To err is human: the effect of distraction on errors in skilled performance

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Publication Date:
2010

DOI:
https://doi.org/10.26190/unsworks/23343

TO ERR IS HUMAN:

THE EFFECTS OF DISTRACTION ON ERRORS IN SKILLED PERFORMANCE

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B.PSYCH (Hons)

April 2010

A thesis submitted in fulfilment of the requirements of the degree of Doctor of Philosophy in the School of Psychology, University of New South Wales

PLEASE TYPE

THE UNIVERSITY OF NEW SOUTH WALES
Thesis/Dissertation Sheet

Surname or Family name: **Hong**

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Abbreviation for degree as given in the University calendar: **PhD**

School: **Psychology** Faculty: **Science**

Title: **To Err is Human: The Effect of Distraction on Errors in Skilled Performance**

Abstract 350 words maximum: (PLEASE TYPE)

The overarching aim of this research was to learn more about the nature, timing and causes of errors that occur in skilled, well-learned tasks. Three empirical studies were conducted in this research each with the aim to further our understanding of the role of attention during skill-based behaviour, in particular, the role of distraction as a major source of skill-based errors. In the first study, 60 participants (low and high skill) performed a primary tracking task under auditory distraction which occurred at three systematic points during task execution: at the beginning, midway through and towards the end of a trial. Results indicated that a distraction at the beginning of a trial was most disruptive to response execution and a distraction toward the end of a trial was most disruptive to subsequent response selection. Both low and high skill performers were susceptible to the negative effects of distraction at these points. These results support suggestions that attention continues to play an important role in mediating the behaviour of skilled individuals.

Using the same approach, a second study was conducting involving 100 participants to examine whether attention is allocated differently depending on the speed and accuracy with which a task is performed. The results of this study confirmed and extended the results of the first study. Specifically, the same critical points were found as in the first study which was at the beginning and towards the end of a trial. These critical points were the same for low and high skill participants and the same for the speed and accuracy group. Skill level and performance instructions influenced the *amount* of attention paid to the task but not *where* attention was allocated. A third empirical study was conducted to further our understanding of the effects of distraction timing on skill-based error. In this study, 30 student pilots performed a simulated checklist task under conditions involving frequent distractions. Results indicated that participants were more vulnerable to the negative effects of distraction when it occurred midway through a task.

Taken together, these results suggest that *where* attention is allocated during task performance is highly dependent on the nature of the task. The results also provide strong evidence that a level of attention or self-regulation is still involved at critical points during skilled task execution. This is contrary to the popular view that skilled performance is not subject to attentional limitations and therefore cannot be disrupted by distraction. These results have important practice and theoretical implications for our understanding of the nature, causes and timing of skill-based errors.

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ABSTRACT

The overarching aim of this research was to learn more about the nature, timing and causes of errors that occur in skilled, well-learned tasks. Three empirical studies were conducted in this research each with the specific aim to further our understanding of the role of attention during skill-based behaviour, in particular, the role of distraction as a major source of skill-based errors. In the first study, 60 participants (low and high skill) performed a primary tracking task under auditory distraction which occurred at three systematic points during task execution: at the beginning, midway through and towards the end of a trial. Results indicated that a distraction at the beginning of a trial was most disruptive to response execution and a distraction toward the end of a trial was most disruptive to subsequent response selection. Both low and high skill performers were susceptible to the negative effects of distraction at these points. These results support suggestions that attention continues to play an important role in mediating the behaviour of skilled individuals.

Using the same approach, a second study was conducting involving 100 participants to examine whether attention is allocated differently depending on the speed and accuracy with which a task is performed. The results of this study confirmed and extended the results of the first study. Specifically, the same critical points were found as in the first study which was at the beginning and towards the end of a trial. These critical points were the same for low and high skill participants and the same for the speed and accuracy group. Skill level and performance instructions influenced the *amount* of attention paid to the task but not *where* attention was allocated.

A third empirical study was conducted to further our understanding of the effects of distraction timing on skill-based error. In this study, 30 student pilots performed a simulated checklist task under conditions involving frequent distractions. Results indicated that participants were more vulnerable to the negative effects of distraction when it occurred midway through a task.Taken together, these results suggest that *where* attention is allocated during task performance is highly dependent on the nature of the task. The results also provide strong evidence that a level of attention or self-regulation is still involved at critical points during skilled task execution. This is contrary to the popular view that skilled performance is not subject to attentional limitations and therefore cannot be disrupted by distraction. These results have important practice and theoretical implications for our understanding of the nature, causes and timing of skill-based errors.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisor, Professor Ann Williamson for her advice and constant encouragement throughout the years. I am also grateful to Jim Lemon for his involvement in the development of the tasks used in this research. Thanks are also due to the Aviation School at the University of New South Wales for providing access to the facilities for the purpose of this research. Thanks in particular to Brett Molesworth and Malcolm Good for offering an applied perspective on issues within aviation psychology. Finally, thanks to my family and friends for their love and support.

PUBLICATIONS & PRESENTATIONS

Hong, H., & Williamson, A.M. (2008). The effects of distraction on errors during skilled performance. *Paper presented at the 35th Annual Meeting of the Australasian Society for Experimental Psychology*. Australia: Perth.

Hong, H., & Williamson, A. M. (2008). Speed and accuracy: A complex interplay in skill development. *Proceedings of the 52nd Annual Meeting of the Human Factors and Ergonomics Society*. New York (pp.697-683)

Hong, H., & Williamson, A. M. (2009). It's only human: Understanding why errors occur in skilled behaviour. *Paper presented at the Human Factors Society Australia*. Australia: Sydney.

Hong, H., & Williamson, A. M. (2009). Pilots thrown off track: The effect of distraction on pilot checklist errors. *Paper presented at the Human Factors and Ergonomics Society, Europe Chapter*. Sweden: Linkoping.

Hong, H., & Williamson, A. M. (2010). The role of distraction as a major source of pilot checklist errors. *Paper presented at the Symposium of the Australian Aviation Psychology Association*. Australia: Sydney.

Hong, H., & Williamson, A. M. (submitted manuscript). Strategic factors in skill acquisition: The influence of speed-accuracy trade-off. Quarterly Journal of Experimental Psychology.

Hong, H., & Williamson, A. M. (submitted manuscript). 'One moment, I'm just in the middle of something': The effect of momentary distractions on error during skilled performance. Journal of Experimental Psychology: Applied.

AWARDS & RESEARCH GRANTS

2006-09 National Health and Medical Research Council (NRMRC) Scholarship

2009-12 It's only human: Understanding why errors occur in skilled behaviour. Australian Research Council Discovery Grant (with A. Williamson & S. Shorrock).

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‘I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.’

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PROLOGUE

The overarching aim of this research was to learn more about the nature, timing and causes of errors that occur in skilled, well-learned tasks. Three empirical studies were conducted in this research each with the specific aim to further our understanding of the role of attention during skill-based behaviour, in particular, the role of distraction as a major source of skill-based errors.

Chapter 1 contains a literature review on the phenomenon of skill including the definition of skill, the benefits of skilled performance and the acquisition of skilled performance. Skill acquisition theories from cognitive psychology and the motor control literature are reviewed followed by a comparative summary and evaluation of these theories. The chapter commences with a review and critique of the empirical literature on practice effects. Attention is then given to reviewing the literature on two core constructs that have attracted a great deal of research over the past decade: attention and automaticity. Theories about the role of attention and the development of automaticity in skilled performance are presented. The evidence supporting the core proposition of automaticity theory, that practice eliminates the need for attention during skilled behaviour is reviewed critically. Chapter 1 concludes with the call for more research investigating skilled performance from the perspective of its vulnerabilities and limitations, also known in the literature as “skill-based error”.

Chapter 2 contains a literature review on the phenomenon of human error, focusing specifically on errors in skilled behaviour. The chapter starts with an introduction to the nature of human error and its contribution to accidents and incidents worldwide. Following this is a review of research on skill-based error including its relative frequency of occurrence, its detection rate and the different forms it takes in everyday situations as well as how it has been induced in laboratory studies. Attention is then given to reviewing the empirical and theoretical literature on the effect of inattention as a result of being distracted on skill-based error. The literature review describes and evaluates in detail two theories which make different predictions about the role of distraction as a major source of skill-based error: (1) Reason (1990) theory that distraction disrupts self-monitoring of actions which ordinarily would ensure the faultless execution of skilled behaviour; and (2) Botvinick and Plaut (2003, 2004) theory that distraction disrupts a more generalised online system which results in a loss of information about the task context. These two theories make different predictions about whether the occurrence of errors in well-learned tasks depends on where acute distractions occur during task execution. Chapter 2 concludes with a summary of the general research questions which the current work was intended to answer.

In Chapter 3 the results of Experiment 1 are presented. The aim of Experiment 1 was to further our understanding of why skill-based errors occur by examining the effect of momentary distractions on errors made by low and high skill performers. The results suggest that skill development reduced capacity demands but a level of attention or self-regulation was still involved at critical points in order to avoid errors. Interestingly, these critical points were the same for low and high skill participants suggesting that skill development does not change where attention is most needed.

In Chapter 4 the results of Experiment 2 are presented. The aim of Experiment 2 was to examine the separate effects of speed versus accuracy instructions in order to clarify the effects of distraction on low and high skill performance. The results of Experiment 2 extended the results of Experiment 1 by showing that although skill development did not change where attention was needed it did reduce the amount of attention required at these critical points. There was also evidence that performance instructions moderated the amount of attention required at these critical points.

In Chapter 5 the results of Experiment 3 are presented. The aim of this Experiment was to investigate whether the results obtained in the first two experiments were due to the distinct nature of the novel task used (i.e., a task-specific phenomenon). This was tested by using a task more similar to Botvinick and Bylsma's (2005) coffee-making task. The task chosen was a simulated checklist task which pilots performed under conditions involving frequent distraction. The results of this study suggest that the nature of the task is an important factor in determining the precise effects distraction has on performance.

The final Chapter 6 contains a summary of the results across the three experiments and a general discussion about the theoretical and practical implications of these findings. The chapter concludes with a call for continued exploration of the skill-based error phenomenon across diverse skill domains. Future research will help to further our understanding of the specific reasons why attention may be necessary at certain points under some conditions but not at others.

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CHAPTER 1

SKILL LEARNING, PERFORMANCE & ATTENTION

1.1 Overview of Chapter 1

This chapter deals with three fundamental issues in skill research: What is skill? How does skill develop? And what is the role of attention during skill learning and performance? The chapter begins with a review of the literature in terms of the definition of skill and its many benefits including reduced effort and improved speed and accuracy. The next part of the chapter reviews theories about the acquisition of skilled performance. Specifically skill acquisition theories from cognitive psychology and the motor skill learning literature are evaluated and critiqued.

Next the role of practice in skill development is discussed in terms of the limitations of the empirical literature. The rest of the chapter reviews the literature on two core constructs that have important implications for the current research: attention and automaticity. Theories about the role of attention and the development of automaticity in skilled performance are presented. The empirical evidence in support of the core proposition of automaticity theory, that is, that practice eliminates attentional capacity demand is then critiqued. It is argued that given the complexity of human behaviour, the role of attention in skilled performance is not an all-or-nothing phenomenon as depicted by automaticity theory. Rather there may be critical points during skilled performance where attention is needed in order to avoid making errors. The chapter concludes with the call for more research investigating “skill-based error” which provides a unique perspective to understand better the role of attention during skilled performance.

1.2 Definition of skill

Skill is a complex and multidimensional phenomenon. At one extreme are skills that require hundreds or thousands of hours of practice to reach expert performance, such as the accumulation of force that allows a professional tennis player to blast an ace serve, the coordination of footwork, hand and eye speed, timing and accuracy in boxing or the flawless rendition of a Rachmaninoff piano concerto. At the other extreme of the continuum are basic skills that we all possess and are usually achieved in a relatively short period of time, such as making the bed, taking a shower, getting dressed and driving to work. Although less remarkable, without these basic skills we would struggle to function. The development of skill is certainly one of the most crucial requirements for regulating our interaction with the environment.

So what is meant by the term ‘skill’? Like many areas in psychology skill is not favoured with a clear definition. Psychologists have been struggling with its definition for decades. Early researchers defined skill in relation to the nature of the task but there was a lack of consistency in the definitions provided. For example, Pear (1927) defined skill broadly as the “integration of well-adjusted performance” (p. 480). This definition allowed everything from a physician making a clinical decision, a mathematician, a pilot and a cricket player to qualify as skill. Following criticisms that a broad definition of skill was not useful for researchers Pear (1948) revised his position on skill by limiting its definition to “well-adjusted muscular performances” (p. 92). Pear’s revised definition of skill as involving largely physical movements left its mark with subsequent researchers, such as Bernstein (1967), Adams (1971) and Schmidt (1975).

In contrast, Bartlett (1948) maintained that skill is a wide behavioural domain that can be both mental and motor and vary in complexity. Contemporary researchers generally agree that there are different types of skills such as perceptual, motor, cognitive, communicative and other skill categories, and that these categories reflect primarily differences in scholarly emphasis (Ackerman, 2007; Newell, 1991; Rosenbaum, Carlson & Gilmore, 2001).

The pursuit of an acceptable definition of skill led some researchers to define skill in relation to the proficiency of performance. For example, Guthrie (1952) said that “skill consists in the ability to bring about some end result with maximum certainty and minimum outlay of energy, or of time and energy” (p. 136). Similarly, Welford (1968) said that “skill consists of competent, expert, rapid and accurate performance” (pp. 12-13). These definitions corroborate common dictionary definition and popular usage of the term skill (i.e., being able to do something well).

One of the problems with defining skill as distinctly proficient performance is that it creates the impression that skill is a one-dimensional construct (i.e., you’re either skilled or you’re not). Clearly this is not the case. Skill is a continuous variable and therefore can lack proficiency (i.e., poor performance) depending on where a person lies on the skill continuum (Adams, 1987). According to Logan (1985) skill is not an absolute concept but a relative judgement. Although we often talk about “skilled” versus “unskilled” performers there is no such sharp demarcation. In reality, skill is open-ended and graded. For instance, an elite junior is surely skilled in reference to a novice yet their performance is likely to be of a lower standard than a professional. Logan argued for skill to be defined in relation to the goals which a person tries to obtain and the set of constraints to which a person must adapt in order to obtain the goals. A performer who can obtain the goals and adapt better to the constraints on the task is said to be more skilled than one who cannot.

More recent discussions about the nature of skill centre on the distinction between everyday skills and expertise (Carlson, 1997; Ericsson & Smith, 1991). According to Ericsson (2003) the goal for most everyday skills (e.g., showering, getting to work, using a computer) is to reach an acceptable level of performance that once attained can be performed with minimal effort. In contrast, expertise is characterised by the goal to constantly improve performance. Ericsson (1993; Ericsson & Lehmann, 1996) proposed that it takes a minimum of 10,000 hr (20 hr for 50 weeks a year for 10 years) of structured, deliberated practice to reach an expert level of performance although this may depend ultimately on the complexity of the structure of specific skills as well as prior knowledge and existing skills.

Although skill has been defined in several ways, there are several common ideas in all of the different conceptualisations. First, skill is a learned behaviour. Proficient performance is built up gradually with practice (Adams, 1987; Welford, 1958). Skill is different to the notion of 'ability' because a person may have the ability to perform a skill but cannot do it because it has not been learned (Bartlett, 1948; Pear, 1927). Secondly, skill is continuous and graded. As Adams noted, it is a function of the nature of skill that it develops progressively with training and therefore can lack proficiency. Moreover, there is no maximum limit on the highest degree of skill that can be attained. Skill develops over time with repetition and may keep improving indefinitely with practice (Ericsson, 2003; Fitts, 1964; Fitts & Posner, 1967; Logan, 1985). Thirdly, skill is goal-directed behaviour. Its development and performance is intentional rather than as due to chance or unintentional (Adams, 1987; Logan, 1985; Marteniuk, 1976). As Whiting (1975) pointed out "whatever processes may be involved in human skill learning and performance, the concern is with intentional attempts to carry out acts, which will bring about predetermined results" (p. 4).

More often than not, researchers in the field of skill have accepted these three defining characteristics. For example, following a comprehensive review of the features of skill, Proctor and Dutta (1995) proffered a definition of skill as "goal-directed, well-organized behavior that is acquired through practice (p. 18). In a more recent review, Rosenbaum et al. (2001) defined skill "as an ability that allows a goal to be achieved within some domain with increasing likelihood as a result of practice" (p. 454). For current purposes, skilled behaviour will be considered to have these three defining characteristics which set the boundaries for this research.

1.3 Benefits of skilled performance

Skill is an attribute sought after in most settings. Whether it is driving a car, piloting a plane, operating machine tools or conducting surgery, we aspire to be able to produce skilled performance. Generally skilled performance is considered to be of a consistently superior quality than less skilled performance whether that is reflected in accuracy, speed, the efficiency of movement or another performance measure. There is abundant evidence on the positive effects of training and skill development on performance (Anderson, 1982; Crossman, 1959; Logan, 1988; MacKay, 1982; Newell & Rosenbloom, 1981).

It has generally been assumed that skill performance improves as a direct function of increases in the amount of task knowledge gained through training and extended experience. However, studies on the memory representations and knowledge that mediate the superior performance of skilled performance reveal that the difference between skilled and lesser skilled performers is not merely a matter of the amount and complexity of the accumulated knowledge. It also reflects qualitative differences in the organisation of knowledge and its representation (Chi, Glaser & Farr, 1988; Ericsson & Smith, 1991; Strakers & Allard, 1993). Perhaps the most well-known study in the realm of expertise research is Chase and Simon's (1973) study on chess expertise. The study compared expert, intermediate and novice chess players' performance on a recall task where the positions of the pieces where arranged either randomly or in game-representative positions. The study found that expert players' recalled nearly all of the 25 to 40 chess pieces when they were arranged in meaningful game positions whereas beginners could only recall around four to six pieces. When the chess pieces were randomly arranged, however, the memory of expert players was reduced to the low levels of beginners. Hence, rather than having superior memory per se, these results suggest that experts' knowledge is encoded around key domain-related knowledge. The superior memory of experts for domain specific information has been replicated in a number of settings as diverse as music (Slobda, 1991), electronics (Egan & Schwartz, 1979), bridge (Charness, 1979), basketball (Allard, Graham & Paaralu, 1980) and hockey (Starkes & Deakin, 1985).

Flexibility is another striking characteristic of skilled performance. Skilled performers are able to modify their actions to accommodate their intentions and changing task demands (Stokes, Lai, Holtz, Rigsvee & Cherrick, 2008; Taatgen, Huss & Anderson, 2008; VanLehn, 1996). For example, a skilled basketball player is able to shoot baskets from a range of different positions and is able to make adjustments so as to direct the ball to a desired location. As MacKay (1982) noted, flexibility is a feature of skill which corresponds to the segmentation of a well-practised behavioural sequence into small, discrete components so as to remain changeable in the course of execution. Flexibility contrasts with another feature of skill, that is, consistency (or ‘fluency’) which corresponds to the unification of the sequence into one large underlying component so that the skill can be executed smoothly. In general terms, fluency or unification can be achieved only at the expense of flexibility or segmentation. In skilled performance, however, fluency and flexibility are positively correlated (Shaffer, 1980). Speech and music performance are examples of two of the most extensively practised, fluent and flexible of human skills (MacKay, 1982).

In addition to fluency and flexibility, numerous studies have also shown that skilled performers have superior anticipatory capabilities than less skilled performers. For example, in sport and movement studies it has been widely reported that skilled athletes demonstrate a superior ability to pick up advance visual cues from an opponent’s postural orientation prior to a key event such as ball-racket contact (Williams, Ward, Hodges &

Smeeton, 2002). There is also evidence that skilled athletes are more effective in using the relative motion between bodily features (Ward, William & Bennett, 2002), are better able to identify patterns of play based on recognition and recall processes (Williams, Hodges, North & Barton, 2006), employ more effective visual search behaviours (Singer, Cauraugh, Chen, Steinberg & Frehlick, 1996) and have greater knowledge of likely event probabilities (Ward & Williams, 2003).

Among other features, skilled performance is often characterised by reduced attentional effort. The apparent effortlessness of skilled behaviour is striking. Consider, for example the changes that occur while learning to type, to read, to play a musical instrument or to play tennis. At first, effort and attention must be devoted to the smallest movement or minor decision. The endeavour is slow, error prone and effortful. Eventually, with practice, long sequences of movement or cognitive processes are carried out with seemingly little effort. William James referred to the notion of "*liberation of attention* (as cited in Carr, 1992) implying a transition towards less attention demanding performance with practice. The decrease in attentional demand permits attention to be allocated to other aspects of performance (e.g., like scanning the environment for obstacles that might impede performance) or to other tasks (e.g., like talking to a friend while making a cup of coffee).

Since the last century, psychologists have believed that there is a strong relation between skill and automaticity, that is, task processing free from conscious attentional demands. For example, Bryan and Harter (1899) argued that automaticity was a necessary component of skill in that higher-level aspects of skill could not be acquired until lower-lever aspects had become automatised. The basic premise of automaticity is a consistent theme throughout the skill literature across both cognitive and motor skill domain (Bernstein, 1967; Fitts & Posner, 1967; Hasher & Zacks, 1979; LaBerge & Samuels, 1974; Posner & Synder, 1975; Schneider & Shiffrin, 1977). An important issue that will be discussed in more detail later is the extent of this transition towards capacity-free processing with skill development.

There is no doubt that skill has many advantages. Understanding the processes involved in the development and execution of skilled performance is thus a critical issue for psychological research. The complexities within the nature of skilled behaviour have led to the examination of skill from a number of different perspectives and from different fields of research, such as cognitive psychology, motor skill learning, educational psychology, applied psychology and human factors. Surprisingly, although research concerning the mechanisms governing skilled performance is abundant (Anderson, 1982; Proctor & Dutta, 1995; Rosenbaum et al., 2001) substantially less attention has been devoted to understanding the causes of suboptimal skill execution. Insight into the mechanisms governing skill failure is important as it will further our understanding of not only the variables responsible for skill decrements but also those responsible for success as well. The lack of knowledge about the limitations and vulnerabilities of skilled behaviour is a significant gap in the literature which this research seeks to address.

1.4 Skill acquisition

Skill acquisition has been broadly defined as “the attainment of those practice-related capabilities that contribute to the increased likelihood of goal achievement” (Rosenbloom et al., 2001, p. 454). It is noteworthy that the process of skill acquisition is distinct from execution of the skill in that learning is a gradual process that occurs over many performance attempts resulting in skilled behaviour. Numerous theories have been proposed to explain the changes that occur as people learn a new skill with practice but the literature on skill acquisition is divided into two separate fields of research. The first are theories concerned with explaining general principles about the cognitive mechanisms of skill acquisition which stems primarily from the cognitive psychology literature. The second are theories concerned with explaining movement and its determinants which stems primarily from the motor skill learning literature. In the following section, skill acquisition theories from cognitive psychology are presented first, followed by a review of the class of motor skill learning theories. At the end of this section is a comparative summary of skill acquisition theories from the two literatures.

