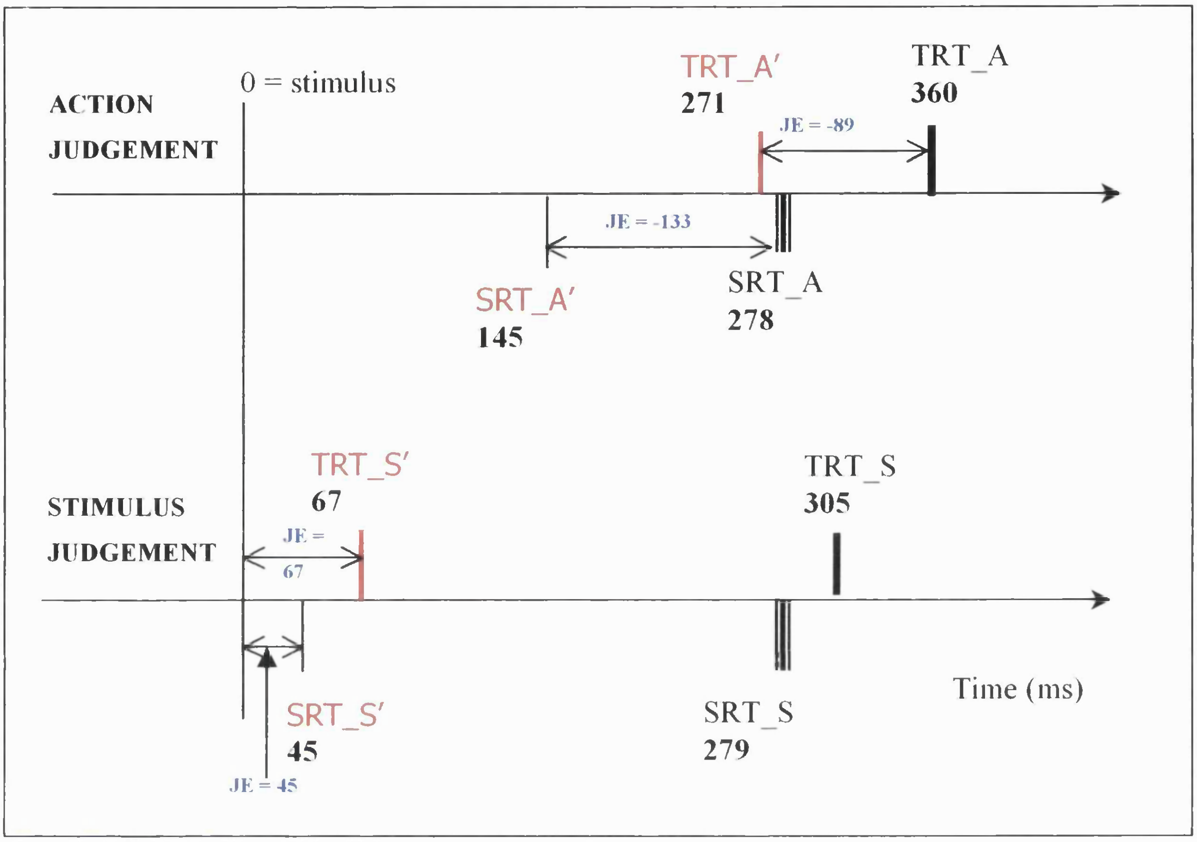
Following the hypotheses laid out previously (in section 7.3.1.1), the results of the experiment suggest:

i. Intentional preparation aids action judgements but is modulated by the occurrence of the stimulus which attracts the action percept.
ii. The RT cost of intention appears to be localised prior to the generation of action awareness.
iii. Intentional preparation does not significantly effect stimulus judgements.
iv. The RT cost of intention is not significantly reduced when subjects focus on the stimulus, rather than the action.