1.4.1 Theories from cognitive psychology

Six prominent skill acquisition theories from cognitive psychology are reviewed: Crossman (1959), Fitts and Posner (1967), Anderson (1982), Newell and Rosenbloom (1981), Logan (1988) and MacKay (1982). These theories were selected for this review because they have been most influential in providing a useful and general conceptual foundation for understanding fundamental aspects of the cognitive mechanisms governing the acquisition of skilled performance across both cognitive and sensorimotor skill domains.

Crossman (1959)

Crossman's (1959) early theory suggested that skill acquisition results from a systematic selection of methods based on the time saved relative to other methods. According to Crossman, during the early stage of practice, methods to perform a task are selected at random among a wide range of possible methods. The probability of its subsequent selection is dependent on its performance speed. With extended practice, the fastest method will have the highest probability of being selected. Crossman's demonstration of the reduction in operator's cycle-time in making 10,000,000 cigars over a seven-year period is well-known. There are, however, three obvious weaknesses in Crossman's theory. First it is unclear what he meant by a "method". Secondly, it is unclear precisely how the method-selection mechanisms works apart from the postulated stochastic function which increases the probability of speedier methods being selected with increased practice. Finally, there is no provision in the theory for the learning of new methods or improving old one as practice progresses which severely limits the applicability of the Crossman's theory.

Fitts and Posner (1967)

Fitts and Posner (1967) were particularly intrigued by Crossman's (1959) demonstration that even after several years of practice, factory workers making cigars were still improving and getting faster. In an attempt to explain how performance continues to improve with practice, Fitts and Posner developed a stage theory of skill acquisition which remains one of the most influential and useful account of skill acquisition. Fitts and Posner proposed that a person passes through three stages as they acquire a new skill. In the early stage of practice, called the 'cognitive' stage, the learner is concerned with understanding the requirements of the task, such as the rules, the actions that have to be performed and the strategies that can be used. Through instructions, observations and feedback, the learner gains a rudimentary factual understanding of the task and is able to use this information to make preliminary attempts at the task. Where the skill involves separate subcomponents these tend to be tackled in isolation and overt verbalisation of the relevant task information is common (i.e., self-talk).

Fitts and Posner (1967) proposed that the cognitive phase merges into the intermediate or ‘associative’ phase which begins when the learner has determined the most effective way of doing the task and starts to refine the skill. Initial errors in understanding the task and inappropriate methods for performing the task are detected and eliminated. There is progressively less reliance on the initial factual representation of task requirements and in their place “cognitive sets and expectancies” (p. 20) for task execution develops. These cognitive sets are pre-prepared action plans that help to reduce workload. The length of the associative phase depends on the complexity of the task, and can persist for quite a long time. The key to the next phase is further practice.

Fitts and Posner’s (1967) last stage - the ‘autonomous’ stage is for some, the essence of what is meant by ‘skilled’ performance. Fitts and Posner defined this stage by the low degree of attention required for performance. Performance is not only smooth and rapid at this stage, but is also less subject to conscious control and interference from other tasks and there is an increasing ability to handle other tasks concurrently. The skill in this stage has been variously described as “automatic”, “unconscious” or “instinctive”. The autonomous stage is the most controversial of Fitts and Posner’s stages given the difficulties in defining automaticity. The nature of automaticity will be discussed later in this chapter. Nonetheless, the description of the autonomous stage conveys the idea that the task is carried out in a very different way to earlier stages. According to Fitts and Posner, the autonomous stage is by far the longest stage as performance continues to improve indefinitely over time and millions of repetitions.

The major strength of Fitts and Posner's (1967) theory is that it is parsimonious and fits well with the kind of transitions athletes experience with improvements in skill. For example, highly skilled athletes often report that they are operating in autopilot when they are at their best (Garfield & Bennett, 1985). The theory also has useful practical applications. For coaches and teachers, it helps to understand what stage a performer has reached. It is questionable, however, as to how complete a description it provides of skill acquisition. The three-phase skill chronology is an idealisation. The boundaries between these phases are not as sharply demarcated as the description suggests. At the time the theory was developed, there was limited experimental data so much of the theorising was based on anecdotes and interviews with instructors and athletes (Hodges, 2002). The theory is therefore couched in very descriptive terms and does not provide a detailed account of the mechanism underlying the transitions between the stages.

Anderson (1982)

Anderson (1982, 1987, 1992) adapted many of Fitts and Posner's (1967) ideas in the development of his Adaptive Control of Thought (ACT) theory. The ACT theory provided a more detailed explanation of Fitts and Posner's three-stage phenomenon. The basic principle of Anderson's ACT model is that as a skill is learned, there is a change in the type of knowledge that underpins its performance. The early stages of skill development are marked by a reliance on declarative forms of knowledge which are a set of describable facts and information about the task, its components and their relationships. Performance is error- prone because some of the declarative memory may be incomplete or incorrect. Performance is also slow because declarative knowledge is held in working memory during online execution. Verbal mediation is commonly used to rehearse the information held in working memory to help execute the skill. Anderson's declarative stage equates with Fitts and Posner's cognitive stage. Anderson, however, provides a clearer account about the changes that take place in the way that knowledge is represented as a result of practice.

Specifically, a process called 'knowledge compilation' is proposed to take place as the task is practised. This compilation has two sub-processes: proceduralisation and composition. Proceduralisation refers to the process whereby declarative knowledge is chunked or compiled into a procedure that is specific to the performance of the skill and is stored in a different form called 'procedural' knowledge. Procedural knowledge takes the form of "productions" which are typically expressed in the form of 'if-then' statements that link actions with a set of conditions under which those actions should be applied. Production rules are used to guide skilled behaviour and enable a task to be performed rapidly and efficiently. Procedural knowledge is stored in long-term memory and is responsible for generating skilled performance.

The second process, composition, describes a process whereby several productions are collapsed into a single production. An important consequence of composition is that the reduction in the number of production rules means that a task is now performed in fewer discrete steps. Concomitant with this is the drop out of verbal mediation. Whereas declarative knowledge is accessible by introspection and represents conscious awareness of facts and can be described as ‘knowing what’, procedural knowledge is not available by introspection and represents ‘knowing how’ to do something. The process of knowledge compilation is equivalent to Fitts and Posner’s (1967) associative phase and the procedural knowledge stage is equivalent to Fitts and Posner’s autonomous phase. As with the declarative stage, Anderson (1982) is more elaborate than Fitts and Posner about the effects of practice on fine tuning the procedural stage. Specifically, the ACT model has three mechanisms reflecting further optimisation of task performance: (1) generalisation, where the ‘if’ condition of a rule is replaced by a variable making the rule more applicable to other contexts; (2) discrimination, where given two rules with similar preconditions then if one rule leads to failure then its activation is decreased; and (3) strengthening, whereby rules accumulate strength (i.e., are more likely to fire) as they successfully apply. Anderson’s (1982) ACT theory has been successfully applied to several kinds of skill acquisition, including learning to write geometry proofs (Neves & Anderson, 1981), short computer programs (Singley & Anderson, 1989), text-editing (Anderson, 1987), calculus (Singley & Anderson, 1989), algebra (Blessing & Anderson, 1996) and numerous other problem-solving tasks (Anderson & Fincham, 1994).

Empirical support for the ACT theory comes from a class of findings demonstrating reduced dependence on working memory representation of declarative knowledge while executing a skilled task (Beilock, Wierenga & Carr, 2002; Gray, 2004; Masters, 1992).

Allard and Burnett (1985) compared low and high skill softball batters while they attempted to pitch while engaged in a secondary task. The study found that highly skilled players' ability to hit was not affected by an auditory digit search task. On the other hand, when the secondary task required attention to be devoted to irrelevant parts of the pitcher's body, performance of the high skill, but not the low skill suffered suggesting that the proceduralised skill depended on information concerning critical features of the pitcher's movements. There is also support for the ACT theory's core prediction that proceduralisation of a skill should decrease the ability to provide a complete verbal account of performance. Beilock and Carr (2001) compared the episodic memories of putting in novice and expert golfers and found impoverished episodic recollection of specific putts among expert golfers, which suggests that skilled putting is encoded in a procedural form less accessible to introspection. In contrast, novice golfers had very detailed episodic memories of the steps involved in individual putts.

On the negative side, there is evidence that human skill learning is less rigid than is assumed by the ACT theory. For example, conscious, explicit knowledge (i.e., declarative) may not always precede unconscious, implicit (i.e., procedural) knowledge as the ACT theory suggests. In a study by Willingham and Goedert-Eschmann (1999) using a serial reaction time (RT) task, one group during training was told that there was a repeating sequence and was encouraged to memorise it. Another group was not informed about the sequence. The study found equivalent performance between the two groups in a transfer task containing the repeated sequence task suggesting that implicit knowledge was acquired in parallel with explicit knowledge.

Further evidence for the view that human learning is more flexible than implied by the ACT theory comes from studies testing one of its core predictions that skill transfer from one task to another depends on the number of productions shared by the production systems that govern performance on the two tasks (Singley & Anderson, 1985). Support for this prediction is provided by Kieras and Bovair (1986) but others have found that the amount of transfer is greater than would be expected from simply counting overlapping productions. For example, Pennington, Nicolich and Rahm (1995) tested the prediction that practice in one sub-skill (such as writing a computer program) would not transfer to a related sub-skill (such as evaluating a computer program) when different productions represent the two tasks. The results revealed that there was considerably more transfer than predicted from ACT theory would predict. Similarly, Müller (1999) found that what was learned on one task transferred well to the other, with transfer to the writing task from the evaluation task being almost perfect.

A more general criticism of the ACT theory is as stated by Copeland (1993) “my actions [when making an omelette] can be described by means of if-then sentences; if the mixture sticks than I flick the pan, and so on. But it doesn’t follow from this that my actions are produced by some device in my brain scanning through lists of if-then rules of this sort” (as cited in Eysenck, 2004, p. 286). Copeland’s criticism suggests that regarding skilled knowledge as production rules may be a useful heuristic but not a reality. In a similar vein, Clancey (1997) argued that it is a mistake to equate knowledge with knowledge representation. The latter is an artefact. Furthermore he criticised the ACT theory and other related production-system architectures for ignoring the cultural and social context of learning which are known to have important influences on the way a person learns skills (Glaser & Bassock, 1989). Another possible criticism of the ACT theory is that it lacks parsimony because it proposes too many mechanisms to account for skill development (Taylor & Evans, 1985). Moreover, Johnson-Laird (1988) suggested that the ACT looks more like a programming language than a theory and hence difficult to refute experimentally.

Newell and Rosenbloom (1981)

Newell and Rosenbloom's (1981) theory is comparable to Anderson's (1982) theory in that it also proposes that practice improves performance via the acquisition of production knowledge. The difference is that that this specialised knowledge is called "patterns" and the knowledge compilation process is called "chunking". Specifically, according to Newell and Rosenbloom's theory, small pieces of knowledge about stimulus patterns are acquired early in practice. With further practice, these small patterns are gradually composed together to form larger "chunks", encompassing more elements of the stimulus and some encompassing the whole stimulus thus allowing the same task to be completed more quickly by applying fewer pieces of knowledge. The theory suggests that at the start of practice, learning will be rapid, as the smaller patterns are acquired and utilised. As practice progresses, learning will be relatively slow as the larger patterns are gradually learned and utilised. The theory is based in part upon Miller's (1956) classic notion of "motor chunks" in his account of information capacity limitations.

Newell and Rosenbloom (1981) proposed that *chunking* is the common underlying mechanism responsible for producing practice-related improvements in task performance. As an example of chunking, Newell and Rosenbloom examined the choice RT data of Siebel (1963). Siebel used a task in which there were ten lights situated over the participant's ten fingers. The task required the participant to simultaneously press the keys that corresponded to the illuminated lights. The number of lights illuminated on a trial could vary from one to 10. Newell and Rosenbloom proposed that at the beginning of practice, independent decisions must be made as to where each finger should be part of the response. However with practice, participants begin to treat the stimulus patterns as chunks. For example, at the lowest level of chunking, two adjacent lights will be treated as a unit. With more practice, a whole stimulus pattern may eventually be organised into a chunk. A limitation of chunking models of skill acquisition is that it seems unlikely that a large-scale collapsing mechanism can take place in numerous simple tasks such as simple choice reaction time or memory retrieval. Another weakness of Newell and Rosenbloom's model is that it unlike Anderson's (1982) theory, it does not offer a precise description of the underlying architecture and mechanisms to explain how information processing operations may be progressively chunked by practice.

Logan (1988)

Logan's (1988) instance theory assumes people start out with a general-purpose algorithm to solve a problem at low practice levels. This level of skill corresponds to the reliance on working memory representations of declarative information as discussed by Anderson

(1982). Like Anderson's notion of declarative knowledge, the application of an algorithm is slow and cumbersome in Logan's theory because it depends on the conscious manipulation of information in working memory.

The critical contribution of practice to skill development in Logan's (1988) theory is the creation of memory for each practice instance. Specifically, each solution is stored as a specific instance in memory. Extended practice produces a large collection of instances. When a previously encountered problem is repeated, Logan theorised that the algorithmic process and instance retrieval process operate in parallel in accordance with a "race" model. The first process to finish determines the response time. According to Logan's theory, with highly practised items, it is very likely that one of these instances will be retrieved before the algorithm computation is completed thus allowing a fast response to be based on memory retrieval alone. This is similar to Crossman's (1959) proposal that skill acquisition results from a systematic selection of methods based on the time saved relative to other methods. Logan's theory is, however, an improvement over Crossman's theory because it clarified many of Crossman's issues. Specifically, Logan's theory described a more detailed selection mechanism in which direct memory retrievals of past solutions to problems race in parallel with a computation-based algorithm solution process.

Evidence for Logan's (1988) instance theory comes from studies showing that the nature of the skill acquired depends on the training instances used. For example, Masson (1986) trained participants with words that comprised one half of the letters of the alphabet. In a subsequent testing phase, participants were presented with (a) old words from the training phase (b) new words consisting of letter used in the training phase and (c) new words consisting of letters not seen in the training phase. In accordance with Logan's instance-based prediction, the study found no skill transfer among words formed from untrained letters whilst the other two conditions showed significant transfer effects.

More recently, Logan's (1988) instance theory has been directly challenged by an alternative theory proposed by Rickard (1997) called the Component Power Laws (CMPL) theory. Although Rickard also assumes that there is a shift to memory retrieval with practice, his theory differed to Logan's theory on the assumption that memory retrieval and algorithmic strategies race in parallel. According to Rickard's theory, on any given trial, the performer must select either the direct retrieval from memory strategy or algorithmic computation strategy but not both. Over practice, the ratio of selection becomes increasingly shifted toward the direct retrieval strategy. At present, the matter of whether direct retrieval and algorithmic processes can, or at least do not, operate in parallel during skill development remains unresolved (Palmeri, 1999).

MacKay (1982)

Another prominent skill acquisition is MacKay's (1982) theory which explains skill acquisition as the strengthening of connections between nodes in a network which are responsible for controlling an organised sequence of behaviour. Nodes are abstract data structures wherein knowledge is embedded. Nodes are hierarchically organised and are responsible for controlling the movements making up an action sequence. For instance, as explained by Lee and Anderson (2001) "a node representing a sentence may consist of abstract nodes for the noun phrase and the verb phrase that branch all the way down to the nodes representing the articulators used to sound the syllables of a word in that sentence" (p. 270). Behaviour occurs only when nodes are activated. In general, activation spreads from top down through the network of nodes and each node is primed when the nodes connected to it become active. In MacKay's theory, practice increases the strength of nodes so that the time to reach activation to produce behaviour is shorter for more practised nodes as well as lowering the probability of error. In this sense, MacKay's theory is similar to Anderson's (1982) ACT theory which specifies that a production's strength determines how rapidly the production applies. Like MacKay's nodes, Anderson's production rules accumulate strength each time they successfully apply and lose strength every time they are applied with an undesirable outcome or through lack of use.

MacKay's (1982) theory differs from other theories, however, such as Logan's (1988) instance theory in that it assumes that practice strengthens connections between generic stimuli and generic responses whereas the instance theory accounts for specific instances of a stimulus. MacKay's theory therefore predicts that the degree of skill transfer is not necessarily correlated with the obvious surface elements of the task. In support of the theory, MacKay reported results from an experiment using a group of English-German bilingual speakers. These bilingual participants were able to demonstrate significant transfer after practice at pronouncing sentences in one language and then pronouncing the same sentences in the alternate language. Transfer occurred despite the complete change in the output motor movements required to produce the alternate language.

MacKay's theory is also unique from other skill acquisition theories in that it is one of the few that explicitly sought to provide an explanation for speed-accuracy trade-off

(SATO). In the theory, the speed of output depends on when nodes are triggered and activated following the onset of priming. If applied soon after the onset of priming for every node in the system, the overall rate of output will be fast but there is a greater probability of error because the strength of the nodes accrued may not be greater than all other extraneous nodes so that no error can occur.

Comparative summary of skill acquisition theories from cognitive psychology

It is clear from the numerous theories outlined that there are a number of distinct and in some cases competing ways of understanding skill acquisition. Overall the main difference between the theories presented is in the specific mechanisms proposed to account for skill development. These mechanisms vary in terms of the systematic selection of methods based on the time saved relative to other methods (Crossman, 1959); the grouping of individual task components into increasingly efficient components (Newell & Rosenbloom, 1981); the creation of memory for each practice instance (Logan, 1988); the strengthening of the connections between the methods that underlie that procedure (MacKay, 1982); or some combination of these factors (Anderson, 1982; Fitts & Posner, 1967).

Although different, the theories converge generally on the view that skill acquisition starts with general knowledge about the task and through practice gains more specialised stimulus knowledge. This specialised knowledge has the advantage of faster memory access and assuming the specialised knowledge is correct also leads to a reduction in errors. In addition, although the specific assumptions underpinning each theory are different, the learning mechanisms underlying skill acquisition are typically seen as mechanistic and entirely stimulus-driven. That is, skill development is driven primarily from practice with consistent stimulus-response relations (Logan, 1979; Schneider & Fisk, 1982b). More recently, this bottom-up view of skill acquisition has been criticised as too simplified and that other factors, such as individual differences and top-down/strategic control also have important influences on skill learning and performance (Ackerman, 2007; Haider & Frensch, 1999; Strayer & Kramer, 1994).

Nonetheless, the theories outlined have contributed significantly to our understanding of how skill develops by offering a rich source of alternative ways of thinking about skill acquisition. The diversity of explanations arises from the fact that the theories' address different tasks and processes. As such, some theories may fit some task situations better than others. For example, Crossman's (1959) theory applies best to situations where there are several different methods for performing a task and where the person has knowledge about all of these different methods when they begin the task. It may account well for the acquisition of motor skills, like cigar rolling or typing. It would not account well for lexical decision and alphabet arithmetic tasks which involve developing and strengthening new methods because the theory has no provision for learning new methods or improving old one as practice progresses. Newell and Rosenbloom's (1981) theory applies best to situations in which the stimuli are highly patterned, allowing the stimuli to be broken down into chunks and responding to chunks at different levels. It would not apply well to situations where participants respond to stimuli as wholes (e.g., memory search, lexical decision, alphabet arithmetic).

MacKay’s (1982) theory assumes that practice strengthens connections between generic stimuli and generic responses. In this sense, the theory may apply well to behaviour that is more complex and flexible (e.g., generating sentences). In contrast, Logan’s (1988) theory would apply better to skills that are highly constrained to the contexts in which they are acquired (e.g., lexical decisions) where every encounter with a stimulus is highly specific with respect to the information that is processed. In terms of Anderson’s (1982) theory, since some of its learning mechanisms are stimulus-specific like those of Logan’s instance theory, but others are more general like those of MacKay’s theory, Anderson’s theory would accommodate a broader range of task situations. Anderson’s theory would apply better than the instance theory to situations in which people learn general procedures rather than specific responses to specific stimuli. Like Newell and Rosenbloom’s (1981) theory, however, Anderson’s composition process will be better suited to situations where the structure of the task allows adjacent steps to be collapsed. It is unlikely to work in tasks in which one single-step process was replaced by another. Ultimately choice among theories may depend on whether their assumptions can be satisfied in a given task situation. Moreover, the theories are not mutually exclusive. It seems likely that humans can learn in more than one way.

Overall the major contribution of skill acquisition theories from cognitive psychology is in their attempt to extrapolate fundamental principles governing skill acquisition across both cognitive and sensorimotor skill domains. Although human skills may be governed by similar general principles, tasks with significant motor requirements (e.g., the keystrokes in typing a word, playing a piece on the piano, or the movement pattern for a stitch of knitting

) are differentiated by what Annett (1993) referred to as an “action system” which is concerned with how actual physical movement is developed and controlled. This class of theories, which stem primarily from the motor control literature is reviewed next.

1.4.2 Theories from the motor skill learning literature

Four prominent motor skill learning theories are reviewed: Keele (1968), Bernstein (1967), Adams (1971) and Schmidt (1975).

Keele (1968)

One of the main issues in motor skills research is the nature of the ‘motor program’ which preserves acquired skills. Keele (1968) defined a motor program as a pre-structured set of centrally stored neural commands which when executed allow a desired movement pattern to be produced without reliance upon ongoing sensory information. There are two major lines of evidence which suggest the existence of some form of internal program. First, by the finding that many skilled motor activities could be produced without sensory feedback (Summers, 1989). Secondly, the rapidity with which actions may be performed implies an internal program (Schmidt & Lee, 1999). For example, swinging a cricket bat is perhaps more a matter of selecting and then launching a pre-programmed or ballistic action than trying to adjust to the feedback cues provided by swinging a fast moving ball. Movements of this kind suggest control by some pre-existing motor program which is executed more or less ballistically once triggered rather than the stimulation of one movement by feedback of the preceding. In Keele’s view, motor programs specify all the necessary details in terms of muscle commands required to execute a movement. Motor programs are capable of being triggered by a decision and then used to initiate and execute a movement in an open-loop fashion without conscious control.

There are three major problems with Keele's (1968) motor program notion. First is the storage problem. The notion that a motor program exists for every movement we make seems implausible because of the memory demand it would place within the limited capacity human memory system. The second problem relates to novelty. Requiring a one-to-one mapping between stored motor programs and specific movements suggest extreme specificity and by extension inflexibility which is clearly not a characteristic of skilled behaviour. The third problem relates to Keele's motor program notion has difficulty in explaining the ongoing correction of errors in long duration, slow velocity movements.

Bernstein (1967)

Bernstein (1967) argued that the complexity of movements was such that it would be terribly inefficient (and perhaps impossible) for the organism to program each movement in detail. Bernstein proposed an alternative theory that aimed to minimise the importance of the central representation of motor programs. Bernstein's early insights strongly influenced the development of the 'ecological approach' to action (Kelso & Scholz, 1985; Kugler & Turvey, 1986). In describing the body as a mechanical system, Bernstein noted that we have many degrees of freedom that need to be controlled. The degrees of freedom of a movement are the number of separate independent elements that must be controlled in the body to produce a coordinated action. For example, we have many joints which can flex, extend and rotate. According to Bernstein, skill emerges when the individual exerts control over the degrees of freedom of a movement, “in other words, its conversion to a controllable system” (p. 27).