7.4.1.2 Main findings

Figure 7.8 schematises the RTs, judged RTs and judged stimulus times. The top part of the Figure represents the RTs and judged RTs for the SRT and TRT action judging conditions (SRT_A and TRT_A). The top of the time-line shows the judged and the actual RT for the TRT condition; and the bottom shows the judged and the actual RT for the SRT condition. The difference between the judged and the actual RTs, defined as the judgement error (JE), was clearly larger and more anticipatory in the SRT condition (-133 ms compared to -89 ms). This implied that subjects were aware of their delayed RT in truncation, and, by implication, were therefore aware of the RT cost of intention. The action judgement section therefore resembles the predicted schematic 7.3 A and C, because the truncation judgement error was clearly not larger than the SRT judgement error.

Figure 7.8. Schematic to show actual reaction times (SRT_A, TRT_A, SRT_S and TRT_S) and subjects judged awareness (SRT_A′, TRT_A′, SRT_S′ and TRT_S′), and judgement errors (JEs) in ms.



The bottom part of the Figure represents the stimulus judging SRT and TRT conditions (SRT_S and TRT_S). Again, the top of the time-line shows the RT and the judged stimulus time for the TRT_S condition, and the bottom of the line shows these values for the SRT_S condition. The judgement errors for these two conditions, defined as the actual stimulus time minus the judged stimulus time were positive and smaller than those found for the action judging conditions. That is, subjects perceived the stimuli to have occurred *after* they actually did occur. Interestingly, the action appears to attract the percept of the stimulus by equal amounts in both the SRT and TRT conditions. That is, the difference between the RT and the perceived stimulus occurrence is 234 ms for TRT and 238 ms for SRT, implying that the stimulus is perceived similarly in both SRT and TRT. This suggests that when subjects were concentrating on reporting the occurrence of the stimulus, they did not perceive their reactions to be slower in TRT compared to SRT. However, this effect was minimal, as shown by the non significant difference between the perceived stimulus occurrence in SRT_S and TRT_S. Alternatively, the stimulus could be said to be exerting a weaker attraction on the TRT_S percept than on the SRT_S percept, resulting in less accurate percepts in TRT.

Notably, the above observation is different to the pattern found in the action judgement conditions, where subjects *were* seemingly aware of their delayed RT in the truncation condition. Taken together, it might be concluded that (i) in the conventional truncation condition, when subjects were not instructed to direct their attention to either the action or the stimulus that a compromise occurs; and (ii) an ambiguity about the action exists in truncation such that the percepts of the stimulus and the action are less strongly affected by efferent binding.

7.4.2 Efferent Binding

The process of efferent binding was clearly occurring in these experiments. The stimulus judgement errors were slightly, though not significantly, more delayed in SRT than in *listen*, suggesting that the action attracted the percept of the stimulus in SRT and TRT. In the action judging experiment, the SRT judgement error was large and anticipatory implying that the percept of the action was strongly attracted to the stimulus.

As previously observed (section 7.4.1) the percept of the action in TRT was attracted to the stimulus to a lesser degree than in SRT, that is, the judgement error was smaller and less negative in TRT. Perhaps this is due to the ambiguity about the action in the truncation condition. The subject starts a truncation condition trial by starting to prepare an intentional action at a time of their own choosing. Therefore, the preparatory activity results in the assumption that the action was intentional and thus, not perceptually bound to a stimulus. However, when the truncating stimulus occurred, the subject reacted and the action became a reaction to the stimulus and was therefore, at some level, bound to this truncating stimulus.

Appropriately, the percept of the action when the subject reacts to the truncating stimulus (TRT) is intermediate between the intentional action and SRT. This ambiguity is also shown in Table 7.10, where the difference between the stimulus and action judgement error in context 3 (truncation) was less marked than in SRT.

7.4.3 Conclusions

The overall RT cost of intention was similar to those found in the preceding five chapters. The RT cost of intention therefore, appears to be relatively robust and replicable. The fact that an RT cost similar to those previously found was produced when the action and stimulus judging conditions were collated, implies that in the truncation condition subjects divided their attention between the internally-driven event, the intentional action and perceiving the stimulus in the external environment.

The judged percept of the truncated RT in the action judging condition was smaller and less anticipatory than the corresponding SRT. This suggests that subjects were aware of their slower RT in the truncation condition. Therefore, the processes or event responsible for the RT cost of intention must occur before the generation of action awareness.

It was implied from previous experiments that this event is perhaps a 'switch' between the internally-generated and externally-triggered motor systems. This experiment has shown that subjects were aware of this event, suggesting that it must occur prior to the generation of action awareness.

Recent research has shown that action awareness seems to be generated at the level of the SMA (Haggard and Magno, 1999). Fried et al (1991) showed that when the SMA was stimulated in 13 patients with intractable epilepsy undergoing pre-operative evaluations, subjects reported the "urge to move" in a certain body part at certain low thresholds. In certain electrodes, increased electrical stimulation produced actual movements of the same body part. These data imply that the SMA "is involved in the intention invested in motor activity". Therefore, if the SMA is involved in the intentional component of willed action and the generation of action and its awareness, then this event, posited to be a 'switch', must occur *prior* to the activation of the areas responsible, possibly the SMA, for generating the awareness of action. It is tentatively suggested that this switch occurs in the prefrontal cortex.

The following and final chapter of this thesis summarises chapter 1 and the findings of the ensuing six experimental chapters. The findings of this thesis are then discussed in the context of their wider implications. Finally, further research is suggested.

Chapter 8

SUMMARIES, CONCLUSIONS AND THE WIDER CONTEXT OF RESEARCH INTO INTENTION AND REACTIVITY

8.1 SUMMARY

Chapter 1 of this thesis began by presenting the background to the study of intention. It was noted that philosophers frequently tackled issues relating to intention such as free will and the mind-body problem using both theoretical reasoning and experience. However, an unambiguous consensus about the nature of intention does not exist. Early scientific research into intention was hindered by the lack of objective measures. Many psychologists at the turn of the last century felt unable to use subjective or introspective means due to the problems that psychology had in establishing itself as a science. Scientists did not use introspection because they believed it was unreliable and essentially difficult to manipulate and, therefore reliably control. A brief review of mental chronometry, task switching and the psychological refractory period was presented next.

The scientific study of intention was reviewed and discussed in the next section. The discovery of the bereitschaftspotential by Kornhuber and Deecke (1965) greatly affected the way that intention could be studied. By measuring the electrical activity from the human brain via non-invasive electrodes, psychologists were able to qualitatively distinguish between an intentional action and a reaction. Libet et al (1983) used the BP in a series of novel experiments in which it was found that subjects' brains were active prior to the awareness of their intention.

The next section of chapter 1 reviewed anatomical, neurophysiological and clinical evidence in support of a dichotomy in the motor system. The evidence presented suggested that there is an intentional or internally-generated motor system and a reactive or externally-triggered motor system. That is, there is a clear difference in the brain between those movements that are made following an intention and those that are made in response to a stimulus. This thesis then went on to examine the inter-relation of these two hypothetical motor systems.

The thesis was divided into two sections: (i) the objective study of the relationship between the internally-generated and externally-triggered motor systems; and (ii) the subjective study of their relationship. The next stage of this summary is therefore divided into two sections.

Table 8.1 summarises the main information pertaining to each chapter.

Table 8.1. Summary of the main features of each experiment presented in this thesis.

Chapter number	TRT (ms)	SRT (ms)	RT cost of intention (ms)	Number of conditions	Number of trials	Percentage of TRT trials
2	355	304	51	6	30	48
3	347	298	49	2	30	48
4	379	320	59	3	30	63
5	337	309	28	3	30	64
6	417	354	63	6	40	38
7 action	360	278	82	3	80	70
7 stimulus	305	279	26	3	80	70

Observation of Table 8.1 reveals that there is no consistent relationship between the RT cost of intention and the percentage of TRT trials. In two of the experiments (chapter 5 and the stimulus judging section of chapter 7) the RT cost of intention was small and non significant. In chapter 5 the RT cost of intention did not reach conventional levels of significance, although the difference between the SRT and TRT conditions was in the predicted direction. If the number of subjects were increased, it would be expected that the RT cost of intention would increase to similar levels as found in the other chapters. In chapter 7, the non significant RT cost of intention implies that subjects reactivity differs when they report stimulus awareness compared to action awareness. This might seem to be a result of attending to the stimulus, although, a non significant main effect of judgment type was found. Overall, six of the eight RT costs of intention were found to be significant. These averaged 51 ms over all the experiments. Therefore, the RT cost of intention appears to be a stable finding.