Bernstein (1967) explained that when we first learn a skill, we tend to freeze out a proportion of the degrees of freedom to reduce the task to a manageable level. This is accomplished by keeping joint angles or the whole body rigidly fixed or by introducing strong coupling between multiple degrees of freedom such as moving two or more joints in close phase relations. Then as the skill is acquired rigid control of the degrees of freedom is released as the learner develops coordinative structures comprising muscle groups and joints which are constrained to act as single functional units (Vereijken, Whiting & Newell, 1992). For example, the stiff upright stance adopted by the rigid coupling of hip, knee and ankle joints in novice surfers gradually becomes loosened with practice. Finally, as skill develops, we learn to exploit the degrees of freedom, an evolution in skill development that is needed to perform at a high level in any context. Evidence for Bernstein’s theory is strongest in natural actions like kicking a ball in soccer (Anderson & Sidaways, 1995), inter-limb coordination in skiing (Hong & Newell, 2006) and aiming movements such as dart throwing and basketball free throwing (Latash, 1996; Muller & Loosch, 1999).

Adams (1971)

Another early influence on the motor skill acquisition domain was Adams’s (1971) closed-loop theory which was developed to explain skill learning of slow, self-paced positioning movements. Adams proposed that motor learning was dependent on two memory structures: the memory trace and the perceptual trace. The memory trace which Adams termed as “a modest motor program” (p. 126) has a limited role in slow, self-paced position movements. The memory trace starts a movement by selecting the direction of movement and initiating it. The perceptual trace takes over the control of the movement by determining the extent of movement to stop it at the final target location. The perceptual trace develops based on extrinsic augmented feedback (i.e., knowledge of results) and the sensory consequences (visual and proprioceptive) of action. The perceptual trace is not a single state but a distribution of traces that have been produced over many practice trials. Each movement creates a set of associated sensory consequences which compounds to lay down an increasing representation of ‘correctness’. With practice, this develops into a perceptual trace which is then used for evaluating performance at hand.

Adams (1971) proposed two stages of learning that are differentiated by the strength of the perceptual trace. The first stage is called the ‘verbal-motor’ stage. At this point in learning, the perceptual trace comprises information from erroneous attempts at the task and is therefore weak and poorly defined. In the final stage, the ‘motor’ stage, the perceptual trace is well-developed and can support performance in the absence of knowledge of results provided there is sufficient sensory feedback received from the movement to enable comparison with the perceptual trace.

Adams’s (1971) theory gave rise to a large body of literature which revolved around tests of the importance of knowledge of results for learning (e.g., Newell, 1974; Newell & Chew, 1974; Wrisberg & Schmidt, 1975). Tests typically involved the use of slow linear positioning tasks and much of the evidence was supportive of Adams’s theory (Glencross, 1977; Smith & Brown, 1980). The theory's biggest weakness, however, is its limited explanatory power for a wide variety of behaviours such as the control of rapid ballistic movements with duration less than feedback time (Schmidt, 1975). The theory was also challenged by the finding that aimed movements can be performed effectively by both animals and humans without proprioceptive, visual or other forms of feedback (Polit & Bizzl, 1979; Taub, Goldberg & Taub, 1975). Moreover, numerous studies found contrary evidence to Adams's prediction that the more knowledge of results a learner receives, the more effectively he or she will perform (Ho & Shea, 1978; Kirschenbaum & Smith, 1983). For example, Winstein and Schmidt (1999) trained participants to reproduce target movements with the arm and showed that explicit feedback given on 50% of trials led to more permanent retention of the movement being learned than did feedback on 100% of the trials.

Schmidt (1975)

Schmidt's (1975) schema theory of motor learning was developed to accommodate the roles of both closed-loop and open-loop mechanisms by differentiating between slow positioning and rapid ballistic movements. The latter defined as having a duration of less than 200 ms. Schmidt's theory retained the motor program's basic premise of central planning program as part of the response process but described a more flexible, generalised system based on "schematic" representations. Schemas are patterns of responses to different situations. Some are under feedback control; others are not, depending on upon the type of movement produced.

According to Schmidt's (1975) schema theory, we learn skills by learning abstract rules about the functioning of our bodies, such as the relations between how our muscles are activated, what they actually do, how these actions feel and the outcome. The abstract rules of how the sources of information are interrelated are stored in two schemas whose development and strengthening support skill acquisition. For rapid ballistic movements, recall schema specifies the motor program and parameters, structured in advance to carry out the movement with little peripheral feedback being utilised. In slow positioning movements, recall memory does not have such an important role. Recognition schema, on the other hand, is a sensory system capable of evaluating the movement-produced feedback after the movement is completed, thereby providing information about the amount and direction of errors. The recognition schema is used to evaluate the movement-produced feedback in slow positioning movements much like the role of the perceptual trace in Adams's (1971) theory. Schmidt and Lee (1999) provide an evaluation of the schema theory, noting both its predictive successes in studies of motor learning and its limitations, such as vagueness about how the generalised motor program is acquired and how the schema acquire the abstract rules that govern their operations.

Comparative summary of skill acquisition theories from the motor control literature

Overall the theories differ mainly with regards to the extent that feedback information is essential for the ongoing control of movement. Adams's (1971) theory emphasised the role of response-produced feedback and knowledge of results in the detection and correction of errors, a capability that was seen as central to the learning process. The theory generated a great deal of research though it had limited appeal as it only dealt with the learning of slow positioning movements. In contrast, Keele's (1968) motor program theory was particularly concerned with the representation and execution of well-learned sequences of movements and the possibility that such sequences could be produced without the need for response-produced feedback. Implicit in Keele's model was a one-to-one mapping between stored programs and specific movement making the storage of programs within the limited capacity human memory system a problem. Schmidt's theory (1975) attempted to incorporate both Adams's and Keele's modes of control and to overcome the storage problem by borrowing from memory and perception research the concept of schema (Bartlett, 1932). In Schmidt's model, 'schemas' are abstract representational structures containing the general characteristics of a class of movements. Although more encompassing than Adam's theory, schema theory was primarily a model of discrete motor skill learning and provoked much laboratory research using simple motor tasks but had little immediate relevance to more complex real life skills (e.g., sports skills) (Shea & Wulf, 2005).

Inherent across the three theories, however, is the same sort of central mechanism that compares the intended outcome with the actual output achieved with any resulting discrepancy being used in the control of future behaviour. Keele's (1968) theory, however, is most problematic because the motor program hypothesis implies that different programs are required for different circumstances which seem implausible. With regards to Adams's (1971) and Schmidt's (1975) theory, one of the problems with siding with either is that it is difficult to categorise many applied skills according to this slow or rapid distinction

(Gentner, 1987). A golf swing, for instance, has characteristics typical of both categories. Depending upon the individual, it takes approximately one second from the beginning of the swing until impact, well in excess of the 200 ms timeframe characterising rapid-ballistic movements. The duration of the swing allows time for feedback to be used to make adjustments to the movement. However, the swing also occurs at a speed not typical of slow-positioning movements.

Conversely, the dynamic, ecological approach, such as Bernstein's (1967) early insights into muscle coordination attempts to minimise the importance of the central representation of motor commands. Rather, movement kinematics is an emergent property of the dynamics of the motor system such as the contribution of the nervous system, the muscle and skeletal systems, as well as the forces of gravity and inertia. The major criticism of ecological theories such as proposed by Bernstein (1967) is the refusal to accept the role of memory in performance and its failure to account for cognitive processes (e.g., decision making in sport, such as when a player chooses an action that is less than optimal) in general. Moreover, without recourse to memory or some form of internal representation, a person should be able to perform the task equally as well the first time as subsequent times. This we know is not the case given the ample of evidence that with practice individuals become better at carrying out tasks (Anderson, 1982; Logan, 1988; Newell & Rosenbloom, 1981).

In general, the main contribution of motor skill theories by Keele (1968), Bernstein (1967), Adams (1971) and Schmidt (1975) is in the flurry of research they provoked. Although the theories were initially aimed at researchers in traditional motor behaviour, they have influenced researchers from a number of different fields, such as cognitive psychology, neuroscience, human factors, motor development, physical therapy and occupational theory as evident from a substantial number of the citations over the years. For example, by the end of 2004, Schmidt's (1975) article on schema theory accounted for 782 citations with 58 disciplines in which the article had been cited (Shea & Wulf, 2005). The theories have played an important role, in particular, in reshaping both the knowledge of results (Wulf & Shea, 2004) and the contextual interference (Lee & Simon, 2004) literatures. Moreover, the theories have in many ways provoked the development of alternative views and serve as models from which new theoretical positions can emerge (Shea & Wulf, 2005).

1.4.3 Comparisons between cognitive and motor skill acquisition theories

Although at face-value skill acquisition theories from cognitive psychology and the motor control literature appear to have little in common, there are number of important associations between the two literatures. For example, Keele's (1986) notion that complex skills are acquired by integrating motor programs for simple movements into a more complex integrated program is much like how Anderson's (1982) knowledge compilation and Newell and Rosenbloom's (1981) chunking process operates. There are also clear links between Adams's (1971) first skill learning stage, the verbal-motor stage and Fitts and Posner's (1967) cognitive stage wherein performance is under verbal control and hence places a demand on cognitive processes including a high demand on attention. Adams's final stage, the motor stage is essentially similar to Fitts and Posner's autonomous stage which is characterised by fluent and seemingly effortless performance. Fitts and Posner's notion of the freeing up of attentional resources as skill develops also is also analogous to Bernstein's (1968) notion of the progressive freeing of degrees of freedom in movement.

Other similarities between the two seemingly disparate cognitive and motor literatures exist. For example, the detection and correction of error that that is so critical in Adams's (1971) closed-loop theory is also central to MacKay's (1982) model. Like Adam's perceptual trace which become solidified as more correct movements are produced with practice, MacKay's nodes strengthen with each correct repetition. Similarly, in Anderson's strengthening mechanism, rules accumulate (i.e., are more likely to fire) as they successfully apply.

On a different note, the highly specific nature of transfer of training predicted by Logan's (1988) instance-based view of skill acquisition suggests inadequacies in Schmidt's (1975) schema theory which is based on the central notion that skills are not constrained to the contexts in which they are acquired. The distinction between declarative and procedural knowledge that is so important in Anderson's (1982) theory also provides compelling account of differences in transfer for training that distinguish declarative and procedural knowledge representations. As for Bernstein's (1967) theory, the information processing and cognitive frameworks have had considerable impact on concepts of motor skill acquisition over the two decades (Newell, 1991) such that most ecological psychologists now hold the view that some form of internal representation does take place (McMorris, 2004).

The most obvious difference between skill acquisition theories from cognitive psychology and the motor control literature is in terms of the type of task demands that are being dealt with. Skill acquisition theories from cognitive psychology (e.g., Anderson, 1982; Logan, 1988; MacKay, 1982) have mostly been developed in the context of intellectual and perceptual tasks, although not all since many of the applications of these theories directly involve simulation of movement tasks (Crossman, 1959; Newell & Rosenbloom, 1981). The main difference between motor and strictly cognitive skill tasks is that the latter aim to minimise the contributions of motor components and focus on the function of cognitive processes utilised during skilled behaviour. This is typically done by developing experimental tasks that require participants to respond as quickly as possible with a very simple and well-learned motor response (e.g., key press). Conversely, motor skill tasks are typically designed to have little or no cognitive component such as the tapping rate task which requires participants to strike a key or alternate keys on a keypad as rapidly as possible to measure pure motor speed.

Despite consensus that ultimately any behaviour that has been called skilled involves combinations of cognitive, perceptual and motor processes with different weights (Rosenbaum et al., 2001) little is known about how these different processes get integrated in the development of skilled performance (Salmoni, 1989). The pervasive trend in the literature is to focus selectively on explaining either motor skills or cognitive skill (Newell, 1991; VanLehn, 1996). Many real-world skills are, however, “cognitive- motor” in nature. That is the operator must carry out some nontrivial processing on incoming data and produce some relatively complex motor behaviour in response. Driving, playing most sports and using the computer are all examples of cognitive-motor tasks in this sense. As Bandura (1986) stated “A novice given factual information on how to ski, a full set of procedural rules, and then launched from a mountain top would most likely end up in an orthopaedic ward...” (p. 12). Clearly some mechanism is responsible for governing the translation from cognition into skilled actions. One of the aims of the current research was to provide a better understanding of how such a mechanism might function through the use of a task paradigm that permits the examination of both cognitive and motor components of skilled performance.

1.5 The role of practice in skill development

Regardless of the theoretical perspective, researchers generally agree on the fundamental view that practice is a key factor in skill development. The conditions of practice leading to skill development are now generally well-known. For example, regarding the distribution of practice, massed practice produces better immediate performance than spaced practice (Glenberg, 1977; Shea & Morgan, 1979) and random or spaced practice leads to better long-term retention than does blocked or massed practice (Magill & Hall, 1990). Similarly, constant training (i.e., using the same materials) leads to better performance just after training but worse performance in later tests. By contrast, exposing learners to variable training (i.e., using different materials) leads to worse performance just after training but better performance in later tests (Magill & Hall, 1990; Shapiro & Schmidt, 1982). The long-term benefits of variable training are observed with a range of tasks such as pressing a button when a moving object reaches a target, tossing a bean bag into a bin (Shapiro &

Schmidt, 1982) and learning new words for familiar concepts (Bransford, Franks, Morris & Stein, 1979). In relation to feedback, providing frequent feedback during skill acquisition leads to good short-term retention but poor long-term retention whereas providing infrequent feedback leads to good long-term retention but poor-short-term retention (Winstein & Schmidt, 1990). This has been found in a variety of different skill acquisition tasks such as learning rapid, serial arm positioning (Schmidt & Bjork, 1992) and verbal paired associates (Krumboltz & Weisman, 1962).

To a remarkable degree, research also converges on a general principle about the effect of practice on skill development that appears to apply across virtually all skill domains. The course of improvement with practice closely follows a power function which is a decelerating trajectory characterised by rapid improvement at the start of practice followed by diminishing improvements with further practice. This pattern of improvement with practice has been observed in a range of different skills such as tracing a mirror image (Snoddy, 1926), cigar rolling, maze drawing (Crossman, 1959), editing text with a computer (Singley & Anderson, 1989), geometry problem solving (Neves & Anderson, 1981), fact retrieval (Pirolli & Anderson, 1985) and even the time for the prolific author Isaac Asimov to write books (Ohlsson, 1992). The ubiquitous nature of the power function has led many researchers to argue that it is a universal *law* of skill development (Newell & Rosenbloom, 1981). Some researchers regard the power function speed up as the gold standard by which the success of all models of skilled performance should be judged (Anderson, 1982; Palmeri, 1997). For example, Logan (1988) remarked that any theory of skill acquisition that does not accommodate the predictions of the power function speed up cannot be serious contenders and therefore can be rejected immediately.

More recently, debate has arisen about whether or not the power function is a sufficiently accurate, general and useful characterisation of skill acquisition (Heathcote, Brown & Mewhort, 2000). One of the criticisms relates to the fact that besides RT data, there is little evidence of a power law for other performance variables such as error rate (or its antithesis – accuracy). The effect of practice on error rates has been investigated only in a few studies and the results are mixed. For example, Anderson and Fincham (1994) trained participants to first memorise examples of input-output stimulus pairs (akin to 'if-then' rule) and then to generate the outputs for a series of new inputs by analogy to the original pairs. When participants made an error, they were informed immediately, shown the correct answer and given unlimited time to study it. Participants were also given points for their speed and accuracy and were penalised for each incorrect response through point deductions. Points accumulated were later converted into dollar amounts that were given as bonus pay upon completion of the experiment. Not surprisingly, the study found that errors reduced significantly as a function of practice according to a power law.

In contrast, Woltz, Bell, Kyllonen and Gardner (1996) trained participants on a task that required them to reduce a four-digit string into a single digit by the sequential application of different rules. A detailed feedback scheme was designed to encourage response speed and to discourage errors. After a correct response, latency feedback was provided for one second. After an incorrect response, a tone and the word WRONG appeared for two seconds. At the end of each training block, summarised speed and accuracy feedback was presented along with conditional instructions for performance on the next block. If participants had an error rate of 15% or more, they were instructed to slow down in order to make fewer errors. If participants had an error rate of less than 5% they were instructed that they may not be responding as quickly as they could. Over 30 training blocks of 24 trials each, RT decreased dramatically in accord with the power law but accuracy on the other hand remained essentially constant at about 10%. The authors provided no explanation for this result.

In a different experiment, Healy, Kole, Buck-Gengler and Bourne (2004) trained participants to type four-digit numbers presented on a computer screen as quickly and as accurately as possible using only their non-preferred (left) hand and using only the digit keypad on the right-hand side of the keyboard. Participants' responses were not displayed and no form of feedback was provided. The study found that whilst RT improved across practice, accuracy of data entry declined reflecting a speed-accuracy trade-off which increased over blocks of trials.

The mixed findings in relation to error rates suggests that practice effects and the practice conditions that produce skilled performance are much more complex than one typically gets from the power law literature that simply reports on RT measures. In a meta-analysis study, Mazur and Hastie (1978) found that accuracy performance on a variety of cognitive and motor learning skills (e.g., typing, adding, mirror tracing, and printing inverted letter) improved according to a hyperbolic function rather than a power function. Logan (1988) dismissed Mazur and Hastie's results based on the argument that power functions do not necessarily make predictions about accuracy. This is a rather weak argument since the so-called power law is purported to be universal depiction of practice effects on skill development which means it should be adequate to explain both RT and accuracy.

On a related issue, Rabbitt and Banerji (1989) criticised research on the power function representation of skill development for its neglect of the issue of speed-accuracy trade-off (SATO). SATO is the well-established finding that RT in any specific task is related to the number of errors that one is willing to make. The effect that speed leads to increased errors and accuracy leads to increased slowing has been demonstrated in numerous studies using a variety of tasks and experimental conditions (Hick 1952; Sanders, 1998; Woodworth 1899). SATO has been found to influence the occurrence of errors from the lowest level errors in muscle movement to the highest level lexical and phonological errors (MacKay, 1971). As Rabbitt and Banerji critiqued, despite the fact that SATO has been known for a long time, the power function has often been indiscriminately applied to RT data without regard to the fact that RT and error are known to trade-off against each other as people make conscious decisions to maximise speed or accuracy of performance. Power law research often assumes that speed and accuracy are interchangeable performance indices. This neglects the fact that practice may alter the compromises between speed and accuracy that individuals adopt (Rabbitt & Banerji, 1989; Strayer & Kramer, 1994).

Debate has also arisen about the specific shape of the function of practice. It has been suggested that the smooth decelerating shape of the power function might be an artefact arising from the treatment of skill acquisition data in power law research, that is, by averaging RT performance data over participants, conditions or practice blocks (Heathcote et al., 2000). Studies that analysed within-individual training data revealed several departures from the standard power function shape (Heathcote et al., 2000; Rickard, 1997; Delaney, Reder, Staszewski, & Ritter, 1998). In a meta-analysis of data from multiple experiments on skill acquisition, Heathcote et al. showed that individual learning curves were better described by an exponential function than by the power function.

Although research on the effect of practice on skill development has come a long way and much has been learned, it is clear that there is still room for a lot more research. A broad criticism is that the extant research is rather circumscribed to a few key variables and task paradigms, namely the exclusive reliance on correct RT as the sole source of information about performance even though it is well know that error and RT are intimately related (Dutilh, Vandekerckhove, Tuerlinckx & Wagenmakers, 2009; Schouten & Bekker, 1967; Wickelgren, 1977). An implication of this limitation is the need for further investigation into the effects of practice such as the extent to which practice changes the nature of errors during skill development, the degree to which practice changes the way speed and accuracy interacts and if and how practice changes the nature of attention and its allocation during skill development.

1.6 Attention, automaticity and skilled performance

The remaining part of this chapter deals with the two core constructs that have important implications for the current research: attention and automaticity. Regardless of the theoretical perspective, a consistent theme throughout the majority of theories of skill acquisition is the notion that practice changes the underlying attentional requirements of a skilled task. At the start of practice, a large amount of attentional effort is required to perform a novel task, but with further practice skilled performance appears to be characterised by a conservation of attentional effort. The concept of automaticity has been evoked to account for the observation that skilled performance appears not to be affected by limited attentional capacity (Ahissar, Laiwand & Hochstein, 2001; Saling & Philips, 2007). In the following section, the theoretical foundations of the concept of attention and the topics that have most concerned attention researchers are presented first, followed by a discussion on the concept of automaticity. The final section evaluates the empirical evidence in relation to automaticity's core proposition, that is, that practice eliminates attentional capacity demand.

1.6.1 Attention: Theoretical foundations

Attention is one of the most important and pervasive themes in psychology with roots back to the beginning of experimental psychology (Bryan & Harter, 1897). Despite a long history of research on attention, a review of the literature reveals a conspicuous absence of a good definition for the word. The most widely cited is James (1890): "Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, or consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others" (pp. 403-404). A century later, Harold Pashler (1998) captured the confusion in the field when he wrote that "No one knows what attention is, and ... there may even not be an 'it' there to be known about (although of course there might be)” (p. 1). It is remarkable that despite the abundance of research on attention, a comprehensive and widely-held definition of attention is as elusive today as it was 100 years ago. Attention has become a ubiquitous concept used in a variety of loosely related ways (e.g., “selectivity”, “top-down control”, “central capacity”, “concentration”, “effort”, “resources”) to infer underlying an mental commodity of limited availability that enables performance of a task.

Posner and Boeis (1971) attempted to categorise the different aspects of attention. This scheme distinguished three features of attention: attention as alertness, selectivity and a resource of limited capacity. First, alertness relates to the ability to maintain attention on a task. Alertness is typically measured in situations where an observer is required to keep watch for inconspicuous targets over prolonged periods of time. The state of readiness to respond is characterised as “vigilance” or sustained attention. Research on vigilance dates from the Second World War when there was great interest in the ability of operators to monitor radar and sonar displays. Mackworth (1948) carried out some of the first laboratory experiments on vigilance using the now-famous clock test. In this task a participant viewed a rotating pointer against a blank-faced clock. The pointer moved once per second but occasionally would jump two increments. Participants were required to detect these jumps. Error on the task increased sharply in the first 15 to 20 minute before showing a more gradual decline.

A more recent test of vigilance is the Sustained Attention to Response Test (SART) (Robertson, Manly, Andrade, Baddeley & Yiend, 1997) which requires participants to monitor a stream of random digits appearing sequentially at a rate of approximately one per second. Participants are to press a response key to each digit presented but to withhold a response when a designated no-go digit appeared which occurred only 11% of the time. Studies have found that this task becomes more difficult over time and few participants last more than four minutes before responding to a no-go digit (Manly, Robertson, Galloway & Hawkins, 1999; Robertson et al., 1997). The research on vigilance indicates that there are limits to attention based on the ability to maintain alertness. An understanding of the decrements associated with extended performance is relevant to many real world situations where operators work in relatively monotonous environments and must stay alert in their jobs (e.g., train drivers, air traffic controllers).

The second feature of attention which Posner and Boies (1971) distinguished is the notion of selectivity which relates to the capacity to focus attention on relevant aspects of the environment and to ignore irrelevant features. The selectivity of attention is fundamental to almost every aspect of functioning. Tasks of selective or focused attention are used to study resistance to distraction both internal (memory and knowledge) and external (environmental objects and events). Early studies of selective attention typically involved complex competing messages often speech (Broadbent, 1958; Cherry, 1953; Neisser, 1967). Cherry devised the dichotic listening procedure which involved the presentation of two messages one to each ear using headphones. Participants were instructed to shadow a verbal message presented on one ear by repeating it out aloud while simultaneously being presented with different types of information to the other ear. The demand for shadowing was assumed to prevent participants paying any attention to information presented on the unattended ear. In one of the first experimental demonstrations of selective attention, Cherry showed that people were very successful in focusing attention on the information presented to the attended ear.