8.2 THE OBJECTIVE STUDY OF INTENTION AND REACTIVITY

The first five experiments of this thesis, chapters 2 to 6, examined the inter-relation between the intentional and the reactive motor systems. Five hypotheses were proposed as possible ways in which these two systems may interact. Briefly, these were: (i) unitary – the ‘two’ systems comprise a single system; (ii) independence – the activity of one system is not influenced by activity of the other; (iii) facilitatory – the activity of one system is facilitated by activity in the other; (iv) inhibitory – the activity of one system inhibits the activity of the other; and (v) competing for limited cognitive resources – if one system is making use of the resources, the other cannot, implying that there is an element of exclusivity.

8.2.1 Summary of Chapter 2

The data from chapter 2 clearly indicated that there was an RT cost when subjects were preparing an intentional action and had to react to a truncating stimulus compared to a condition in which subjects simply reacted to a stimulus. This RT cost of intention was large (51 ms) and significant. Comprehensive analyses of the data, including the types of errors made, implied that the internally-generated and externally-triggered systems were unlikely to be related in an independent, facilitatory or unitary manner.

In the choice RT condition, subjects were unable to prepare for the stimulus in advance because there were two possible truncating stimuli. In the SRT condition, due to the possibility of only one truncating stimulus, pre-stimulus preparation could occur. A significant RT cost of intention was found in SRT, as previously noted. In contrast, no RT cost of intention was found in the choice RT condition, suggesting that (i) the systems were unlikely to be related in an inhibitory manner; and (ii) there was an incompatibility between intentional and reactive preparation in the SRT condition. Intentional preparation was apparently the cause of the RT cost of intention since intentional preparation appears to prevent the type of preparation that is generally advantageous in SRT. The lack of RT cost of intention in the choice RT conditions does not exclude a switch process between intention and reaction. A possible reason for the lack of an RT cost of intention might be that there was an overlap between the perceptual (stimulus) and executive (switch process) functions occurring following the presentation of the truncating stimulus.

It was concluded that the process of swapping from the internally-generated to the externally-triggered system occurred at the higher level of the motor system (brain level) rather than at the lower level (muscles or effectors); and that the first stage of this process involved the stopping of the intentional action which was then followed by a switch mechanism between the two systems.

8.2.2 Summary of Chapter 3

A control experiment, manipulated the foreperiod within which the truncating stimulus occurred. It was proposed that the RT cost of intention might be an artefact of the use of variable foreperiod. That is, whether the longer RT in the truncation condition might be due to the effect of varied expectation of when the stimulus is going to occur. The foreperiods from the truncation condition were recorded, randomised and re-used (yoking) in the simple reaction time condition, in order to equate the temporal distributions of the event outcomes of SRT and truncation.

The results indicated that the when the effect of variable foreperiod (or *when* the truncating stimulus occurs) was removed, an RT cost of intention comparable to that found in chapter 2, was still produced (49 ms). Hence, the RT cost of intention is unlikely to be an artefact of variable foreperiod.

8.2.3 Summary of Chapter 4

Chapter 4 used an indirect measure of cognitive processing, pupil dilation, to examine differences between intention and reactivity. The pupil dilates when a subject is preparing an intentional action, similar to the BP, although temporally delayed.