Broadbent (1958) postulated that selective attention was mediated by a filter situated early in the system. According to Broadbent's early-selection theory, an unattended stimulus is completely filtered out at an early stage based on the physical features of the stimulus. Subsequent dichotic listening studies indicated that focusing attention on one message does not completely prevent the processing of information in the unattended channels (Moray, 1959). One's name, for example, has a low a detection threshold such that it will be consciously noticed even when it is delivered via an unattended channel (Moray, 1959; Tresiman, 1960). Consequently, Treisman (1960) proposed that the filter must be located later in the processing system such that unattended stimuli receive rudimentary analysis. Other late selection models (e.g., Deutsch & Deutsch, 1963) proposed that stimuli are fully processed up to the stage where they are identified and a response is needed. According to this view, attention selects what is responded to and what the response will be. The response may include either physical actions or cognition operations on the selected items (Allport, 1980, 1993). Irrespective of whether theorists postulate early or late selection, a shared assumption was that attention was a structural property of the information processing system situated at a fixed stage in the processing sequence. As a consequence, information is processed in a serial fashion. This implies that when two tasks are performed concurrently performance decrements will occur due to the structural bottleneck (Welford, 1967).

The third feature of attention which Posner and Boies (1971) distinguished is that attention has a limited capacity or resource. Researchers interested in this aspect of attention has attempted to gain an understanding of the limits of processing and to measure the extent to which tasks may be accomplished simultaneously without loss, characterised as “divided attention”. The dual task paradigm is often used to locate the stages of processing that limit performance and the division of attention among two or more tasks (Pashler, Johnston & Ruthruff, 2001; Van Selst, Ruthruff & Johnston, 1999). According to general capacity theories (e.g., Kahneman, 1973) attention is not a processing structure as implied by bottleneck theories, rather attention is conceived as a source of energy of a definite capacity that can be flexibly allocated in graded quantity to any stage in the information processing chain. Different stages in processing vary in the amount of attentional capacity they require. Unlike bottleneck models, general capacity models allow for parallel processing of information. With this flexibility available, Moray (1967) argued that there was no need to assume a given locus of task interference. The source of interference would be when the total processing requirements of different tasks exceed the total capacity of the system. Modifications to this theory have suggested that rather than one central pool, many resource pools exist and that the extent to which tasks draws on the same pool is what will determine whether any interference will occur between concurrent tasks (Wickens, 1980, 2002).

The phenomenon of skilled performance is fascinating from the perspective of these three features of attention (alertness, selection and limited capacity) because skilled behaviour appears to operate in the absence of consciousness (alertness), appears immune to the effects of distraction (selectivity) and appears not to be affected by limited attentional resources (capacity). To account for these observations researchers have evoked the concept of automaticity.

1.6.2 Automaticity: Skilled performance without attention

The concept of automaticity generally means the performance of tasks without the need for attention (Hasher & Zacks, 1979; Posner & Synder, 1975). Psychologists have believed there is a strong relation between automaticity and skill for years (Bryan & Harter 1897; LaBerge & Samuels, 1974). Fitts and Posner (1967) were one of the first to describe the relations between automaticity and skill development, although they used the term ‘autonomous’ instead of ‘automatic’. Another well known theory explicitly linking automatic processing with skilled performance is that of Shiffrin and Schneider (1977; Schneider & Shiffrin, 1977). Shiffrin and Schneider proposed two different modes of processing that underlie skilled and unskilled performance. In their view, unskilled performance is associated with controlled processing, which is slow, deliberate and effortful processing, and is by definition under the person’s direct and active control. In contrast, skilled performance is associated with automatic processing which is fast, efficient and independent of attention. Within this dichotomy, automatic processing depletes minimal resources and controlled processing draws on substantial resources. Because controlled processes require substantial attentional resources, the simultaneous occurrence of multiple control processes is not possible and the processes must be executed serially. In contrast, because automatic processes do not draw on attentional resources, it frees attentional resources for other activities. As a result, they may run in parallel with other concurrent automatic or control processes with no interference. Hence, within Schneider and Shiffrin's view, skilled performance would be immune to the introduction of a concurrent or distraction task because it no longer requires voluntary allocation of limited attentional resources.

Central to Schneider and Shiffrin's (1977) theory is the view that consistent practice is a necessary condition for the development of automaticity. Consistent practice is when there is a consistent mapping between stimulus-response relations as opposed to varied mapping between stimulus-response relations. The experimental procedure used by Schneider and Shiffrin was to have participants memorise a small set of letters designated as targets. Participants were trained in either two conditions: (1) consistent mapping (CM) practice, which is when the set of target letters is held constant for many trials (e.g., target items would be always letters while the distracter items would be always digits); (2) varied mapping (VM) practice, which is when the set of target letters varied from trial to trial (e.g., targets and distracters would be a mixture of letters and digits). After several hours of practice, participants were then presented a visual display of one or more letters on each trial to which the participants had to determine as fast as possible whether or not the display contained a target. Sometimes distracter items (e.g., irrelevant task items) would be included in the displays.

The results of these studies revealed a marked difference between the consistent and varied conditions on the time taken to analyse the displays for the target items. In the CM condition participants were able to report equally quickly on the presence or absence of one or four memorised targets in displays of one, two or four items. On the other hand, in the VM condition, the more targets to be searched and the more items in the array to be analysed the longer the participant took. Based on these results, Schneider and Shiffrin (1977) concluded that automatic processing develops as a result of extensive practice with CM whereas VM produces controlled searched, which demands attention. In addition, using a multiple frame perceptual detection task, Schneider and Shiffrin demonstrated that the duration of stimulus presentation could be reduced for CM practice items without a cost in target detection sensitivity. Fisk and Schneider (1983) generalised these results to tasks using a semantic target category to demonstrate that detection does not depend only on consistency of physical stimulus. Schneider (1985) also found positive effects of CM training using nonverbal stimuli like time-space trajectories of aircraft viewed by an air-traffic controller.

Using a dual-task paradigm Schneider and Fisk (1982a, 1982b) demonstrated that a skilled task can be performed with another task without degrading performance. In these experiments, a primary task (i.e., a visual search task) was practised repeatedly under CM conditions to allow automaticity to develop in the task (which it was argued would free attentional resources for a second task). Differences between participant groups on their performance of the CM practised primary task after introducing the second task were interpreted as indicative of whether or not automaticity had been achieved on the primary, practised task (Moors & Houwer, 2006). In a series of dual-task experiments, Fisk and Schneider (1983; Schneider & Fisk, 1982a, 1982b; Schneider & Fisk, 1983) reported negligible interference (as low as 2%) by a second task after extended practice under CM conditions.

Several psychological refractory period (PRP) studies of dual-task performance also demonstrated significant improvements after extended practice. In this paradigm, participants are required to perform two speeded tasks close together in time. Each task requires participants to make a specific response to a stimulus presented, however, the second stimulus is presented in between the onset of the first stimulus but before the first response occurs. The common finding is that responses to the first presented stimulus are little affected by temporal proximity to the second task but responses to the second stimulus are usually slowed as the interval between stimuli presentation is reduced. The increase in response time in the second task is the most common measure of the magnitude of the PRP effect. The PRP effect provides an interesting experimental design to examine whether a practice "automatic" task can be performed concurrently with another task.

Many early experiments found that the PRP effect remained even after extensive practice (e.g., Gottsdanker & Stelmach, 1971; Karlin & Kestenbaum, 1968). The generality of these results was limited, however, because they often combined tasks that were likely to conflict. For example, most used pairs of tasks that both required a manual response. Subsequent experiments showed that practice dramatically reduces the PRP effect when input and output conflicts are minimised. For example, Schumacher et al. (2001) trained participants for 5 sessions in a dual task design to compare single task performance to dual task performance. One task was to respond verbally to pitch tones and the other task was to press one of three response keys that corresponded to the position of a disk on the computer screen. By the fifth session, participants were able to perform these tasks together with no significant impairment in either RT or accuracy on the two tasks. Similar findings were reported by Hazeltine, Teague and Ivry (2002) and Ruthruff, Johnston and Van Selst (2001) suggesting that practice to an automatic level of performance eliminates bottleneck interference.

Outside the scope of the PRP, a number of well known studies evaluated the effects of extensive dual tasks practice, observing minimal or no interference. Spelke, Hirst and Neisser (1976) had two participants practice reading short stories while writing down spoken words (taking dictation). Given that these tasks have shared requirements for processing codes (both are linguistic) a high level of interference between the two tasks would be predicted to the detriment of both tasks. Initially this was the case, with reading speed, handwriting and recall of comprehension passages all being adversely affected. After 6 weeks of daily practice, however, participants were reading approximately as fast while taking dictation as they were in the single task condition. After 4 months, the participants could carry out an additional activity, categorising dictated words at the same time as understanding the dictated passages.

Studies have found similar findings using skilled individuals who have already practised an activity for a long time outside the laboratory. In one well-known study, Shaffer (1975) reported the case of a highly skilled typist who could type at nearly normal speed (at a rate of about 100 words per minute) and accuracy while carrying out any of several other activities, including reciting nursery rhymes and shadowing (repeating spoken input). Similarly, Allport, Antonis and Reynolds (1972) found that expert musicians could sight-read at the piano while shadowing speech. Beilock, Wierenga and Carr (2002) found that experienced putters showed no significant decrements in putting while simultaneously performing a secondary task of monitoring a stream of auditory signals for a particular target signal. Similar findings have been reported in other dual-task sports-based studies such as netball (Parker, 1981), ice hockey (Leavitt, 1979) and soccer (Smith & Chamberlin, 1992). In all these cases, practice resulting in expertise at the tasks produced highly successful task combination without apparent interference.

Also in support of the automaticity view of skill are studies demonstrating that conscious intervention during the execution of well-learned behaviours can adversely affect performance (Beilock, Bertenthal, McCoy & Carr, 2004; Gray, 2004; Singer, Lidor & Cauraugh, 1993). For example, Beilock, Carr, MacMahon and Starkes (2002) found skill deterioration when soccer players were directed to pay close attention to the side of the foot that contacted the ball. Analogous results have been reported in baseball batting (Gray, 2004) and golf (Beilock et al., 2004). These results are consistent with the constrained action hypothesis (Wulf, McNevin & Shea, 2001) which proposes that attention to skill execution disrupts the proceduralised processes in highly skilled performance that are normally completed without such close attention.

1.6.3 Empirical challenges to automaticity theory

On the basis of the evidence presented, it is tempting to conclude in support of automaticity's core proposition that skilled performance is not subject to attentional limitations. But the story is not straightforward. Since the 1980s, researchers have increasingly questioned the evidence in support of automaticity theory with many concluding that a literal interpretation of automaticity as requiring no attention at all may be too broad (Bargh, 1992; Cheng, 1985; Kahneman & Treisman, 1984; Logan, 1985; Logan & Cowan, 1984). As Pashler (1998) stated “although practice improves performance in various ways, we have encountered no strong evidence that it eliminates capacity demands in tasks where such demands are evident early in practice” (p. 370).

To start, there is little empirical support for the two core propositions of automaticity theory that practised operations become involuntary and no longer involves capacity demands (Moors & Houwer, 2006; Pashler, 1994; Saling & Philips, 2007). For example, Stroop interference, generally thought to be unintentional and uncontrollable is not independent of attention because it can be diminished when attention is directed away from the targets (Besner, Stoltz & Boutilier, 1997). Studies have also shown that attention modulates semantic priming (Kiefer & Brendel, 2006; Spruyt, De Houwer & Hermans, 2009) which was considered another paradigm case of automaticity. Others showed top-down attentional influences on preattentive processing (Cave & Wolfe, 1990) which earlier researchers had thought were independent of attention. For example, Joseph, Chun and Nakayama (1997) demonstrated that a “preattentive” task such as orientation pop-out target detection, often assumed to require no attentional resources, does indeed suffer from dual task interference.

Evidence for whether practice causes mental operations to show a lack of voluntary control (the other property associated with automaticity) is also unconvincing. As noted by Pashler (1994), many highly practised behaviour can be readily inhibited even when the appropriate stimulus is presented. For example, Logan (1982) studied the ability of skilled typists to monitor each individual keystroke and found that they could prevent themselves from typing a word when a stop signal was sounded. In accord with Rabbitt's (1978) earlier work, Logan found that the time to inhibit their responses was independent of the time of occurrence of the stop signal.

Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory of the development of automaticity with skills has also been challenged empirically on several grounds. Central to Shiffrin and Schneider's theory is the view that CM training results in automatisation. Anderson (1992) pointed out that while the interference effect of distraction on performance is smaller after CM practice, it is not true that the interference effect totally disappears. Contrary to Shiffrin and Schneider's proposal, consistent practice does not completely eliminate attentional demands. In addition, in terms of Schneider and Fisk's (1982a, 1982b) dual task studies, Cheng (1985) noted that in all but one experiment a clear dual-task decrement was observed even after extended practice indicating that the CM task was not entirely immune to interference. Similarly, Hoffman, Nelson and Houck (1983) found that even after extensive practice on a visual search task, dual task interference which was produced when the visual search task and a visual discrimination were performed simultaneously was not eliminated.

Close inspection of other reportedly successful dual task studies have also revealed subtle interference. For example, as Broadbent (1982) pointed out, the absence of interference in Spelke's et al. (1976) experiments should not be overstated. Participants in the study made substantially more errors taking dictation while reading than they did while taking dictation by itself. Similarly, claims of no interference from applied dual-task studies (e.g., Beilock et al., 2002; Leavitt, 1979; Parker, 1981; Smith & Chamberlin, 1992) are potentially confounded due to the nature of the secondary tasks used. The difference between low and high skilled players reported in these studies under dual-task conditions may be exaggerated by structural interference. For example, in Smith and Chamberlin's study, which combined a soccer dribbling primary task with a similar secondary visual monitoring task, lower skilled players spent more time looking down at the ball in performing the dribbling task since they require visual feedback as they attempt to control the ball. Consequently the visual system could not be directed to the secondary task which compromises conclusions regarding comparisons of the attentional demands between highly skilled and less skilled players. Moreover, Beilock's et al. (2002, 2004) and other related evidence (Gray, 2004; Singer et al., 1993) suggesting that conscious attention to the step-by-step components of a skill can disrupt performance does not necessarily indicate that skills are performed without attention. Rather, these results indicate that *too* much conscious attention to movement details can hinder performance.

In terms of PRP studies, although several studies have shown that practice reduces the PRP effect, it has been noted that the effect does not entirely disappear (Pashler, 1994). For example, Dutta and Walker (1995) examined the PRP effect over a period of 2500 trials. The study found no change in the pattern of RT effects suggesting that even after substantial practice there remained a central cueing for the production of responses which suggests the persistence of bottleneck interference even after extensive practice. Van Selst et al. (1999) studied the effects of 36 practice sessions in a PRP design combining an auditory-vocal task (saying aloud whether a tone is high or low in pitch) with a visual-manual task (pressing a button to indicate the identity of a letter on the computer screen). Van Selst et al. observed that even after extensive practice on two tasks with minimal modality interference, a residual PRP effect remained (albeit small – about 50 ms). When the experiment was repeated with manual responses on both tasks, a much larger residual PRP effect remained after practice confirming that the choice of response modalities can be important (Wickens, 2002). Similar dual-task costs have been observed in other dual-task paradigms, such as writing while tapping (Moretti, Torre, Antonello, Fabbro, Cazzato & Bava, 2003), orientation detection and letter identification (Ahissar et al., 2001) and detecting digits and category exemplars (Schneider & Fisk, 1984).

Even though some dual-task studies have demonstrated zero-interference by a secondary task (Ruthruff et al., 2001; Schumacher et al., 2001) this in itself is not conclusive evidence that attention plays no role. This is because there are other plausible explanations for non-interference other than an elimination of attention. There is the possibility that neither task may be sufficiently demanding to yield a decrement. For example, in the Beilock et al. (2002) study, experienced golfers were required to perform a putting task while listening to a target word. The study found no difference in putting accuracy performance under dual task compared to single task conditions. It is possible the auditory monitoring task made very few demands on the attentional resources involved in putting performance, an argument supported by the observation that very few errors were made on the secondary task and a point the authors acknowledged in their discussion.

Training may also result in the learning of attentional control and task coordination strategies so that people learn to perform concurrent tasks better but it does not necessarily mean that attentional demands are reduced (Cheng, 1985; Logan, 1988). According to this view, people do not ultimately achieve simultaneous performance of concurrent tasks. Rather people learn only to juggle tasks better. Damos and Wickens (1980) found that participants developed specific strategies for coordinating two tasks (e.g., time sharing versus time switching) during task training and that these strategies transferred to a different set of tasks. Cheng proposed that the formation of processes in skilled behaviour does not involve a complete withdrawal of attention. According to Cheng, skill development results from the discovery of the relevant features of the task and the compilation of efficient procedures. She calls these processes ‘restructuring’. The result, she argues, is a substantially low but not a zero demand on attentional resources.

Logan and colleagues (Logan, 1992; Logan, Taylor & Etherton, 1996) argued that here is no change to attentional capacity when skill develops. Specifically, in Logan’s (1988) instance theory, attention is needed during the practice phase of a task and determines what gets learned during practice. Attention also determines what will be remembered after practice. According to Logan, attending to a stimulus is sufficient to store it in memory or to retrieve from memory all information that was associated with it during a former presentation. Logan argued that both storage and retrieval processes are influenced by the quality and quantity of attention focused on the stimulus. When storage is improved, stronger retrieval cues are created and direct retrieval is more likely. In Logan’s theory, attention affects what information gets encoded into a memory and what information is later retrieved. Similarly, Haider and Frensch (1999) argued that skill acquisition may be accounted for, in part, by qualitative changes in attentional strategies with practice. Specifically, with practice, people learn to focus their attention on task-relevant subsets and increasingly reduce the processing of the task irrelevant. From the expertise literature, Ericsson and colleagues (Ericsson, 1998; Ericsson & Lehmann, 1996) made a similar proposal that cognitive involvement continues to mediate skilled processes. According to Ericsson, in order to constantly improve and achieve the highest level of performance, highly skilled or expert performers retains a higher level of cognitive involvement than lesser skilled performers. At the centre of Ericsson's theory of expertise is the role of deliberate practice, which is by nature a controlled process that involves highly focused, concentrated attention. The aim of deliberate practice is to resist skill 'automation' in order to improve from one's current level to the next level.

1.6.4 Summary of attention and automaticity research

The concept of automatic processing remains controversial. Some researchers have suggested the general concept of automaticity to be abandoned in preference for mental processes to be examined with respect to separate features related to automaticity (e.g., unintentional, uncontrollable, unawareness) (Regan, 1981). Others have offered an alternative to abandoning the concept of automaticity (Logan, 1985). In Logan's words, "we don't want to throw the baby out with the bath water" (p. 375). Logan conceptualised automaticity as a graded concept which lies on a continuum and is determined by the amount of training. It should be noted, however, that the gradual view tends to weaken the notion of automaticity. As a gradual concept, automaticity loses its ability to distinguish one type of process (automatic) from another (non-automatic) because any process can be labelled ‘automatic’ to some degree.

In all likelihood, given the complexity of human behaviour, the role of attention in skilled performance is not an all-or-nothing phenomenon as depicted by automaticity theory. Logan and Cowan (1984) noted that nearly all of the paradigm examples of automatic processes in everyday skills, such as reading, writing, typing and driving are sufficiently complex to comprise of both automatic and controlled components. In a recent publication, Schneider and Chein (2003) conceded the possibility that “automatic and controlled processes can operate in parallel, with the fast (automatic) process producing the response, and the subject using controlled processing as a check on the response” (p. 543). This suggests that there may be points where attention to the skilled task is needed to ensure that performance is going according to plan (Norman, 1981; Reason, 1990). Little is known, however, as to if and when a switch from relatively automatic to non-automatic processing of task components occurs. There is some empirical evidence as well as theoretical speculation, however, that these attentional checkpoints do occur during skilled performance and that the failure to make these timely switches causes error to occur (Reason, 1990).

An investigation into the breakdown of skilled performance, also known in the literature as “skill-based error” provides a unique perspective from which to understand better the role of attention during skilled performance. Specifically, a systematic study of errors in skilled behaviour may provide valuable insight about the underlying structure and organisation of skilled performance at large. As Reason (1979) argued “in the same way that an adequate theory of language production must draw upon an account for slips of the tongue, so also must a theory of skills consider the apparently non-random lapses of attention and memory that appear so frequently among our daily actions” (p. 68). Indeed the processes of normal behaviour are usually revealed best through the study of its breakdown which makes the study of skill-based errors an important and essential aspect of understanding skilled performance.

Compared with the abundance of research concerned with the mechanisms governing successful skilled execution (Anderson, 1982; Proctor & Dutta, 1995; Rosenbaum et al., 2001) substantially less attention has been devoted to understanding the limitations and vulnerabilities of skilled behaviour. In part, this is because the literature on attention/automaticity and skill-based errors are often considered separately. This research seeks to address this gap in the literature by making connections and comparisons between these two seemingly disparate literatures. The literature on skill-based error is reviewed in the next chapter.

CHAPTER 2

SKILL-BASED ERROR

2.1 Overview of Chapter 2

In this chapter the breakdown of skilled performance or “skill-based error” is discussed. The chapter begins with an introduction to the phenomenon of human error, its definition, and its involvement in accidents and taxonomies. Following this is a review of research on skill-based error including the relative frequency of its occurrence, its detection rate, the different forms it takes in everyday situations as well as attempts to induce it in the laboratory. Attention is then given to reviewing the empirical and theoretical literature on the effect of inattention as a result of being distracted on skill-based error. Finally, a summary of Chapter 1 and 2 is provided and the research questions to be addressed in the current research are introduced.

2.2 The breakdown of skill

There is no doubt that skilled performance has immense benefits (Anderson, 1982; Logan, 1988; Newell & Rosenbloom, 1981; Shiffrin & Schneider, 1977). . As reviewed in Chapter 1, there is abundant evidence on the positive effects of training and skill development on performance such as superior memory for domain-specific knowledge (Chase & Simon, 1973; Chi et al., 1988; Ericsson & Smith, 1991; Strakers & Allard, 1993), fluency (MacKay, 1982), flexibility (Stokes et al., 2008; Taatgen et al., 2008; VanLehn, 1996) and superior anticipatory capabilities (Singer et al., 1996; Ward & Williams, 2003;

Ward et al., 2002; Williams et al., 2002; Williams, et al., 2006). Among other features, skilled performance appears strikingly effortlessness (Bryan & Harter, 1899; Schneider & Shiffrin, 1977). A consistent theme throughout the majority of skill theories is the notion that practice changes the underlying attentional requirements of a skilled task (Bernstein, 1967; Fitts & Posner, 1967; Hasher & Zacks, 1979; LaBerge & Samuels, 1974; Posner & Synder, 1975; Schneider & Shiffrin, 1977). At the start of practice, a large amount of attentional effort is required to perform a novel task, but with further practice, skilled performance appears to be characterised by a conservation of attentional effort.