Observation of the pre-movement and pre-stimulus pupil dilation indicated that subjects appeared to prepare the intentional action, as requested in the truncation condition. An RT cost of intention similar to those in previous experiments was found (59 ms), and there were clear differences in the pre-movement mean dilation, the latency and amplitude of the peak dilation between an intention, a reaction and a truncated intention (TIN) and truncated reaction (TRT). Summarily, (i) there was pre-movement dilation in the intentional action and truncation conditions and none in SRT, supporting previous findings that intentional preparation results in pre-movement pupil dilation; (ii) the peak dilation was larger in the truncation conditions than in the intentional action and SRT conditions, implying that the truncation condition involves a larger cognitive load than simple reactions; (iii) the peak dilation was earlier in the truncation condition than in a simple RT condition, implying that delayed stimulus processing was not a contributing factor to the longer RT in the truncation condition.

8.2.4 Summary of Chapter 5

A control experiment was performed in order to manipulate the expectation of the truncating stimulus. The effect of *when* the truncating stimulus occurred (a by-product of variable foreperiod) was examined in chapter 3 and found not to affect the RT cost of intention. In contrast, chapter 5 examined the effect of *whether or not* the truncating stimulus occurred. It was also important to exclude the possibility that the expectation of whether or not the stimulus occurred was producing the pre-movement dilation.

The data suggests that intention and not expectation was the probable cause of the pre-movement dilation. The RT cost of intention was smaller than the RT cost of expectation. Although this might suggest that there is a facilitatory relationship between the internally-generated and externally-triggered system, the data from previous and subsequent experiments, refutes this suggestion.

8.2.5 Summary of Chapter 6

Chapter 6 used ERPs to further examine the inter-relation between the internally-generated and externally-triggered motor system, particularly, whether the RT cost of intention might be due to delayed stimulus processing. It was proposed that in the truncation condition, subjects would be attending to their intentions, thus delaying their reaction to the external stimulus. Measures of auditory evoked potentials largely failed to support this suggestion. Therefore, it was concluded that the RT cost of intention is due to a switch between the intentional and reactive motor systems.

Analysis of the EMG data, in order to further examine the inhibitory and switching hypotheses, was supportive of the switching mechanism. However, analysis of the EMG data supposes that the switch from the internally-generated to externally-triggered systems is occurring at the lower level of the motor hierarchy (muscles) rather than at the higher level (brain). Nonetheless, although analyses in the experiment in chapter 2 implied that the switch process was occurring at the higher level, the involvement of the lower level, although not prevalent, may contribute to the overall process.

The *intend stop* condition, similar to the truncation condition in terms of intentional preparation and different to truncation in terms of response to the stimulus (stop rather than react), produced an ERP very similar to that seen in truncation. This similarity suggested that the majority of the RT cost of intention is due to stopping the intentional action rather than due to a delay in activation of the externally-triggered system following its inhibition due to the activation of the internally-generated system.

8.3 THE SUBJECTIVE STUDY OF INTENTION AND REACTIVITY

Chapter 7 first reviewed the conscious awareness of actions and stimuli and briefly mentioned the associated concept of efferent binding. Two related experiments in chapter 7 examined the conscious awareness of action and stimuli respectively. Both experiments involved an SRT condition and a truncation condition.

The RT cost of intention was larger in the action awareness experiment than in the stimulus awareness experiment. Judgements of the awareness of the action were generally anticipatory in contrast to delayed judgements for stimulus awareness. Subjects appeared to be aware of the event responsible for the RT cost of intention, because they reported a delayed percept of their reactions in truncation (TRT), which they would not have done had they perceived their reactions to be equal to those in SRT. Also, the percept of the action was bound more closely to the stimulus in SRT, implying a possible ambiguity on the subject's part about the relationship between the stimulus and the action in the truncation condition (TRT).

The variance in judgement error from trial-to-trial in the action awareness judgements was larger in SRT than in the truncation condition. This implied that subjects reported an average movement time, that is, they were unaware of their trial-to-trial variations. In TRT however, the inter-trial variance appears to be smaller, suggesting that subjects were aware of their delayed RT on a trial-by-trial basis. This supports the idea that (i) the awareness of the RT cost of intention is manufactured after the cause of the variance; (ii) subjects are able to accurately report their slower responses in the truncation condition; and (iii) therefore, the event responsible for the RT cost of intention seems to occur prior to the generation of action awareness.

The latter observation coheres with the notion that the locus of this process of changing from intentional action preparation to reaction (postulated to be a 'switch process') is in the pre-frontal areas, that is, an executive function locus. As previously discussed, (chapter 7, sections 7.3.2.1, 7.4.7) recent research (Haggard and Magno, 1999, Fried et al, 1991) suggests that the conscious awareness of action occurs after the activation of the frontal motor areas. The implication of this reasoning is that for subjects to be consciously aware of their delayed RT in truncation, the event responsible for the delay must occur prior to the activation of the processes generating action awareness. Existing studies suggest these include the frontal motor areas (Haggard and Eimer, 1999). It is tentatively suggested that the switch from intention to reactivity occurs in the pre-frontal cortex.

8.4 Conclusions

8.4.1 Relationship Between the Intentional and Reactive Motor Systems

When subjects switched from intentional action preparation to reaction following the presentation of a truncating stimulus, a substantial and significant RT cost of intention was typically found. This averaged 51 ms over seven experiments. The occurrence of this RT cost of intention suggested that the internally-generated and externally-triggered motor systems were not related in a unitary, independent or facilitatory way, because these hypotheses predicted equal or smaller RTs in the truncation condition than in the simple RT control.

The key psychological difference between the SRT and TRT condition is the presence of intention in the latter but not in the former. In SRT, the subject reacts to the stimulus, and in TRT the subject prepares to make an intentional action, but then reacts to the truncating stimulus. When two conditions are similar on all measures bar one, and a significant difference is found between them, it is generally assumed that the feature that is different is the cause of the significant difference (Donders, 1868). It seems safe to suggest therefore, that the difference between the two conditions, the intentional preparation, is the cause of the RT cost, hence the phrase "RT cost of intention". Since the switch between the two motor systems cannot easily be examined experimentally in the opposite direction (reaction to intention), it cannot be established whether the same RT cost would occur. This would be interesting to study in further research. However, since there are fewer preparatory stages in reaction than in intention, it would be expected that the RT cost would not be as substantial.

The conclusion that a switch exists between the intentional and reactive motor systems has only been studied in this thesis in the restricted case of simple keypresses. It is not, therefore intended to explain the relationships that occur in more complex actions. It has been suggested that the switch between intention and reactivity occurs gradually, along a gradient (Ellis and Tucker, 2000) rather than as a definitive switch from one to another. This implies that there can be an overlap of intentional and reactive features in actions. The status of the RT cost of intention in these more complex situations remains an issue for future research.

8.4.2 Exclusion of Alternative Causes of the RT Cost of Intention

Other factors which might have contributed to the RT cost of intention were examined and rejected. These included: (i) the effect of variable foreperiod, or the expectation of *when* the truncating stimulus was going to occur; (ii) the expectation of *whether* the truncating stimulus was going to occur; and (iii) delayed stimulus processing. It was concluded that none of these were the main factors contributing to the RT cost of intention.

8.4.3 Location of the Switch Process

Further experiments and analyses suggested that the systems were not related in an inhibitory way, but were most likely to be related by a switch mechanism. This switch process seems to be located at the brain level of the motor hierarchy, rather than at the muscular or effector level. The *intend stop* condition in chapter 6 produced an ERP that was very similar to the one produced by the reactive trials in the truncation condition. This finding implied that the majority of the costs responsible for the RT cost of intention, postulated to be a switch mechanism, were due to the stopping of the impending intentional action, rather than activating the reaction.