As discussed in Chapter 1, since the last century, psychologists have believed that there is a strong relation between skill and automaticity, that is, task processing free from conscious attentional demands (Bryan & Harter, 1899; Fitts & Posner, 1967; Schneider & Shiffrin, 1977). Since the 1980s, however, researchers have questioned the basic premise of automaticity (Bargh, 1992; Cheng, 1985; Kahneman & Treisman, 1984; Logan, 1985; Logan & Cowan, 1984; Pashler, 1998). If skilled behaviour is automatic and therefore does not consume any attentional resource then distraction should logically have minimal impact on performance. Clearly this is not the case as evident by the plethora of studies documenting the negative effects of distraction on skilled performance.

In examining the phenomenon of skill from the perspective of its limitations and vulnerabilities, researchers have also noted that it is often overlooked that skilled performance does not imply completely error-free performance (Beilock & Carr, 2001; Reason, 1990). Even highly skilled individuals performing familiar, routine tasks make errors. We see examples of this is in everyday situations such as when walking into a room intending to do one thing but you end up doing something else instead; finding that you've left the house keys in the fridge; or locking yourself out of the car with your keys still in the ignition. The timeless quality of these inconsequential blunders is demonstrated in the following quotation taken from the writings of Jean de La Bruyere in the seventeenth century: "He plays backgammon and asks for something to drink; it is his turn to play, he gulps down the dice, and almost the box as well, throwing the liquor on the board and half drowning his antagonist" (as cited in Reason, 1984, p. 518).

Although skill-based errors in everyday situations are often trivial and can be comical, they can be costly in other contexts. For example, in sport, skill-based error is encapsulated in a phenomenon known as 'choking' which is a term used to describe situations where athletes make uncharacteristic errors under pressure. Free throws in the game of basketball are an interesting case because the players get an unobstructed shot at the basket from a distance of 15 feet. The on-court conditions for taking this shot are always the same. Professional players are well-practised at making this shot yet there are numerous cases where some of the best NBA players have missed a crucial throw late in a close game (Worthy, 2009). Choking is also well-documented in other sports such as golf, darts and tennis. A classic case was in the third set of the 1993 women's Wimbledon finals when Jana Novotna was serving at 4-1 and was one point away from a seemingly insurmountable 5-1 lead. But she proceeded to miss an easy volley, later served three consecutive double faults and hit some wild shots allowing Stefani Graf to come back to win 6-4.

Skill-based errors are also a component of human performance in high-risk tasks (Williamson & Feyer, 1990). Air traffic controllers, pilots, nuclear plant operators, automobile drivers, medical staff and military personnel all operate in environments where even a minor slip can lead to serious injury or loss of life. For example, in 1979 an operator at the Oyster Creek nuclear power plant in New Jersey intended to close two pump discharge valves (A and E) but accidently switched off four (A and E, B and C) and in doing so, closed off all circulation to the reactor core. This was an error which led to a dangerous situation. Before discussing in detail the nature of errors in skilled behaviour, it is worthwhile to consider first what we mean by the word “error” and where “skill-based error” fits within the general theoretical framework of human error.

2.3 Introduction to human error and its involvement in accidents and incidents

That error occurs, even in the most highly skilled or habitual behaviour is testament that error is a fundamental facet of human behaviour. Error is a normal part of everyday life and work and a central part of continuous learning and development (Reason, 1990). Human error is, however, also a central issue in accident causation. The involvement of human error in catastrophic accidents is well-documented. Frequently cited examples of disasters involving human error are the Tenerife runway collision in 1977 which resulted in 583 fatalities and remains the worst accident in aviation history in terms of the number of fatalities; the Chernobyl nuclear reactor disaster of 1986 which continues to claim victims of radioactive poisoning; and the accident in the Indian city of Bhopal in 1984 where over 2500 residents died in a space of a few hours when poisonous gas and toxins escaped from a Union Carbide chemical plant.

It is estimated that over two thirds of accidents and incidents have human error as a major cause (Shorrock, Young & Faulkner, 2005; Williamson & Feyer, 1990). For example, estimates of the involvement of human error in accidents range from 70-85% in aircraft accidents (Aviation Safety Foundation Australasia, 2006; Hawkins, 1993), 80-85% in shipping accidents (Lucas, 1997), 70% in US nuclear power plants (Van Cott, 1994), up to 95% in traffic accidents (Aberg & Rimmoe, 1998), 90% in air traffic control (Van Cott, 1994) and about 58% of preventable deaths in healthcare (Institute of Medicine, 2000).

Although the extent of human error involvement in accidents and incidents has been widely documented, knowledge about the specific nature and causes of human error is poor, with only a handful of systematic studies worldwide. Compared to other aspects of human behaviour, the topic of human error has received little empirical attention by psychologists. Although error research is an old theme in psychology such as Freud's (1914) as some researchers have pointed out, error research has roots but no tradition (Gray, 2004; Wehner & Stadler, 1989). In 1928, Spearman wrote "psychologists positively decline to investigate error. They regard it as not being 'their job' " (p. 30). In recent years, this attitude has changed somewhat as evident by the emergence of several lines of "pro-error" research. These include research suggesting that errors may be beneficial to learning (Frese et al., 1991; Ivancic & Hesketh, 2000) and the identification of a neural signal that is associated with error-making using electroencephalography (EEG) methods (Falkenstein, Hohnsbein, Hoormann & Blanke, 1990; Gehring, Goss, Coles, & Meyer & Donchin, 1993). Recent theoretical development has also incorporated errors as an important source of information in the regulation of cognitive processes (Botvinick, Braver, Barch, Carter &

Cohen, 2001). Morever, there is growing realisation in applied fields that total elimination of human errors may not be possible to achieve (Homsma, Van Dyck, De Gilder, Koopman & Elfring, 2009). This is accompanied by the view that reduction of accidents will require a better understanding of the nature, causes and timing of human error to help practitioners manage errors in ways that consequences are contained or mitigated. In general, there appears to be greater appreciation of the view that in order for psychological theory to provide an adequate understanding of human performance, it must explain not only correct performance but also the predictable varieties of human fallibility.

2.3.1 Definition of human error

The word 'error' is derived from the Latin *errare* 'to wander' or 'to stray' and this original meaning would appear to permit a wide variety of actions to be considered as error. Within the published literature, the concept of error has been defined in different ways. From a systems perspective, error is often defined in relation to behaviour or its effects which compromises a system's "tolerance" (Matthews, Davies, Westerman & Stammers, 2000), "effectiveness" (Wickens, Gordon & Liu, 1998) or "limits" (Lourens, 1989). Such limits vary from system to system and so the same action can constitute an error in one system, but not in another.

From a psychological perspective, the concept of intention is central to defining human error (Rasmussen, Duncan & Leplat, 1987). Reason (1990) defined error as "a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency” (p. 9). Reason distinguished between two broad types of error based on the concept of intention. First, errors occur when intended actions proceed as planned but fail to achieve their intended outcome. In this case, errors result from a discrepancy between the plan that have been formulated to achieve the desired task outcome and the plan that was actually formulated. Reason termed these errors as “mistakes”, that is, when the actions run according to plan but where the goal and/or plan is inadequate in the first place to achieve its desired outcome. Thus mistakes are error of planning and judgemental processes.

According to Reason (1990), the second type of error occurs when the plan is adequate to achieve the desired outcome but fail because a person did not do what they intended to do, either due to a failure of response execution which has been called a “slip”, or to a failure of memory which has been called a “lapse”. Slips and lapses are different to mistakes in that the conscious goals and plans are correct but they do not proceed as intended. For current purposes, human error will be considered to be behaviour which fails to achieve desired outcomes either because the actions did not go as planned (slips and lapses) or because the plan itself is inadequate (mistakes).

2.3.2 Taxonomies of human error

Errors have been classified in many different ways. Early researchers focused mainly on describing and classifying the observable forms that errors take, such as not moving a lever, or activating a wrong switch in order to attach probabilities to each error (Swain & Guttman, 1983). Such descriptions of the outward forms of errors have been termed error ‘phenotypes’ by Hollnagel (1993) and ‘behaviouristic descriptions’ of errors by Cacciabue (1997). Miller and Swain’s (1987) widely used error of commission (i.e., carrying out an action that should not have been at all or in that way) versus error of omission (i.e., not carrying out an action that should have been) distinction is an example of such an approach. A similar distinction was drawn by Chapanis (1951) between constant (i.e., deviation from accuracy) and variable (i.e., consistency of performance) errors. These behavioural descriptions of errors tend to be task specific, provide limited insights into the causes of errors and provide limited guidance for effective interventions.

Other approaches to error classification seek to specify in more general terms the information-processing systems or the cognitive mechanisms that may underlie different types of errors. Cognitive models of human error have helped to reveal more fundamental forms or underlying error ‘genotypes' (Hollnagel, 1993). One of the main distinctions made by information processing approaches to human error is that between mistakes, slips and lapses (Norman, 1981; Reason, 1990). Norman (1981) summarised the distinction between mistakes and slips/lapses succinctly as “if the intention is not appropriate, this is a mistake. If the action is not what was intended, this is a slip” (as cited in Reason, 1990, p. 8). Another way of distinguishing these two basic error forms is as planning failures (mistakes) and execution failures (slips and lapses) (Reason, 1990).

Rasmussen’s (1982) distinction between Skill-, Rule- and Knowledge-based error (SRK) is another well-recognised cognitive-oriented classification of human error. Each error type in Rasmussen’s SRK model is defined by the degree of conscious control guiding behaviour at the time of the error (see Figure 1). Specifically, *skill-based error* occurs during the execution of well-organised, highly practised, largely physical actions which appear to take place without conscious control. *Rule-based error* occurs at the intermediate level of conscious control whereby performance is in familiar situations controlled by stored rules. Errors at this level occur as a result of wrongly classified situations leading to the application of a wrong rule, or the incorrect recall of procedures. These rules may be procedures which have been learnt through trial and error and are then applied to situations as an aid to decision making in an 'if-then' manner. Conscious control is necessary to select the appropriate rule but it does not require the person to go back to first principles. Finally, *knowledge-based error* occurs in situations where the task is novel and considerable mental effort is required to perform the task. Errors at the knowledge-based level are characteristics of unskilled performers and are a result of failed problem-solving and/or incomplete or incorrect knowledge about how to perform a task.

An integral component of Rasmussen's (1982) SRK model is attention. Performance at knowledge-based level requires considerable attention and is therefore slow and effortful. Rule-based performance requires less attention but is still to some extent demanding because attention is needed to interpret a familiar situation and apply the appropriate rules and procedures to select a course of action. At the lowest skill-based level, behaviour is fast and accurate and carried out without the need for attention. According to Rasmussen, the three levels of cognitive control are related to an increasing familiarity with the task at hand. At the beginning, the task will demand full attention. With practice on the task, less and less attention is needed until actions are performed in an automated manner.

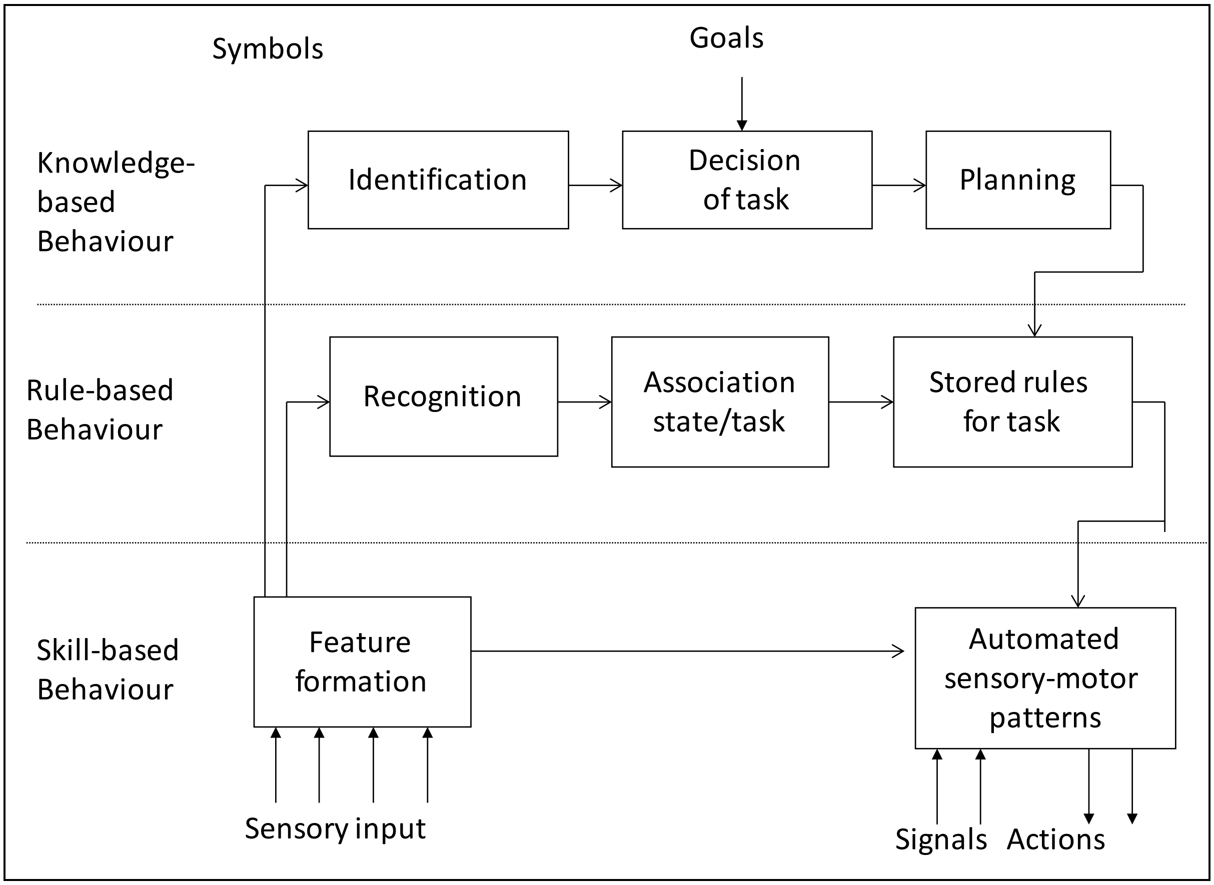


Figure 1. Rasmussen (1982) level of cognitive control

Rasmussen's SRK taxonomy was originally developed for the study of electronic troubleshooting and nuclear power incidents but has in recent years acquired the status of 'industry standard' among error models (Sanderson & Harwood, 1988). Reason (1990) contributed significantly to popularising the SRK model by merging it with his error taxonomy of mistakes versus slips and lapses. Specifically, Reason classified knowledge- and rule-based errors as "mistakes" (i.e., planning or judgement errors) and skill-based errors as "slips" (i.e., execution errors). The SRK model has been applied to errors in a wide variety of settings including aviation (Wiegmann & Shappell, 1997), medicine

(Runciman et al., 1993) and fatal workplace accidents (Williamson & Feyer, 1990). A particular strength of Rasmussen's SRK model is that it draws together insights from cognitive psychology on the control of activity as a person deals with progressively more familiar and predictable situations. Specifically, the cognitive, associative and autonomous stages of Fitts (1964; Fitts & Posner, 1967) and the declarative, knowledge compilation and procedural phases of Anderson (1982) can be seen as similar to Rasmussen's knowledge-, rule- and skill-based level of processing. The SRK framework was also influenced by Schneider and Shiffrin's (1977) theory of automatic and controlled processing wherein the skill- and knowledge- categories can be seen as representing automatic and controlled processing respectively. Rasmussen's rule-based category also fits well with the psychological concepts of scripts or schemata (Bartlett, 1932) in which the person possesses a previously developed solution which can be applied in familiar situations.

Despite its widespread application and theoretical underpinnings, Rasmussen's (1982) model has several notable limitations. The SRK model is a classification, descriptive tool. It provides limited explanation in terms of the mechanisms underlying the three cognitive levels and is unfalsifiable. The model thus falls short of the requirements for a scientific psychological model (Harwood & Sanderson, 1986). The model is also too simplified in that in reality, a person's task performance may involve simultaneous levels of control. Driving is a good example where both low and high levels processing occur simultaneously. Nonetheless, the SRK model has provided a common terminology for many researchers and practitioners and is currently one of the few tools which enable the person/task interaction to be described in terms which give insights into the cognitive demands of the task. The focus of the present research is on errors associated with the skill-based level of regulation, namely errors in routine, well-practised performance – skill-based errors.

2.4 Skill-based error

As proposed by Rasmussen (1982) skill-based errors are distinct from the errors that occur during unskilled behaviour in that they are not the result of incomplete or incorrect knowledge about how to perform a task (i.e., knowledge-based error) or the application of recall of wrong rules (i.e., rule-based error). Skill-based errors occur at the level of behaviour which is well-practised and appears to occur without conscious attention.

Reason (1990) distinguished two types of skill-based errors – lapses and slips. Whereas slips are observable error forms that manifest as performance of an action that was not intended (e.g., slips of the tongue, slips of the pen) lapses do not typically result in actual behaviour. Lapses are failures of memory and only observable to those who experience them (Heckhausen & Beckmann, 1990; Norman, 1981; Reason, 1990). Lapses are typically cited as an extra behaviour which is forgotten (e.g., forgetting to post a letter when driving). However, in this example, the skill of driving is intact and so the error of forgetting to post a letter cannot be classified as a skill-based error but rather a rule-based error which occurred in a skilled process. In Reason's conceptualisation, this fine-grain distinction is not always made clear. In this research, the terms "skill-based error", "slips" and "action slips" will be used interchangeably in accordance with Reason to refer to an errors that occurs in a skilled action sequence but the term "lapse" is only considered a skill-based error if it results from a memory failure to do something in a skilled action sequence (e.g., the omission of an item in a routine checklist procedure). In other words, the error has to occur within a skilled action sequence and not an overlay of an additional behaviour as in the case of forgetting to post a letter when driving.

2.4.1 The frequency of skill-based error

There is a plethora of studies worldwide documenting the occurrence of skill-based error in a wide range of tasks and occupational settings. The general finding from these studies is that skill-based errors occur frequently and often predominate as the most common error type. For example, in an investigation of fatal occupational accidents in Australia between 1982 and 1984, Williamson and Feyer (1990) attributed around 55% of accidents to skill-based errors and about 14% of rule-based and knowledge-based errors respectively. Similarly, Salminen and Tallberg (1996) examined a sample of fatal and serious occupational accidents in Finland and reported that 66% of fatal accidents were associated with skill-based errors compared to 46% of serious accidents, while 33% of serious accidents were associated with rule-based errors. Only 10% of fatal accidents and 5% of serious accidents were associated with knowledge-based errors. Further studies of error in specific occupational settings also showed the predominance of skill-based error such as in aircraft maintenance engineers (Hobbs & Williamson, 2002), in general aviation accidents (Wiegmann, Shappell, Boquet, Detwiler, Holcomb & Faaborg, 2005), train drivers (Edkins & Pollock, 1997), air traffic controllers (Pape, Wiegmann & Shappell, 2001) and hospital staff (Rothschild et al., 2005).

There are, however, some inconsistent findings. For example, Wiegmann and Shappell (1997) analysed pilot-related aviation accidents and found that about a quarter of the errors were skill-based while the remaining were either rule or knowledge-based mistakes or violations. Runciman et al. (1993) analysed 200 anaesthetic incidents and found that skill-based errors were significantly rarer than rule-based or knowledge-based errors. Shryane, Westerman, Crawshaw, Hockey and Sauer (1998) in a study of computer software design errors in a safety critical system found that rule-based errors predominated even through knowledge-based tasks were considered to be the most difficult.

A limitation of these studies is that none involved an assessment of the opportunities for different types of error. It is important to account for the ratio of error to opportunity because human behaviour generally has a very substantial skill-based and rule-based component. These are the ready-made routines of everyday life. Therefore the absolute numbers of skill- and to a lesser extent rule-based errors will often exceed those specifically due to knowledge-based failures simply because the involvement of skill- and rule-based processing in human performance is larger. A study by Hobbs and Williamson (2002) on aircraft maintenance found that although skill-based errors predominated, once error frequencies were normalised against opportunities for error for which the situation or task presents, skill-based performance was in fact more reliable than rule-based performance which in turn was more reliable than knowledge-based performance. Hence as expected, there is nothing intrinsically unreliable about skill-based behaviour. The tendency for skill-based errors to predominate as the most frequent error type reflects greater opportunities for errors to occur at the skill-based level.

2.4.2 The detection of skill-based error

The detection of errors is an important issue for obvious reasons in that an error that goes undetected and therefore uncorrected is more likely to lead to a disaster (e.g., an undetected slip by an air traffic controller or physician). Error detection is often triggered by a mismatch between observed outcomes and expected effects (Blavier, Rouy, Nyssen & de Keyser, 2005). There is some evidence suggesting that skill-based errors are easier to detect than rule and knowledge-based errors (Reason, 1990; Rizzo, Bagnara & Visciola, 1987; Wickens, 1992). For example, Woods (1984) in an analysis of simulated nuclear power plant incidents reported that overall operators detected 38% of the errors they had made. When these errors were categorised into error types, it was found that while about half skill-based errors were detected none of the rule-based and knowledge-based errors were detected. The latter errors were corrected only through the intervention of some external agent. Similarly, in an experimental study using a database search task, Rizzo found that whereas 71% of skill-based errors were detected, only 10% and 19% of rule- and knowledge-based errors were detected, respectively. Reason averaged error detection rates across three studies by Allwood (1984), Bagnara, Stablum, Rizzo, Fontana and Ruo (1987) and Rizzo and found detection rate was 86% for skill-based errors, 73% for rule-based errors and 70.5% for knowledge-based errors.

Findings from studies using relatively simple sensorimotor tasks also corroborate the finding that skill-based errors can be detected relatively easily. For example, skilled typists performing a highly practised sensorimotor skill can detect and errors they may make extremely rapidly and with virtually perfect accuracy (Rabbit, 1978). Studies using simple choice RT tasks indicate that participants can successfully detect and correct response execution errors (Rabbitt, 1966, 1978, 2002). In Rabbitt's study, participants detected 79% of their errors taking an average of about 700 ms to detect these errors and a mean time of around 250 ms to correct these errors.

Skill-based errors (i.e., errors in execution) are more likely to be detected because their outcome is more immediate whereas the outcome for rule and knowledge-based errors (i.e., errors in forming plans) may not be so immediate (Sarter & Alexander 2000). As Rizzo et al. (1987) suggested, it is generally easier to notice a mismatch between action being executed and actions intended during execution. For skill-based behaviour, information coming from the action's feedback can be easily matched with the intention that initiated the action. In the case of rule- and knowledge-based behaviour, the action's feedback even when matched with the intention cannot allow a detection of an error of intention since in such a case the feedback confirms that the intended actions have been executed.

2.4.3 The forms that skill-based error take

In an attempt to understand and predict the occurrence of skill-based errors, several researchers have attempted to classify the different forms errors can take in everyday situations. The two major skill-based error classification schemes in the literature emerged around the same time. These schemes were proposed by Reason (1977, 1979, 1984) and Norman (1981). Using a diary study approach, participants were instructed to record of all the errors they made in carrying out everyday activities. The main purpose was to generate a corpus of errors in everyday skilled actions as a means to both classifying and conceptualising the various ways in which skilled performance can go wrong. The two schemes will be described first, followed by a critique of the schemes.