The subjective experiments (chapter 7) suggested that subjects were aware of their delayed RT in the truncation condition. Therefore, their action awareness must be generated *after* the event responsible for the RT cost of intention. Action awareness seems to be generated somewhere between the activation of the SMA and the M1 (Haggard and Magno, 1999). Fried et al's (1991) experiment indicated that epileptic patients were aware of their intentions and imminent actions in the region of the SMA. Hence, the switch process must occur prior to the M1 activation, possibly pre-frontally, perhaps between the two areas comprising Brodmann's Area 6, the SMA (or pre-SMA) and the PMC, and their outputs to the M1. It is important to note, however, that there are other areas of the brain involved in the control of action, for example the cerebellum and the basal ganglia. In particular, the SMA receives inputs from the frontal lobes and the basal ganglia and the PMC receives inputs from the parietal lobes and the cerebellum. The tentative suggestion that the switch process occurs between the SMA and the PMC does not intend to exclude the involvement of these other areas in the control and coordination of action.

Hierarchically, a frontal (or possibly pre-frontal) locus of the switch process would seem plausible, since the executive control of human action is known to occur in the frontal lobes. Numerous experiments over the last hundred years involving patients with damage to the frontal lobes have demonstrated that the frontal lobes are involved in a variety of executive functions concerned with appropriate behaviours, including inhibition and awareness of behaviour (Shallice, 1988). Moreover, recent theoretical models, for example, introspective physicalism proposed by Jack and Shallice (2001) have stressed the strong relationship between executive function and conscious awareness.

Cognitive models, such as the supervisory attentional system (SAS) [Norman and Shallice, 1986], provide ways to conceptualise the processes involved in stimulus-driven and willed actions and in some cases postulate a possible relationship between these two main classes of action.

In the case of the SAS, stimulus-driven actions are automatic and occur via the horizontal threads by a process called contention scheduling. When someone attends to their behaviour and activates the procedure involved in a willed action, the SAS overrides the process of contention scheduling and a willed action occurs. Therefore, the postulated relationship between reactive and intentional actions is one in which the reactive actions can be *overridden* by intentional or willed actions.

However, the actual process by which the willed action, via the SAS, actually overrides the processes of automatic stimulus-driven actions is not clearly defined. It implies that willed actions are capable of overriding these reactive actions, but does not suggest how willed actions may be overridden by reactive processes, and indeed whether they can be.

The findings from this thesis suggest a model in which the activity of the internally-generated and externally-generated systems do not directly affect each other, in terms of mutual inhibition or facilitation. That is, they appear not to be related in an inhibitory, facilitatory or unitary manner. It has also been shown that they appear to be linked in some way, that is, they appear not to be independent. It has been suggested that the internally-generated and externally-triggered motor systems are related by a switch process.

As just observed, a switch process suggests that the systems are linked in some way, perhaps by competing for limited resources, perhaps inputs to the M1. The switch is perhaps, therefore, between the outputs of the SMA and the PMC. That is, there is an element of exclusivity about this model; if one system is active, and if its outputs have access to the motor apparatus, via M1, then the other is not. This pattern of activation is perhaps due to limited resources, but not due to direct inhibition. However, the activity of one system, does not completely remove the possibility that the other system might be partially activated. That is, the hypothesis that the two systems are related by a switching mechanism does not imply that the activity of each system is all-or-nothing. Evolutionarily, there may be reasons for the systems not being active simultaneously, for example, in the attribution of agency. People have to be able to correctly attribute their actions to their intentions or to reactions to the external environment (in the form of stimuli).

Actions consist of many components both intentional and reactive. However, studies that consider the intentional and reactive components to be inseparable, generally involve complex actions such as those described by Ellis and Tucker (2000). Subjects made precision or power grips in response to a stimulus. Ellis and Tucker (2000) suggested that "seen objects potentiate a range of actions associated with them irrespective of the intentions of the viewer". This implies that the intentions of the subjects were not accounted for – the stimulus provided the required information to make the requisite response, regardless of the subjects' intention.

However, the fact that actions can consist of many components does not prevent one from investigating actions where these components can be logically separated. RTs for example, consist of a large number of different components processes. Nonetheless, it is possible to isolate a component, vary it and attribute the RT differences to that one component (Donders, 1868). The actions in this thesis were concerned with varying the initiation of action – either the subject intended to make the action or the response was initiated by the presentation of a stimulus. This is different to the studies of affordances where the initiation of the action is not varied, and is always driven by a stimulus.