Reason's (1977, 1979, 1984) skill-based error classification scheme has been continually updated. However, with each revision to the classification system, new terms are introduced and no attempt is made to link the schemes or identify how they have developed. In the first diary study, 35 people were asked to keep a diary of all the action slips they were aware of over a two week period. The study yielded 433 errors mostly involving normal domestic activities such as dressing, cooking and washing (Reason, 1977, 1979). Based on this data, Reason identified five categories of skill-based error: discrimination, program assembly, test, subroutine and storage. Discrimination errors occur from the misclassification of input usually due to confusion between the perceptual, functional, spatial or temporal attributes of the object (e.g., "I put shaving cream on my toothbrush", p. 71). Program assembly errors are the result of the transportation of elements within or between programmes (e.g., "I put the butter on the draining board and two dirty plates in the fridge", p. 72). Test errors stem from a failure to verify the progress of an action sequence at critical points (e.g., "I went up to my bedroom to change into something comfortable for the evening. I stood beside my bed and started to take off my jacket and tie. The next thing I knew I was getting into my pyjama trousers, p. 72). In subroutine errors an unwanted action in a sequence is added, omitted or misordered (e.g., "I came out of the sitting room in the daytime and flicked on the light as I left the room", p. 73). Storage errors are characterised by the forgetting of plans and actions (e.g., "I started to walk home and had covered most of the distance when I remembered I had set out by car", p. 74).

In a second diary study, Reason (1984) expanded the database of errors with the addition of 192 extra errors and developed the original classification system further. The study revealed that the majority of errors can be assigned to one of four basic behavioural categories: repetition, omission, wrong object confusion or intrusion. Repetition involved repeating some action in a sequence (e.g., “I started to pour a second kettle of boiling water into a teapot of freshly made tea” – Reason, 1979, p. 74). Whilst in omissions some part of the action sequence was left out (e.g., “I picked up my coat to go out when the phone rang. I answered it and then went out the front door without my coat” – Reason, 1979, p. 74). Wrong object confusions entailed making the intended actions but with the wrong objects (e.g., “I unwrapped a sweet, put the paper in my mouth and threw the sweet into the waste basket” – Reason, 1979, p 72). Intrusions involved the incorporation of unintended actions into the action sequence (e.g., “I went to get my car out, but as I passed through the back porch on my way to the garage I stopped and put on my wellington boots and gardening jacket as if to work in the garden” – Reason, 1979, p.73).

Based on the results of the diary studies, Reason and Mycielska (1982) noted that a defining characteristic of skill-based errors is that they occur during the execution of highly practised and routinised activities. In other words, these errors are characteristics of skilled rather than unskilled activity. Reason noted that this was an interesting departure from the normal expectation that errors decrease with the acquisition of skill as embedded in traditional psychological research. Moreover skill-based errors are not novel or random occurrences. Rather they flourish in familiar environments and follow systematic and predictable patterns. Not only are these errors a feature of well-practised activities, the error themselves frequently resemble stray fragments of habitual behaviour. For example, the common error of writing the date of the previous year during the first weeks of January is a right action but performed in the wrong context. Such actions are referred to by Baars (1992) as *liberated automatism* in recognition of their apparent relationship to automatic information processing.

The second major skill-based error classification scheme was proposed by Norman (1981). Norman based the classification scheme on the notion that skilled actions are controlled by sensorimotor knowledge structures called schemas. Briefly, a schema is defined simply as an organised memory unit much along the lines proposed for perception ad memory. Schemas are hierarchically arranged to produce action from the formation of intent. The highest level schema is the parent schema and is in direct control of lower, child schemas which are responsible for controlling component parts of the action. Schemas only evoke actions when they have been triggered and this requires satisfaction of specific trigger conditions plus a sufficiently high level of activation. Skilled actions need only be specified at the highest level parent schema. Once activated, the lower level child schemas of that action sequence complete the action to a large extent autonomously without further need for intervention when there is a need to deviate from formed intentions. Based on the functioning of this schema system, Norman classified skill-based errors into three broad categories: (1) error in the formation of the intention which is further subdivided into errors in classifying the situation (e.g., “I put my hand up to my face to take my glasses off, but my fingers snapped together rather abruptly because I hadn't been wearing them in the first place”, p. 7) and errors that result from ambiguous or incompletely specified intentions (e.g., replacing of the lid to the sugar container on the coffee cup); (2) error resulting from the faulty activation of schemas which is further subdivided into unintentional activation thereby causing an action to intrude where it is not expected (e.g., "I was using a copying machine, and I was counting the pages. I found myself counting 1, 2, 3, 4, 5, 6, 7, 8,9, 10, Jack, Queen, King - I have been playing cards recently", p. 8) or a loss of schema activation thereby leading to omission of its components of the action sequence (e.g., "I was at the end of a salad bar line, sprinkling raisins on my heaping salad, and reached into my left pocket to get a five-dollar bill. The raisins knocked a couple of croutons from the salad to the tray… I reached and picked them up, intending to pop them into my mouth. I rested the hand with the croutons on the tray and put the bill in my mouth, actually tasting it before I stopped myself", p. 10); and (3) error resulting from the faulty triggering of schemas which includes the subcategories of spoonerisms, blends, intrusions of thoughts and premature triggering (e.g., saying "you have tasted the whole worm" instead of the intended "you have wasted the whole term", p. 10).

Although different in semantics, Norman's (1981) scheme essentially covers the same range of skill-based errors as Reason's (1977, 1979, 1984) scheme. At a general level, classification studies of skill-based error must be treated with some caution. There is no consensus in the literature about how this task is to be done objectively and systematically. As a result, there are difficulties in terms of classifying particular slips. Often there are no discrete boundaries between the different categories of error. Many turn out to be unclassifiable while others substantially overlap and fit equally well into several categories.

Moreover, there are numerous methodological problems with observing and recording one's own slips (Nisbett & Wilson, 1977; Rabbitt & Abson, 1990). The success of the diary method depends largely on the ability of respondents to monitor and remember their own performance which may vary depending on range of situational, emotional and individual difference factors (Rabbitt, 1990). Rabbitt and Abson listed seven methodological problems including that people may fail to detect their errors or forget them. Indeed in many situations it is difficult to record exactly what occurred because records from memory are notoriously unreliable (Nisbett & Wilson, 1977). The fact that diary studies only record the errors that people are aware of or remember is problematic. There is no way of checking how many errors went undetected and for what reasons. The categories of any particular kind of skill-based error is meaningful only when we know the number of occasions on which that kind of error might have occurred but did not.

Further, due to the subjective nature of the reporting system this information may be biased. Accuracy and objectivity may be influenced by social desirability of responding. There is evidence that the extent to which errors are perceived as a bad characteristic can affect the detection sensitivity of reported action slips (Fisher & Doogan, 1984). Norman (1981) and Reason (1984) also considered further limitations of the diary study methodology such as volunteer bias (e.g., individual agree to take part in the diary study on the assumption that they are unduly prone to error) and selection bias (some types of error pass unnoticed whilst others are recorded). The selection bias prevents any estimation of the relative and absolute frequencies of occurrence of the various types of error.

Although diary studies give an interesting insight into the available varieties and recurrent types of action slips that people make in everyday life and is necessary for a complete understanding of human error, these very qualities also mean that the investigator has no control over the circumstances of their occurrence. Without the possibility of systematically manipulating the various predisposing factors it is virtually impossible to achieve scientifically satisfactory causal explanations by ruling out alternative hypotheses concerning the underlying causes of error. This limitation makes clear that subjective report is not an adequate methodology to support an elaborate theory of cognitive functioning. Convincing counter arguments supporting the reliability and validity of subject report have been proposed (Ericsson & Simon, 1980) yet limitations remain. Empirical investigation is required to explore the causal mechanisms attempting to explain how skill-based errors occur. A complete understanding of error should provide information on when and why skill-based errors occur.

2.4.4 Laboratory induced skill-based error

Little experimental work has investigated human error particularly those occurring in skilled behaviour. Although psychologists have taken errors into consideration as a quantitative measure in assessing human performance (alongside RT) not much attention has been paid to explain which (and how) cognitive processes are involved in producing them. It has been suggested that the lack of interest in studying human error in psychology may be in part because it is notoriously difficult to provoke (and hence study) error in controlled laboratory settings (Anderson & Fincham, 1994; Sellen & Norman, 1992).

Nonetheless, numerous studies have been designed to study a wide variety of errors in the laboratory such as errors in decision making under uncertainty (Tversky & Kahneman, 1974), errors in statistical problem solving (Allwood, 1984) and judgements in complex situations (Brehmer, 1987; Dorner, 1987). Error rates are relatively high on these tasks because they tend to be novel and participants are given limited training on the task.

At high levels of practised it is harder to detect effects in error rates. Several studies have, however, been successful in experimentally inducing errors in well-practised, skilled tasks, such as action slips in a coffee making task using distractions (Botvinick & Blysma, 2005), absentminded errors using repetitive prolonged trials (Robertson et al., 1997), prospective memory errors using time lapses (Einstein, McDaniel, Smith & Shaw, 1998) and post-completion errors using interruptions (Li, Blandford, Cairns & Young, 2008; Monk, Boehm-Davis & Trafton, 2004).

Most notably, Baars and his co-workers (Baars & Motley, 1974; Mattson & Barrs, 1992) studied speech errors by artificially inducing errors in the laboratory through a technique called the 'Spoonerisms of Laboratory-Induced Predisposition' (or SLIP).
The SLIP method involves presenting word pairs to participants that resemble the phonology of the desired spoonerism. For example, the word pair 'darn bore' is expected to spoonerise into "barn door" if preceded by similar words such as ball doze, bash door or bean deck. It has been found that some 10 to 30% of speech errors were induced with this technique (Motley & Baars, 1976; Stemberger & Treiman, 1986). Baars (1980) also observed that people could be made to produce lexically sensible spoonerisms (e.g., saying 'barn door' for 'darn bore') significantly more often than non-word spoonerisms ('bard

doard' for dart board). This finding corroborates naturalistic data and suggests that errors obeying lexical rules are more likely to evade the scrutiny of the internal 'editor'.

Using a similar technique, Hay and Jacoby (1996) asked participants to complete paired associates (e.g., knee: b_ n _). Sometimes the correct response was also the strong response (e.g., bend) based on previous learning trials and sometimes it was not (e.g., bone). Hay and Jacob also varied the amount of time participants had to provide an answer (one second or three seconds). The study found that errors were most likely to occur when the correct response was not the strongest one and when the response had to be made rapidly.

Another experimental task that readily demonstrates laboratory-induced error is the oak-yolk task (Reason, 1992). Participants are asked to answer a series of questions as quickly as possible. For example, what sound does a frog make? Croak. What do we call a funny story? Joke. What do you call the white of an egg? 85% of the participants answered "yolk" even though it was the wrong answer. The effect of the preceding questions is to build up a response set such that participants respond on the basis of rhyming rather than the meaning. This small body of research demonstrates that it is possible to design appropriate laboratory paradigms to experimentally induce errors in well-practised tasks. There is some debate, however, as to the validity of laboratory induced skill-based errors (Sellen & Norman, 1992). Lave (1988) argued that everyday skill-based error is quite different from skill-based error evoked in laboratory experiments. Similarly, Reason (1990) noted that the greater the measure of control, the more artificial and unnatural are the conditions under which the error is elicited. In direct contrast, Adams (1971) argued "the villain that has robbed “skill” of its precision in applied research. . .This approach is backwards for scientific productivity. . . it is a limited way of achieving the larger scientific goals of laws and theory” (pp. 112–113).

Carlson (1997) suggested that the debate about naturalistic versus experimental methods is ideological and is unhelpful for the progression of research. The co-existence of different investigative techniques yields benefits in terms of our overall understanding of skill-based errors. As stated by Baars (1980) “without naturalistic facts, experimental work may become narrow and blind: but without experimental research, the naturalistic approach runs the danger of being shallow and uncertain” (as cited in Reason, 1990, p. 15). The legitimacy of applied and experimental approaches to studying skill-based error reflects the fact that each offers unique insights into different aspects of skill-based error. Naturalistic research permits the study of errors in real world environments which maximises ecological validity and offers a much broader perspective of the mental landscape. Experimental research, by contrast, is suitable for asking fundamental questions about human performance and enables processes (or mechanism) to be exposed more completely and manipulated more effectively to test alternative predictions about underlying psychological mechanisms.

2.5 Sources of skill-based error

A consistent theme throughout the literature on skill-based error is that they are associated with attentional failures (Heckhausen & Beckmann, 1990; Kruysse, 1992; Norman, 1981; Reason, 1977, 1979, 1984, 1990; Reason & Mycielska, 1982). This is recognised at a commonsensical level in the notion of “absent-mindedness”. Reason suggested that there are two major attentional sources of skill-based error: overattention and inattention. According to Reason “to achieve an error-free performance when we have reached a certain level of proficiency, it is necessary to strike a very delicate balance between attending too closely or not enough to the ongoing activity” (p. 41). Specifically, overattention involves the intrusion of attention at inappropriate moments during the progress of a skilled action sequence. Mistimed checks produce two kinds of wrong assessment. Either a person concludes that the process is further along than it actually is, and as a consequence, omits some necessary step like forgetting to switch on the kettle. Or, a person decides that that it has not yet reached the point where it actually is and then repeats an action already done such as setting the kettle to boil for a second time. Suspecting that one has not performed necessary checks in the immediate past can prompt an inappropriate check which can lead to an error. For example, suspecting that you have not locked your car often prompts you to press the remote central lock again. In some cases, this could undo an action already done. The intriguing thing is that if this check had not been made, the automatic ‘lock car after leaving’ schemata would have been carried out without a hitch.

Inattention involves the omission of necessary attentional monitoring at critical points during the execution of a skilled task. Specifically, skill-based error as a result of inattention occurs when the greater part of the limited attentional resource is claimed either by some internal preoccupation or by some external distracter at a time when a switch to higher order, controlled processing is needed to ensure that current actions proceed according to plan.

The effect of inattention on skill-based error as a result of being distracted is the primary focus of the current research. In the following section, the effect of distraction on performance is discussed, followed by a review of the evidence in relation to existence of critical distraction points including two theoretical accounts that have different predictions about the location of these critical points.

2.5.1 The effect of distraction

Distraction can be broadly defined as a disruption to performance as a result of task irrelevant stimuli. This definition implies that before a distracting event occurs, attentional resources are distributed to optimise performance in the current task, that is, they are mainly allocated to the processing of task relevant stimuli. It is worth noting that the study of distraction in cognitive psychology is somewhat subsumed in the numerous studies on dual-task interference. It is possible, however, to distinguish between the intention of distraction and dual-task studies on the basis that the latter usually aims to measure the extent to which tasks may be accomplished simultaneously without loss (i.e., is concerned with divided attention). Distraction studies aim to measure the capacity to focus attention on relevant aspects of the environment and to ignore irrelevant features (i.e., is concerned with selective attention). When a distraction occurs, attentional focus changes in a way which may make it no longer optimal for performing the current task.

The term distraction and interruption are also often used interchangeably. According to Boehm-Davis and Remington (2009) cases of pure distraction involve a momentary shift of attention away from the primary task without a requirement to engage directly in the distracting task. Interruption generally requires some judgment of the distracting task and thus involves a more complete disengagement from the primary task at hand. In any case, both distraction and interruption evoke an orienting response away from a main task, at least briefly and involve the need to reorient to the task.

The study of distraction in experimental psychology is part of broader topic on attentional control. There are two forms of attentional control typically distinguished in the literature: endogenous and exogenous. Endogenous control refers to the ‘top down’ modulation of attending according to an individual’s intentions or goals. In contrast, exogenous control refers to the ‘bottom up’ mediation of attention which is driven by external events impacting on our senses generally termed “distracters”. These concepts are consistent with everyday notions of attention where our focus may be controlled by voluntarily paying attention to something or having our attention captured by a sudden change in the environment such as a siren. Decades of research on attentional capture have shown that under many conditions the abrupt appearance of task irrelevant stimuli can capture attention (Folk, Remington & Wright, 1994; Yantis & Jonides, 1984).

Attentional capture research has typically examined visual attention (Yantis, 2000). The effects of attention capture (or distraction) for the auditory modality have not been as well defined as those for the visual modality. The effects of attentional capture on task performance by irrelevant sound changes have been shown to be similar to those in the visual modality (Escera, Alho, Schroger & Winkler, 2000). An orienting response evoked by irrelevant sounds changes has been found to influence a range of different tasks such as immediate recall (Jones & Macken, 1993; Salamé & Baddeley, 1986), visual discrimination

(Alho, Escera, Diaz, Yaho & Serra, 1997) and auditory discrimination (Schroger & Wolff, 1998). The cost of behaviourally orienting to irrelevant events has been observed as a slowing down of performance in a primary task (increase of the RT to targets by about 40 ms) (Schroger & Wolff, 1998; Theeuwes, 1992) or as other studies have found, resulting in a mean increase in errors (up to 30 to50%) (Ellermeier & Zimmer, 1997; Jones, Beaman & Macken, 1996). The cost in performance on the primary task, attributable to the momentary shift of attention away from the primary task (Theeuwes, 1992) has been called a 'distraction effect' (Schroger & Wolff, 1998; Theeuwes, 1992).

In terms of applied research, the study of the effect of distraction on performance has mostly been confined to the fields of transportation, computing, medical and aviation and labelled variously under the topics of "distraction" "interruptions" and "mental workload". The negative effect of distraction is most well-documented in the driving literature. For example, an analysis of nearly 700 mobile phone-related accidents, Redelmeier and Tibshirani (1997) concluded that talking on a mobile phone increased the probability of a collision between 3 and 6.5 times. They also suggested that these distraction effects are comparable to a blood-alcohol-content (BAC) above the legal limit. Strayer, Drews and Crouch (2006) found that in a driving simulation task, mobile phone users showed greater impairments as measured by increased number of rear-end collisions and time required to regain speed following braking than drivers who were legally drunk (i.e., BAC of .08). Additionally, Strayer and Johnston (2001) reported that drivers engaged in mobile phone conversations missed twice as many traffic signals and had slower reaction times. Consigilio, Driscoll, Witte and Berg (2003) also found that mobile phone use (hand hand or hands-free) slowed drivers' braking reactions compared to when they drove without distraction or when listening to music on the radio. There is also evidence that experienced drivers are just as susceptible as novice drivers to the distracting effects of talking on a mobile phone. Kass, Cole and Stanny (2007) found that in a driving simulation task, both experienced and novice drivers suffered similar losses to driving performance (e.g., the number of pedestrians struck, speed limits obeyed or road departures) than those not using a phone.

The negative effect of distraction is also well-documented in the aviation domain. For instance, several official reports by the US National Transportation Safety Board (NTSB) and NASA revealed that nearly half of reported accidents and incidents involved lapses of attention associated with interruptions, distractions, or preoccupation with one task to the exclusion of another (Dismukes, Young & Sumwalt,1998; Dornheim, 2000). Reason (1979) examined a number of British civil aircraft accidents and found that a significant proportion of the skill-based errors occurred when the crew was dealing with a genuine emergency such as an engine failure. The emergency itself was rarely sufficient to cause a crash but captured the pilots' attention (the pilots were distracted) and created the conditions for skill-based errors to occur. For example, a number of accidents involving twin-engine light aircraft occurred after developing problems with one engine. The pilots responded promptly to the emergency but switched off the healthy engine rather than the failing engine. There is also evidence that experienced pilots are susceptible to distraction and interruptions during the performance of routine checklist procedures (NTSB, 1988a). Other laboratory evidence also showed that commercial pilots who were interrupted while flying a simulator had 53% more errors in their performance than those who were not (Latorella, 1998).

In other domains, such as in the medical area, a study reported that hospitals attributed 53% of medication errors to distraction (Santell, 2005). In the software engineering domain one study reported that software developers often spend 15 to20% of their time dealing with interruptions which equates to 15 to 20 min for each interruption (van Solingen, Berghout & van Latum, 1998). The authors did not measure if there were any decrements to performance as a result of interruptions but observed that recovery time was longer when software developers were interrupted during actual programming work, and less so when it occurred during other activities (e.g., documenting, meetings).

In everyday situations, Reason (1984) found that preoccupation or distraction was associated with 75% of the recorded diary errors. In an interesting study, Reason and Lucas (1984) found distraction to be major reason for action slips such as unintentional shoplifting (i.e., leaving a store without paying for merchandise) – shopping being a highly practised routine for many people. When asked to give reasons for their action slips, respondents typically blamed distractions (e.g., their child had suddenly disappeared from sight, they had become involved in a conversation, they had tripped over a display or a shopping bag had burst).

Thus far, only the negative, 'disruptive' effects of distraction have been considered. It is important to note that the direction of distraction effects is by no means constant. Research on the effects of distraction on performance has yielded mixed results. A sizeable part of this literature is concerned with the effect of noise on task performance (Hockey, 1984). For example, in a dual task study, Hockey (1970) found that 100 dbA noise improved performance on tracking task, while impairing the detection of peripheral targets in the secondary task. The difference between performance levels in the primary and secondary tasks was much less marked in the control, quiet condition. The distribution of attention appears to be different in noise and quiet conditions. Hockey explained the results in terms of attentional selectivity, with attention becoming more selective in noise, so that more attention is devoted to the primary task and less to the secondary asks. Increased attentional selectivity in noise has also been reported in memory-based tasks (Smith, 1982). Smith found that noise benefitted performance on whichever of two memory tasks was given priority in the instructions. In contrast, Pearson and Lane (1986) found that noise had no effect on the way in which participants responded to central versus peripheral stimuli. On the other hand, Gawron (1982) reported that noise improved performance on both a simple and complex tracking task.

One factor considered to be important in mediating the effects of distraction on performance is the mental workload of a task or more generally, the amount of spare capacity available (Gillie & Broadbent, 1989; Hockey, 1970; Pearson & Lane, 1986; Lavie & Cox, 1997; Wilson, McLeod & Muroi, 2008). Several dual task studies have shown that detrimental effects of noise are accentuated as task demands increase (Boggs & Simon, 1968; Finkelman & Glass, 1970). According to Eysenck (1982) noise drains attentional resources and so performance is impaired only when the overall level of task demands is sufficiently high. The findings, however, are not entirely consistent with this view. For example, Kreifeldt and McCarthy (1981) found an apparently low memory load main task was negatively affected by a short interruption. Gillie and Broadbent (1989) used a main task with a higher memory load than Kreifeldt and McCarthy's experiment and yet found no disruptive effects by the interruption. Gillie and Broadbent concluded that memory load in a task was not a crucial factor in determining whether or not a distraction will be disruptive.

In contrast, Lavie and Cox (1997) maintained load as significant moderating factor of distraction effects. According to their load account of selective attention, under low load (characteristic of simple tasks or well-practised tasks) the presence of distractions should cause greater impairment to performance because the resultant spare capacity is involuntarily allocated to the processing of distracters, producing significant distracter interference. Under high load, without spare capacity, distracters are not processed thereby eliminating distracter interference on performance. This leads to the counter-intuitive prediction that a low load, well-practised task should be more vulnerable to interference than a relatively high load, unpractised task. This prediction was recently confirmed in an experiment by Wilson et al. (2008).

Adding further to the complex effects of distractions, there is also evidence of individual differences in susceptibility to the effects of distraction (Ellermeier & Zimmer, 1997; Neath, Farley & Surprenant, 2003). For example, a study by Ellermeier and Zimmer (1997) found that about 10% of participants showed either no effect of irrelevant speech or a beneficial effect. There was also considerable range in the amount of errors made by participants with up to 329% increase in errors for one participant. The individual differences were also relatively stable after four weeks.

Over the years, it has become increasingly clear that the effect of distraction on performance may not be as generalisable as commonly thought. Although the investigation into the effects of environmental stress such as distractions has a long history in cognitive psychology (Bell, 1978; Graydon & Eysenck, 1989; Hockey, 1970) up until recently, the investigation of distraction has mainly observed whether performance improves or deteriorates in the presence or absence of a given distraction. It is now important to look at performance in much greater detail. One avenue of interest to this research is whether there are critical points during performance that are more vulnerable to the effects of distraction than at others points. There is some empirical evidence as well as theoretical speculation that suggest that distraction at critical points during task performance is a major source of skill-based errors (Botvinick & Plaut, 2003, 2004; Li et al., 2008; Monk et al., 2002; Norman, 1981; Reason, 1990). This literature is reviewed next.

2.5.2 Empirical evidence for critical distraction points

Cognitive psychology is only now beginning to investigate the temporal dynamics of distracter effects as a means to understanding when and where attention is needed during task execution. With the exception of a few studies, distractions are often presented randomly during task execution in part because experimental control over the timing of a distraction relative to performance of a task has been difficult to achieve (Altman & Trafton, 2002). Nonetheless, through careful experimental control over the presentation of distraction, several studies have shown that there are critical points where performance is more vulnerable to the effects of distractions (Bailey & Konstan, 2006; Castiello & Umilta, 1988; Davids, 1988; Li et al., 2008; Monk et al., 2002; Rose & Christina, 1990).

Studies examining the distribution of attention during skilled task execution have provided valuable insight. For example, Rose and Christina (1990) compared elite, sub-elite and novice shooters' performance on a primary precision shooting task while making a manual response to an auditory distraction stimulus presented at various times during the period leading up to the shot. Results indicated an increase in the time to react to the distraction stimulus as shot time approached for the three groups suggesting greater attentional demands leading up to the shot. The interesting finding was that there was a much greater decrement in performance on the distraction task for the skilled shooters compared to the novice shooters. In particular, these differences were most pronounced at the aiming stage, suggesting that the skilled performers focused their attention more intently at this stage than the novices. Using a similar approach, Castiello and Umilta (1988) examined how attentional demand alters during the performance of a return of serve in volleyball and tennis. The study found that the period immediately prior to the initiation of the return serve stroke required most attention. These results suggest that attention is required at the beginning of the movement, perhaps attributable to pre-programming or attention required in the planning of movements.

In contrast, in a study examining developmental differences in the allocation of attention Davids (1988) found results suggesting that attention is required most at the end of the movement. In this study, participant groups ranging between 10 and 20 years of age were required to perform a two-handed ball catch while simultaneously processing a peripheral visual signal presented early in, in the middle of, or late in the flight of the ball thus simulating many typical interceptive actions in a ball game situation. The study found greater attention demanded during the late segment of flight (i.e., 50 to90 ms) across all age groups. Comparable findings have been observed when dual task procedures have been used to examine the attention demands during self-paced tasks (e.g., manual aiming). These studies suggest that high attention demand is required at end of the movement attributable to processes involved in error correction (Glencross, 1980) whereas the middle portion of the task may be performed in a fairly automatic mode (Ells, 1973; Glencross, 1980; Posner & Keele, 1969).

Although these results support the notion that there are critical points where attention is needed during skilled task execution they have limited value in terms of our understanding of skill-based errors. In these studies, the focus is on measuring RT rather than error rates and the performance decrement is measured in the secondary task not in the primary task. A few studies have demonstrated the existence of critical points where attention is needed to avoid errors but these studies also have limited generalisability to skill-based errors because the tasks used are not necessarily well-practised. For example, Li et al. (2008) investigated the causes of post-completion errors (PCE) which are a specific kind of error that involves omitting a final task step after the main goal of the task is accomplished (e.g., leaving your change behind after purchasing from a vending machine; forgetting to retrieve the original from a photocopier). The study used a simulated Doughnut making task, which required participants to carry out a set of predefined procedures to produce a specified number of doughnuts by operating a doughnut machine. The follow-on task which essentially served as a distraction task was a “Call Center” task which required participants to look up a specified location to collect a doughnut order. The post-completion step was to click “Process/Clean” at the bottom of the computer screen in the Doughnut task before responding to the next doughnut order. Failure to execute this final step was classified as a “post-completion error” (PCE). Participants were given two training trials on the Doughnut task, one with and without the Call Center distracting task. The study found that a PCE was more likely to occur when the task was interrupted *just before* the execution of the PCE step than when there was an interruption earlier in the task.

The study explained this result based on Altmann and Trafton’s (2002) activation-goal memory (AGM) theory which is a general theory about how people remember their goals or states of the world they want to achieve. The AGM theory predicts that distraction just before the completion of a PCE step is more disruptive because it results in suspended goals to complete the task. This is because the amount of activation associated with a memory item is subject to time-based decay. In order for the cognitive system to refocus attention to the task it needs to undergo a priming process to reactivate the associative links because it will be less active than the goals encoded in the interim. This associative priming mechanism in procedural task execution is similar to the traditional chaining approach in serial recall in basic memory research (Lewandowsky & Murdock, 1989) in which neighbouring memory items in a list are associatively linked to each other.

In another study, Bailey and Konstan (2006) examined the effect on error rates as participants performed multiple interleaving tasks. In this study, while participants were completing a series of primary computer-based tasks (e.g., adding, counting, reading comprehension) they were interrupted by other tasks (a ‘peripheral tasks’) that appeared on the screen. They were instructed to attend to the peripheral tasks as soon as they appeared. The peripheral tasks were presented at two points: about halfway through the execution of the primary tasks, and towards the completion of the primary tasks. The study found that when peripheral tasks interrupted the execution of primary tasks midway users required from 3% to 27% more time to complete the primary task, committed twice the number of errors and experienced from 31% to 106% more annoyance and twice the anxiety than when the peripheral task appeared at the boundary between primary tasks.

Similarly, in another study, Monk et al. (2002) tested the timing of interruptions on the time to resume a primary task. The primary task was a simulated VCR programming task which required participants to perform several subtasks such as entering the show’s start time, end time, day of week and channel number. The interruption task was a pursuit tracking task which required participants to track a moving target. Participants were interrupted at two points during the primary task: at the start of a subtask and in the middle of completing a subtask. The study found that participants were slower to resume the primary task when they were interrupted during the middle of a subtask than when interrupted at the start of subtasks. According to the authors, returning to the primary task in the middle of subtask requires encoding more information relevant to the subtask such as its position in the task sequence and the next subtask in the sequence. There is also some evidence that people strategically postpone engaging interruptions until they finish a task (McFarlane, 2002). This finding suggests that people actively avoid mid-subtask interruptions possibly because of the greater attentional cost as compared with waiting to complete some portion of the task before turning attention to the distraction.

As mentioned, the results of Li et al. (2008), Monk et al. (2002) and Bailey and Konstan (2006) have limited generalisability to the phenomenon of skill-based errors because in these studies participants were not necessarily skilled performers. In Li's et al. and Monk's et al. study, participants were given only two practice trials on the primary task. With regards to Bailey and Konstan's study, it is unclear as to whether any practice trials were given at all.

There has only been one study which has tested the effect of distraction positions on errors made by skilled performers. This study is Botvinick and Bylsma's (2005) experiment involving repeated performance of a coffee-making task (an example of a routine, well-practised task). In this study, participants were asked to prepare 50 cups of instant coffee while coping with intermittent distractions involving the subtraction of dollar amounts. Subtasks were defined as the action of adding in the coffee, cream and sugar. Subtask boundaries were defined by requiring participants to stir after the addition of each ingredient. While participants prepared these cups of coffee they were distracted at mid-subtask and end-subtask points. Mid-subtask distraction occurred just following pouring the relevant ingredient into the cup. End-subtask distraction occurred as participants completed stirring. The study found that a distraction midway through a subtask (e.g., while adding sugar) resulted in more errors in the next subtask (e.g., adding sugar twice) than when a distraction occurred towards the end of a previous subtask (e.g., after stirring in the sugar).

As evident from the review, the literature is scattered with mixed results regarding the exact point in a task where a distraction is most disruptive. The conclusions reached appear to be dependent on a variety of factors such as the nature of the task at hand, the modality used for stimulus presentations/response initiation, the aspect of performance being measured (speed, accuracy, efficiency of movement etc.,) and the way subtasks were operationalised. In some cases, depending on the way researchers define a "subtask" and its boundaries as well as the specific terminology used to describe these subtask points it could lead to fundamentally different assertions (i.e., "early" versus "late"; "mid" versus "end" versus "begin"; "later" versus "earlier"; "before" versus "after"). There is no consistency in the terminologies used in part because many of the studies stem from relatively disparate fields of research, such as motor skill learning, neuropsychology, cognitive psychology and human-computer interaction.

One solution to provide some level of consistency is to examine the extent to which the manner in which task performance fails varies as a function of the specific nature of tasks and skill level. From the perspective of well-practised cognitive-motor tasks, there are two distinct theories that make differential predictions about the effect of distraction at different subtask points on error. These are Reason's (1977, 1979, 1984, 1990) attentional capture theory and Botvinick's and Plaut's (2003, 2004) degradation of task context theory. Both theories assume that attention is needed at critical points during skilled task execution to avoid making subsequent errors in performance. The theories differ in terms of the precise location of these critical points. For Reason, a distraction should be most disruptive when it occurs near the completion of a subtask (i.e., end-subtask) whereas for Botvinick and

Plaut,a distraction should be most disruptive when it occurs midway through a subtask. The distinctions between theories are discussed next.

2.5.3 Reason's attentional capture theory

Reason's (1977, 1979, 1984, 1990) theory of human error is an expansive rather than unified theory as a result of it being continually updated since its early conception. Reason's theory is a collection of somewhat diffuse conceptualisations about the nature and causes of human error. In this review, only the parts relevant to his theorisation of skill-based error will be discussed in detail. According to Reason's (1977, 1979, 1984) model of human action there are two principal components that handle information processing functions. The first is the intention system which is "the chief executive within the hierarchy of action control" (Reason, 1984, p. 533). The intention system is concerned with formulating and organising plans of future actions, monitoring and testing ongoing activity, and evaluating and reviewing action outcomes. Intentions may be prompted by external events (via the perceptual input function) or by internal states (via the need system). Activities of the intention system are highly verbal (plans are held as short verbal tags e.g., "Must buy milk" or "I want to make a cup of tea") and is a function of attentional focus. It is this attentional component that limits the capacity of the intention system and Reason argued that this is reflected in the fact that only one plan or intention can be maximally activated within the system (though other plans may be weakly activated). The second principal component is called the action system and is "best regarded as its [intention system] operations branch" (Reason, 1977, p. 533). The role of the action system is to assemble the necessary action schemas or motor programs (i.e., largely pre-programmed action sequences or subroutines) to execute an action plan as issued by the intention system. Norman (1981) made a similar proposal referring to parent and child schemas as representing the intention and action system, respectively. Similarly, Heckhausen and Beckmann (1990) proposed actions to be guided by goal intentions and instrumental intention, the latter further subdivided into initiation, implementation and termination intents.

Within this framework, Reason (1979) described three “explanatory notions” which accounts for the occurrence of skill-based error. The first is the notion of modes of control which associates the acquisition of skill with the gradual transition from a predominately “closed-loop” model of control to a predominately “open-loop” mode of control (Adams, 1971; Keele, 1968). The intention system varies to the extent to which it is involved in closed or open-loop control of ongoing activity. When carrying out an unfamiliar task, the intention system functions primarily in a closed-loop mode of control. Closed-loop mode of control relies heavily upon visual and proprioceptive feedback and hence conscious attention for the moment to moment control of behaviour. During the execution of familiar, well-practised tasks, the intention system functions primarily in an open-loop mode of control, whereby behaviour is largely governed by pre-programmed subroutines that can run off autonomously and independent of feedback information thus freeing up the intention system to do other things.

The second of Reason’s (1979) explanatory notions is that of critical decision points. Reason proposed that skill-based or automatic actions comprise segments of pre-programmed behavioural sequences (i.e., subtasks) that are interspersed at the subtask boundaries with critical points called “decision nodes”. During the execution of any skilled action sequence, no matter how familiar or well-practised they may be, these periodic checkpoints at subtask boundaries (i.e., end-subtasks) are required to ensure that skilled actions run smoothly. Reason described these critical decision points as momentary shifts from low maintenance, highly automatic skill processing (i.e., open-loop mode) to controlled, higher level processing (i.e., closed-loop mode). This contrasts with Shiffrin and Schneider’s (1977) view of skilled performance as involving automatic processing which does not require conscious attention. It is, however, consistent with other prominent theories of skill learning (Hockey, 1997; Hollnagel, 2005; Norman & Shallice, 1986; Stein & Glickstein, 1992).

Reason’s (1979) third explanatory notion relates to the role of distraction which suggests that errors in skill-based actions can occur at critical decision points when the intention system, operating in an open-mode of control is occupied or distracted by some other parallel activity. Reason postulated that distraction at critical points during skilled task execution is a major source of errors because distraction captures one’s attentional focus which leads to the omission of these routine checks. The theory makes a specific prediction that distraction should be most disruptive when it occurs near the completion of a subtask (i.e., end-subtask) because at that point distraction is most likely to interfere with execution of the checking operation.

The main criticism of Reason’s (1977, 1979,1984, 1990) theory is that most of its assumptions lack empirical evidence. Most, if not allof Reason’s predictions were developed based on diary studies and examination of accident reports and as yet few of these predictions have been subject to rigorous empirical investigation. There is no controlled experimental data presented in support of the proposed explanatory notions of skill-based error. Empirical investigation is required to explore the causal mechanisms attempting to explain how these errors occur and even why these deficiencies in attentional functioning occur.

2.5.4 Botvinick and Plaut's degradation of task context theory

More recently, Botvinick and Plaut (2003, 2004) proposed an alternative account of action slips based on a different conceptualisation of the way skilled tasks are internally represented. In contrast to Reason's (1979) notion of "motor programs" and Norman's (1981) notion of "schemas", Botvinick and Plaut argued that skill reflected in routine activities cannot be identified with discrete, isolable knowledge structures. More precisely, Botvinick and Plaut argued against the central assumption in schema-based theories that the hierarchical structure of sequential behaviour is directly reflected in the structure of the information processing system as a hierarchy of nodes or schemas. In this way simple actions such as lifting a teapot, moving it and tilting it are grouped together into subroutines such as pouring tea into a cup which are themselves part of a larger routine, that is, making tea.

Rather than localised, standalone knowledge structures, knowledge about action sequences in Botvinick and Plaut's (2003, 2004) model takes the form of a recurrent neural network model which is distributed and superimposed over a large set of connection weights among processing units. Neural network models are styled after the concept of densely interconnected cells that characterise the organisation of the brain. The critical idea regarding representation in neural network models is that knowledge consists of weighted connections among an entire network of processing units. In Botvinick and Plaut's model, there are three sets or layers of processing units, mapping from environmental inputs to action inputs via a set of internal units.

The internal units play a key role in Botvinick and Plaut's model (2003, 2004). First, because they lie between the input and output layers they serve as an intermediate stage in the stimulus-response mapping performed on each processing step. Secondly, they store all task context information which relates to past, current and future steps in an action sequence (i.e., the internal representation of a task). In this model, practice on a task "carves up" up the distributed space in the internal unit to represent different task contexts. The more practice on a particular task, the larger the region used for representing that task. Task representations may be "shared" or "overlapped" by multiple, structurally similar tasks (e.g., making tea and making coffee). In Botvinick and Plaut's model, errors occur when the system's representation of task context becomes degraded during online execution which results in a loss of information about the task context. When the internal representation of a task context is distorted it occupies the wrong space in the representational space often residing in familiar task contexts. According to Botvinick and Plaut this is why skill-based errors are not necessarily novel or random but are often the right actions in the wrong context.

Like Reason (1990), Botvinick and Plaut (2003, 2004) maintained that errors in skilled performance tend to fall at transitions between subtasks (i.e., decision errors) but offer a different explanation for their cause. Specifically, they assume that context information is more susceptible to loss when a distraction occurs earlier in a subtask, that is, midway though a subtask than at the boundaries between subtasks. This is because in Botvinick and Plaut's model, distinctions between different task contexts are represented more robustly towards the boundaries (i.e., at end-subtasks) where such distinctions are directly relevant to action selection. Elsewhere and in particular, toward the middle of subtask sequences, differences in temporal context are represented less strongly. An example to illustrate this point was provided by Botvinick and Bylsma (2005) using a coffee making task. At the end of adding cream to coffee, the critical piece of context information needed next is whether or not sugar has been added. In order for this sugar information to be available for use at the end of the creaming-adding subtask, it must be preserved through the course of the cream adding subtask. Note that this information about whether sugar has been added or not is not directly relevant during the cream adding phase (it just needs to be held in the internal units). According to Botvinick and Plaut's model, this lack of immediate relevance leads the context information to be represented relatively weakly toward the middle of the subtask. This in turns renders it more susceptible to distraction and loss during performance of mid-subtask actions setting the scene for a decision error to occur in the next subtask. This is a novel and counterintuitive prediction relative to Reason's (1990) account because it predicts that an error should be more likely following a distraction that occurs earlier in a subtask (i.e., mid-subtask) than following a distraction at the end of a subtask even though the latter subtask point is temporally closer to where the error occurs.

As mentioned, the particular susceptibility of mid-task distraction was confirmed in an experiment involving repeated performance of a coffee-making task (Botvinick & Bylsma, 2005). The study showed that a distraction in the form of a subtraction task involving dollar amounts was more disruptive when it occurred in the middle rather than the end of a subtask. This is an important study because this is the first empirical study to examine the effect of the timing of acute distraction on errors during performance of a routine, well-practised task. Clearly more rigorous empirical testing of Reason's (1990) and Botvinick and Plaut's (2003) alternative predictions is needed.

2.6 Summary of Chapter 1 and 2

To summarise, skilled performance is often equated with the development of automaticity. The concept of automaticity creates an interesting contradiction in relation to the importance of attention during the performance of highly skilled behaviour. It contrasts with another widely accepted proposition that the ability to concentrate and maintain attention during the execution of skilled behaviour is essential for producing optimal performance. The importance of attention to skilled performance is often emphasised in the literature. For instance, Ericsson (2001) suggests that during a golf routine and execution the player's attention is fully concentrated to minimise distractions from external and irrelevant stimuli. Indeed the culture of the game dictates silence during the preparation and execution of each shot. If skilled behaviour is automatic and therefore does not consume any attentional resource then distraction should logically have minimal impact on performance. Clearly this is not the case as evident by the plethora of studies documenting the negative effects of distraction on skilled performance.

Theories of skill-based error converge on two core assumptions. First, that distraction or interruption is a major source of errors in well-learned, skilled tasks and secondly, that there are critical points during skilled task execution where a distraction or interruption is most likely to cause a subsequent error. The theories differ, however, in terms of their explanation of the effect of distraction on skill-based error and their prediction about the precise location of these critical points. According to Reason (1990) skill-based errors can occur because of a distraction to attentional focus or an internal preoccupation which captures attention and leads to the omission of conscious checking or monitoring operations that ordinarily would ensure the correct execution of skilled behaviour. The theory makes a specific prediction that distraction should be most disruptive when it occurs near the completion of a subtask because at that point distraction is most likely to interfere with execution of the checking. Botvinick and Plaut (2003, 2004) proposed an alternative account of skill-based errors arguing that they are not due to executive failure as proposed by Reason, but rather they occur because distraction degrades task context information that is held internally during online task execution and that the critical points appear to lie during mid-subtask performance.

Overall, Reason’s (1990) and Botvinick and Plaut’s (2003, 2004) theories suggest a much more complex understanding of the attentional requirements underlying skilled performance than typically described from the automaticity literature. The theories suggest it may not be just the presence or absence of a distraction that affects skilled performance but rather the timing of distractions as one characteristic which may critically affect performance. The two theories are, however, clearly very different, which makes it difficult to reconcile their differences theoretically. This is because Reason's and Botvinick and Plaut's theory stem from two different literatures and have been applied in different contexts. Despite being different, both theories share the assumption that attention is needed at critical points during skilled task execution. One worthwhile pursuit to distinguish between the two theories is to test their different predictions about *where* these critical points are located and the precise effects of distraction on skilled performance at these posited critical points. Given that there has only been on one study that has empirically investigated the differential effects of distraction timing on skill-based error (Botvinick & Bylsma, 2005) there are many worthwhile opportunities for further investigation..

2.7 Research questions to be addressed

While we have some evidence on the form that skill-based errors will take (Norman, 1981; Reason, 1990; Reason & Mycielska, 1982) and the relative frequency with which they occur (Hobbs & Williamson, 2002) and can be detected (Reason, 1990; Rizzo et al., 1987) there has been comparatively little research on their causes. Given the mounting evidence that errors in skill-based behaviour can be serious (Salminen & Tallberg, 1996; Williamson & Feyer, 1990) there is need for research to go beyond descriptions and classifications of error types and to understand better the critical issues of why and how skill-based errors occur. The overarching aim of this research was to learn more about the nature, timing and causes of errors that occur in skilled, well-learned tasks. Three broad research questions are addressed with this aim:

Research question 1: *What is the role of attention during skilled performance?* The notion that skill-based errors occur as a result of distraction that captures attention at critical points is at odds with the automaticity notion that skilled performance is not at all reliant on attention. Is it the case, as suggested by Schneider and Shiffrin (1977) that skilled tasks can be performed without attention and therefore performance is immune to distractions because it no longer requires voluntary allocation of limited resources? Or is it that when a skill develops with practice attention is still required to ensure its correct execution? In this research, low and high skill performers will be compared under conditions of distraction and no distraction in order to test the fundamental assumption that skilled performance affords greater protection against distraction.

Research question 2**:** *Are there "critical points" during skilled task execution wherein attention must be paid to the task in order to avoid errors?* Or is the presence or absence of a distraction sufficient to account for the effect of distraction on skilled performance? Specifically, does the timing of distraction matter and are there differential effects depending on the nature of the task, the nature of the types of error being measured and/or skill level? To answer these questions, skill level will be manipulated, distinct skilled tasks will be used and different types of performance errors will be measured (e.g., movement errors, decision errors, memory errors).

Research question 3**:** *What underlying mechanism is being disrupted at various points when an acute distraction occurs?* Two alternative explanations will be tested: (1) that distraction interferes with the execution of an executive checking operation near the completion of subtask points which ordinarily would ensure task-appropriate behaviour (Reason, 1990); and (2) that distraction plays a key role in degrading the system's representation of task context and attention is needed at mid-subtask points in order to avoid making subsequent errors (Botvinick & Plaut, 2003, 2004). Begin-, mid- and end-subtask points will be manipulated in order to test the spectrum of subtask positions and thus provide a more rigorous test of Reason's (1990) and Botvinick and Plaut's (2003, 2004) theoretical predictions.