The data in the pupil dilation experiment (chapter 4) seem to suggest that when actions are very simple, they can display the characteristics of an intentional (clear pre-movement dilation) or reactive (no pre-movement dilation) action alone. The BP in chapter 6 displays the same pattern of not occurring in the simple RT condition where there is no intentional preparation. Since the pupil dilation and BP can be associated with intention, there does seem to be support for the psychological examination of solely intentional or reactive components of certain tasks.

The truncation paradigm has provided a useful way to examine the relationship between the hypothesised internally-generated and externally-triggered motor systems. The following section will suggest further uses for this paradigm and will discuss the questions that were raised following the findings of this thesis and therefore, possible further research.

8.5 FURTHER RESEARCH

The first and most obvious issue that has arisen from this thesis is the question of the location of this switch process. Can the switch be localised to a specific part of the brain, using the methodologies of fMRI or PET, for example? Support for the suggestion that a switch between the two systems occurs between Brodmann's Area 6 and the M1 would be produced if these areas, or particular parts of them were active during the switching process inherent to the truncated reactions.

Examining this switch process would be difficult, due to the activation of other motor areas, which are potentially irrelevant and would, therefore, cloud the issue of the switch. Perhaps asking subjects to imagine the actions, rather than actually making the actions would be more effective in reducing activation of the motor areas, although other areas involved in perhaps visual imagery or motor memory might be activated and would then complicate the findings. The temporal relationship of the activity of the PMC and the SMA is of vital importance in determining whether they are related by a switching mechanism. It might be that MEG would provide a more temporally and anatomically accurate device for examining these issues.

It would also be interesting to see where the first signs of neuronal activity occur when subjects start preparing an intentional action, that is, where the first signs of intentional preparation are. If this is somewhere very different to the SMA or pre-SMA, then this area might instead be involved in the switch process.

8.5.1 Clinical Applications

Clinically, it would be interesting to see whether patients with schizophrenia, for example, are aware of the RT cost of intention, and therefore, the switch. Based on the findings that schizophrenic patients with delusions of control are frequently inaccurate at attributing actions to themselves and others, it might be expected that the RT cost of intention would be normal, but that they would not be aware of it.

Specifically, if schizophrenic patients are unable to accurately state whether they were responsible for an action, it might be expected that they would not be aware of their truncated reaction and therefore, their truncated reaction time. Frith and Done (1989) demonstrated that schizophrenic patients with "delusions of control" (and "thought insertion" and "thought blocking") cannot remember or are not aware of the response they had just made. Therefore, they might fail to distinguish between their own intentional actions and actions that the stimulus 'made' them do.

If they were not aware of their previous movement and therefore, the truncated reaction time, it would be concluded that they were not aware of the RT cost of intention. An ERP study by Dreher et al (1999) demonstrated that schizophrenic patients had reduced BP associated with intentional actions. There was a concomitance of reduced BP and a lack of ownership for the action. It would be expected therefore, that the BP associated with the truncation condition would also be reduced, resulting in the patient being inaccurate at assigning the action to themselves and therefore, when it occurred.

If the switch responsible for the RT cost of intention is located in the frontal cortex, then depending on the exact locus of the damage, frontal patients might be unaware of the RT cost of intention. Also, those patients who have difficulties inhibiting behaviours might find that they are unable to react quickly and accurately to the truncating stimulus, because that would require a change in behaviour. Therefore, it would be predicted that they would produce large RTs in the truncation condition and thus, large RT costs of intention of which they were unaware.

8.6 FINAL COMMENT

The impact of behaviourism, in which subjective experience was largely ignored, had a profound effect on psychology, resulting in little conclusive psychological examination of intentional actions. Intentional actions constitute a major aspect of our mental life. Thus, attempts to examine and locate their neuronal substrate, and their effect on or relationship with reactivity, are crucial to psychology.

This thesis has provided a useful behavioural hallmark, the RT cost of intention, of an inherently subjective phenomenon, which could be used to further research into intention and reactivity.

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