CHAPTER 3

EXPERIMENT 1: THE EFFECT OF DISTRACTION ON SKILLED PERFORMANCE IN A NOVEL PSYCHOMOTOR TASK

3.1 Overview of Chapter 3

In this chapter the results of the first experiment are presented. Specifically this chapter deals with the design and development of a novel psychomotor task which enabled participants to be trained to a skilled level from a baseline level of performance. The effect of momentary distractions on low and high skill performance was investigated. The aim of Experiment 1 was to further our understanding of why skill-based errors occur by examining the role of attention during skilled performance. The results suggest that skill development reduced capacity demands but a level of attention or self-regulation was still involved at critical points in order to avoid errors. Interestingly, these critical points were the same for low and high skill participants suggesting that skill development does not change where attention is most needed.

3.2 Introduction

Skill-based error occurs at the level of behaviour which is well-practised (Rasmussen, 1982; Reason, 1990). It is a fascinating phenomenon because despite the advantages which skilled performance confers these errors persist at non-trivial rates and can have devastating consequences in certain contexts (Salminen & Tallberg, 1996; Williamson & Feyer, 1990). To date, the little research on skill-based error has focused mainly on describing and classifying the different forms they take in everyday settings (Norman, 1981; Reason, 1977, 1979, 1982). Based on the results of diary studies, Reason and Mycielska (1982) outlined three crucial conditions for the occurrence of skill-based errors. First, they occur during the execution of well-organised, highly practised, largely physical actions which appear to take place without conscious control. Secondly, they are associated with distraction or preoccupation. Thirdly, they flourish in familiar environments.

According to Reason (1990) skill-based actions comprise segments of pre-programmed behavioural sequences (i.e., subtasks) that are interspersed at the subtask boundaries (i.e., end-subtask) with critical points called “decision nodes”. Skill-based errors arise due to a failure to perform intermittent attentional operations or conscious checking at critical points during skilled task execution. Norman (1981) made a similar proposal that “conscious attention to the task can vary, with the task itself demanding attention at critical action points” (p. 5). Reason postulated that a necessary condition for the occurrence of a skill-based error is the presence of a distraction to one’s attentional focus, which leads to the omission of routine conscious checks. The theory makes a specific prediction that distraction should be most disruptive when it occurs at the end of a subtask because at that point distraction is most likely to interfere with execution of the checking operation.

Botvinick and Plaut (2003, 2004) proposed an alternative account of skill-based errors, arguing that they are not due to executive failure at the end of a subtask as proposed by Reason (1990) but rather they occur because distraction degrades task context information that is held internally during online task execution and that the critical point is during mid-subtask performance. The impact of mid- and end-subtask distraction on the rate of subsequent errors was evaluated in an empirical study by Botvinick and Bylsma (2005). The researchers conducted an experiment involving repeated performance of an instant coffee-making task while coping with frequent distractions at mid- and end-subtask points. Using a distraction task involving the subtraction of dollar amounts, the study found support for Botvinick and Plaut’s prediction that a distraction midway through a subtask (e.g., while adding sugar) was more likely to result in an error in the next subtask (e.g., adding sugar again when sugar had already been added) than when a distraction occurred towards the end of a subtask (e.g., after stirring in the sugar).

There were, however, a number of limitations with Botvinick and Bylsma’s (2005) coffee-making design. These limitations are first, there was no control over prior learning. Participants in the study no doubt had experience with making coffee and would have employed a number of past sequences (e.g., adding sugar before coffee, not adding sugar at all, adding more than one sugar, not adding cream at all). It was not clear if and how previous learned routines were extinguished. In an attempt to standardise performance there were a number of guidelines for making the coffee to which participants had to adhere. For example, ingredients had to be added in the same order, for each ingredient only one pack was to be added to each cup and each ingredient was to be stirred in, directly after its addition. Hence rather being a naturalistic observation of routine actions, the experiment was relatively contrived.

The second limitation related to the sample size which was small and errors were relatively few. Only 22 participants were tested and only nine participants made at least one error. Overall, less than 2% of trials in the study contained an error. To maximise error rate, the authors included “micro errors” in their analysis. These are cases where an erroneous action is initiated but aborted (i.e., reaching for an incorrect target, and quickly retrieving and redirecting towards a different target). The inclusion of these micro errors may very well reflect the intervention of Reason’s (1990) proposed checking or monitoring functions at end points. However, this was not statistically verified possibly because of the study’s low error rate.

The third limitation related to the operationalisation of mid and end points which was potentially problematic. Mid-subtask was defined when the pouring action was completed (i.e., when the hand used for pouring began to withdraw from its position above the cup) and not *during* the actual pouring of the relevant ingredient which seems like a more appropriate mid-point. End-subtask was defined by requiring participants to stir after the addition of each ingredient of coffee, cream and sugar which is a rather contrived way to operationalise the end of a subtask. The authors noted that participants occasionally neglected to stir in an ingredient which suggests problems with the repetitive stirring requirement.

The fourth limitation related to the study’s failed to fully account for the spectrum of subtask points. The study only investigated the effects of distraction at mid- and end-subtask points. The study did not assess the potential impact of distractions at the beginning of a subtask (e.g., at onset of a reaching action) which may have an important influence on visuomotor skill performance as in the case of coffee making. There is some evidence from the motor skill literature that distraction at the start of a skilled action is most disruptive because this is where a response is planned and triggered into action (Adams, 1971;

Schmidt, 1975). The disruptive effect of begin-subtask distraction has been attributed to response pre-programming (Castiello & Umilta, 1988).

Botvinick and Bylsma's (2005) study was also limited in that it did not measure latency on the coffee making task. This is rather crucial information for understanding potential speed-accuracy trade-off (SATO) functions (Pachella, 1974; Rabbitt & Banerji, 1989). As Wickelgren (1977) pointed out, the basic fact of SATO makes it inadequate to look at either RT or error date alone as the dependent variable. This is because any level of error might be obtained depending upon what level of RT the participant decided to adopt in performing the task.. Although the error rate was low in the study, as Wickelgreen (1977) argued, it is precisely in tasks with low error rates (i.e., high accuracy) where SATOs play a significant role because it is at low error rates where variations in RTs is largest. Because of this, it is important to measure both speed and accuracy.

A final limitation relates to the fact that Botvinick and Bylsma (2005) did not report any data on the distraction task that they used which severely limits the interpretation of the study's findings (Fisk, Derrick & Schneider, 1987). The distraction task used was a mental subtraction task which involved dollar amounts between $1.00 and $9.99 and required the carrying of one digit. The task demanded considerable effort rather than simply absorbing attention for a short period such as a brief tone. Moreover, the disengagement process was also quite complex in that in response to the distraction participants were required to stop what they were doing (putting down whatever objects they were holding) and to direct their attention to a card which contained the problem and was held at eye level by the experimenter. Participants were asked to state their answer aloud and then to write it down on a sheet of paper. Hence the process of reorienting in Botvinick and Bylsma's task involved not only a physical reorientation (i.e., visual re-acquisition of the primary task) but also a memory reorientation for important task information (e.g., where one left, what to do next). It is likely that processes involved in coping with distractions in skilled behaviours are complex and hence the same pattern of results may not replicate if a different distraction task is used. Clearly, more rigorous empirical testing is needed.

The current research adopted a different approach to testing the effect of distraction at different subtask points during skilled performance: by using a novel psychomotor task, training participants to an asymptotic level of skilled performance on the task and then using distraction at various points to disrupt skilled performance and produce errors. In studying skilled behaviour using a novel task, training was a fundamental aspect of the study's manipulation. In order to make claims pertaining to skill theories, it was important to demonstrate skill attainment. The typical learning curve is a decelerating trajectory, characterised by rapid improvement at the start of practice followed by diminishing improvements with further practice. This pattern of improvement with practice is known as the power function of practice in the skill acquisition literature and is widely considered the gold standard by which the success of all models of skilled performance are judged (Anderson, 1982; Logan, 1988; Palmeri, 1997).

The disadvantages of using a novel task over a pre-established skill, like coffee making, were that it was time consuming to train participants to an asymptotic level of skilled performance and the tasks required time for development and piloting. The main benefits of using a novel task, however, were that it addressed many of the limitations in Botvinick and

Bylsma's (2005) study such as control over learning effects, to obtain baseline measures of performance and to manipulate skill level in order to make comparisons between low- versus high-skill performers. Given the emphasis on the role of skill it is important to characterise the patterns of distraction timing effects for low skill individuals as well as high ones.

The task used in the current study required participants to use a computer mouse to align a pointer with a target light in one of five positions on a computer screen. The task was novel as there was an inverse relation between the mouse and the pointer movement on the screen. Movement of the mouse to the right swings the pointer to the left and vice versa. The primary skill in this task (acquired through training) was the ability to track accurately and precisely in this anti-stereotypical way. The task provided a means to assess what Pratt, Chasteen and Abrams (1994) saw as the important feature of skill "to make fast and accurate goal-directed movements ... (within an) ... ever-changing environment" (p. 325).

The distraction task used in the current study was also different to Botvinick and Bylsma's (2005) study. The task involved simple auditory stimuli (i.e., pure tones) which was designed to shift attention away from the primary task for a brief period and has been shown to be effective in numerous distraction studies (Hochman & Meiran, 2005; LeCompte, Neely & Wilson, 1997; Schumacher et al., 1997; Van Selst et al., 1999). The primary task and distraction task used in this study were chosen because tracking is representative of many real world tasks such as continuous vehicular control (e.g., automobiles, aircraft) combined with concurrent discrete operation of auxiliary devices (e.g., radio, navigation equipment). The implications of the study's findings will thus be relevant to many applied areas.

Another benefit of the tracking task was that it provided data on different aspects of performance. The task was sufficiently complex to be divided into two relatively distinct decision and movement subcomponents. The decision component of the task required participants to select the direction of movement, left or right, taking into account the anti-stereotypical nature of the task. The movement component of the task involved the actual execution of the movement by aligning a pointer with a target. Four types of performance variables were thus measured on this task: (1) decision time and (2) decision error (herein referred to as 'wrong way error') which reflect processes involved in planning and decision making in relation to the direction of a movement, and (3) movement time and (4) movement error (herein referred to as 'overshoot error') which reflect processes involved in the control and execution of a movement.

In psychological terms, the decision and movement subcomponents of this task are analogous to processes involved in response selection and response programming, respectively. Response selection refers to mapping response alternatives to the stimulus presented and response programming refers to the organisation of actions programs (Adams, 1971; Keele, 1968; Schmidt, 1975). There is evidence that both processes are attention demanding (Buckolz & Hall, 1982; DeJong, 1993; Keele, 1973; Logan & Burkell, 1986) but less is known about precisely where during task execution this occurs (Ketelaars, Khan & Franks, 1999) and even less is known about whether skill development modulates attentional requirements of these processes (Klein & Posner, 1974; Logan, 1982; Pashler et al., 2001).

The examination of both response selection and response programming processes in one task paradigm as in the case of this research is also rare (Ketelaars et al., 1999; Netick & Klapp, 1994). Studies have typically used discrete tasks (e.g., lexical decision, arithmetic problem solving) which have no or minimal motor components or in complete contrast, tasks with no or minimal cognitive/decision component such as various types of tapping tasks which only measures pure motor speed (Pashler, 1994). Although the coffee making task in Botvinick and Bylsma's (2005) study involved both the accurate selection of actions and the accurate execution of selected actions, the authors were only interested in explaining errors in response selection. Given that many real-world skills are "cognitive-motor" in nature there is a need to understand both processes.

The operationalisation of subtask points in this task was arguably clearer than Botvinick and Bylsma's (2005) study because each movement to a target was defined as a subtask and within each subtask required the completion of three steps: initiating a directional movement, moving to the target and acquiring the target. Therefore, there were obvious beginning, middle and end points. In this study, begin-subtask distraction occurred immediately following the presentation of a target (i.e., just before the initiation of a movement), mid-subtask distraction occurred during the middle of a movement towards a target and end-subtask distraction occurred as soon as the pointer was about to align with the target.

The current study thus improved and extended that of Botvinick and Bylsma (2005) in four major ways: (1) by using a different skilled task and distraction paradigm to see whether the results of Botvinick and Bylsma's coffee making task can be reliably replicated; (2) by comparing the patterns of distraction timing effects for low and high skill individuals; (3) by examining whether there are differential effects of distraction and its timing on response selection and response programming processes; and (4) by extending the test of distraction positions to include beginning, mid and end in order to test the spectrum of subtask positions and thus provide a more rigorous test of Reason's (1990) and Botvinick and Plaut's (2003, 2004) theoretical predictions.

Overall the primary aim of this study was to investigate the role of attention during skilled performance. Assuming that skill development on the primary task frees up more processing resources that can be used for a secondary task, as previous studies have found (Beilock et al., 2002; Leavitt, 1979; Parker, 1991; Smith & Chamberlin, 1992) then high skill performers should perform better than low skill performers on both the primary and secondary task. Although skill development frees up more resources, it does not completely eliminate attentional demands. According to this view (Cheng, 1985; Logan, 1988; Pashler, 1998) a level of attention is still involved at a skilled level of performance. This leads to the prediction that both low and high skill performance will be degraded by the negative effects of distraction. Alternatively, according to automaticity theory (LaBerge & Samuels, 1974; Posner & Synder, 1975; Shiffrin & Schneider, 1977) well-practised performance is immune to the introduction of a distraction because it no longer require voluntary allocation of limited resources. This leads to the opposite prediction that only low skill performance will be degraded by the negative effects of distraction. High skill performance under distraction will be comparable to no distraction.

In relation to the nature of attention allocation, assuming that low skill performers need to pay more constant attention to the task at hand then it is likely that different distraction positions will have equal negative effects on errors compared to no distraction condition. For high skill participants, there should be differential effects of distraction positions. If errors occur because distraction degrades task context information then as predicted by Botvinick and Plaut's (2004) theory and as demonstrated by Botvinick and Bylsma (2005) empirical study, distraction should be most disruptive when it occurs mid-subtasks. If, by contrast, and in accord with Reason's (1990) prediction, skill-based errors are due to a failure to perform a conscious checking operation then distraction should be most disruptive when it occurs at end-subtasks. Alternatively, according to the class of motor skill theories, distraction at the beginning of a subtask should be most disruptive to skilled performance because this is where the planning of skilled action takes place (Adams, 1971; Keele, 1968; Schmidt, 1975).

3.3 Method

3.3.1 Pilot study

Twelve introductory psychology students (*M* = 21 years; 7 females, 5 males) aged 18 to 32 years (*M* = 21.17; *SD* = 4.32) from the University of New South Wales took part in a pilot study. Pilot participants received course credit points for their participation. The purpose of the pilot study was to test the functioning of the task program, to assess the effectiveness of the stimulus materials and the experimental manipulations and to estimate the approximate running time of the experiment. As results from the pilot study revealed no problems with the task program, stimulus materials and experimental manipulations, the researchers proceeded with the experiment.

3.3.2 Design

A 2 × (4) between-within subjects design with one between-subjects variable, skill level (high versus low) and one within-subjects variable, distraction positions (no distraction, begin, mid, and end points).

3.3.3 Participants

A total of 60 introductory psychology students (34 female, 26 male) aged 18 to 26 years (M = 19.93; SD = 2.13) from the University of New South Wales were tested individually in a single session lasting approximately 60 min for participants in the low skill condition and 180 min for participants in the high skill condition. There were 30 participants in each skill condition. The sample size was based on a power analysis which calculated at least 25 participants in each between-condition to achieve a power of .80, based on a moderate effect size (h^2= .06) (Botvinick & Bylsma, 2005) and .05 significance level. Participants received course credit points for their participation. All were right-handed and had normal or corrected-to-normal vision.

3.3.4 Apparatus & materials

The experiment was performed with an IBM computer, keyboard and computer mouse. The computer controlled stimulus presentation and response registration. Visual stimuli were displayed on a 15-inch CRT monitor running in 640 x 480 x 16 VGA mode 2. The viewing distance from the participant was approximately 70 to100 cm. Auditory stimuli were played with the computer speakers, presented without earphones and were well above threshold. Written materials used in the experiment were a consent form, participation information sheet and a debrief information sheet.

3.3.5 Primary task description

The task was a simple psychomotor task which required participants to align a pointer with a target light by means of the computer mouse. The task display was a black computer screen with a simulated blue pointer centred in the middle and five simulated light-emitting diodes (LEDs) appeared in an arc around it (see Figure 2). The simulated LEDs were labelled with the integers 1, 2, 3, 4 and 5 and were placed at 20, 55, 90, 125 and 160 degrees angle in a clockwise direction, respectively. Integer characters centred 15 pixels above the corresponding LED. The LEDs were four pixel radius circles with two pixel white highlights offset to appear three-dimensional. The LEDs were dark red in colour when non-illuminated and a light red colour when illuminated. The simulated blue pointer was of three pixel thickness and 160 pixel length. The tip of the blue pointer was linearly mapped onto the arc along which it moved. The position of the blue pointer along the arc was measured in the basic units “mickeys” which are the smallest

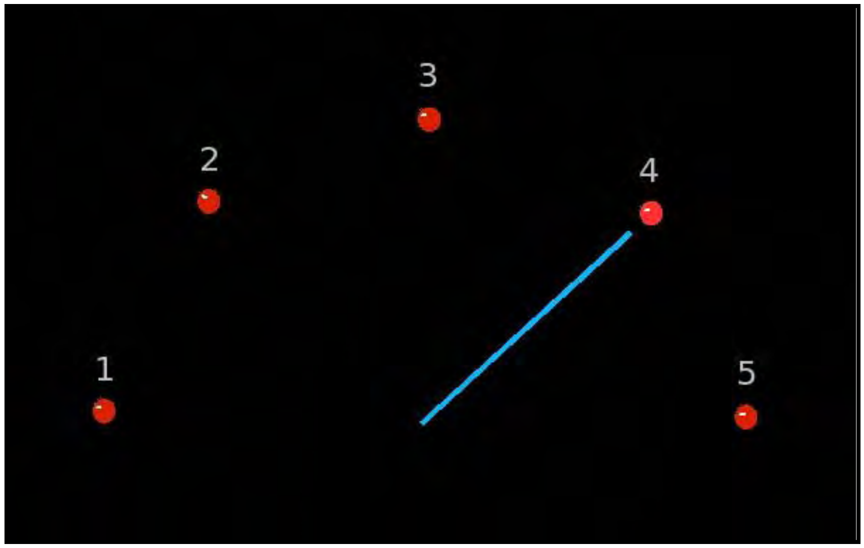


Figure 2. Task display.

detectable movement of the computer mouse. This was more accurate than the actual movements of pixels on the screen which depends on the aspect ratio (i.e., how "square" a real pixel is on a real screen). The range of pointer movement was designated at positions 1 to637. The pointer could be moved anywhere in this range. Simulated LEDs were set at 126 (LED 1), 222 (LED 2), 319 (LED 3), 416 (LED 4) and 512 (LED 5) on this range (see Figure 3).

There were there were approximately 96.5 mickeys mapped along the arc between each LED positions. The task program recorded the position of the pointer along the arc once every 55 ms. The task program was written in C and made use of C and 8086 assembly language library routines as well as Borland C library routines. The program was compiled with the Borland C compiler version 2.0. The task program ran under the FreeDOS operating system.

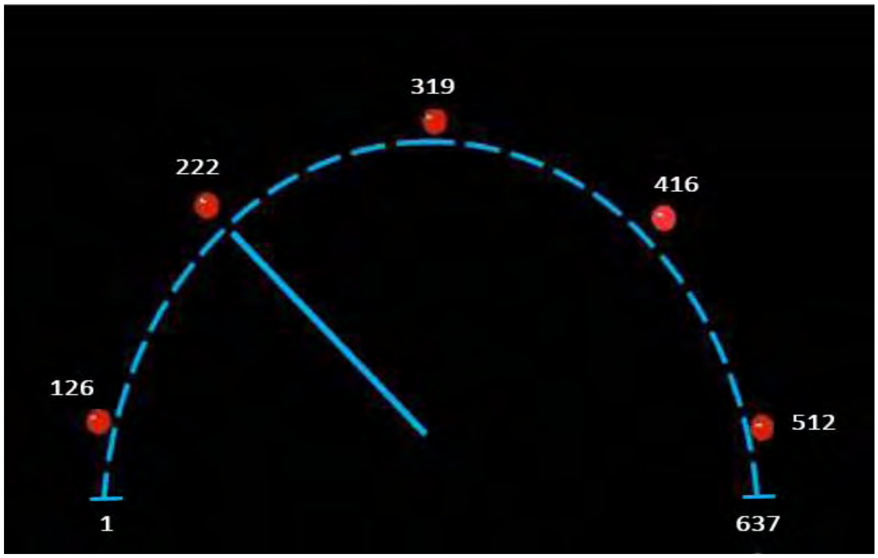


Figure 3. Range of pointer movement and pointer position corresponding to each LED.

The current task required movement of the pointer to each illuminated LED (herein called “target”). Pointer movement was controlled by movement of the computer mouse. The computer mouse was controlled by using the right hand as is conventional. The nature of the movement required to move the blue pointer was a simple lateral movement of the computer mouse (there was no need to click or drag and click the computer mouse). Movements of the mouse/pointer were only in the left/right direction (forward/back was disabled) much like moving a fixed rod at its pivot point. The task was novel to the participants in that there was an inverse relation between the mouse and the pointer movement. Specifically, movement of the mouse to the right swings the blue pointer to the left and vice versa. The primary skill in this task was being able to perform the task accurately and precisely in this anti-stereotypical way.

The task was adapted from a previous electromechanical apparatus which was developed by Buck, Leonardo and Hyde (1981) based on an original design by Gibbs (1965). The original apparatus comprised a panel with five LEDs in a circular arc and a knob controlling a pointer that could be moved along that arc to point to any of the LED. The mechanical coupling of the knob to the pointer was such that the pointer rotated in the opposite direction to the knob. The device was used in a number of previous studies examining psychomotor functioning under various conditions such as sleep loss, time of day, alcohol and age-related decrements (Blais, Kerr & Hughes, 1993; Buck et al., 1981; Kerr, Blais & Toward, 1996; Kerr & Teaffe, 1991; Rawana & Vogel-Sprott, 1985).

Previous studies have demonstrated that participants could be trained to a skilled level on the task with relative ease (Blais et al., 1993; Buck et al., 1981; Fazey & Fazey, 1989). The skill could also be seen in some real world tasks, such as reversing a car which involves turning the steering wheel in the opposite way to normal or in some work tasks, such as laparoscopic surgery which is often described as like trying to tie a bow tie in the mirror.

Unlike traditional laboratory tasks where a trial would usually terminate if an incorrect response is given, in the present task, successful alignment with the target had to be achieved before the next target appeared. The overall pace of the task was therefore subject-paced rather than experimenter-paced. This avoided the problem experienced by previous studies using the experimenter-paced version of the task (Gibbs, 1965) whereby participants sometimes inadvertently lost alignment with the target while waiting for it to change position (or, for that matter, had not yet achieved it) and as a result information about decision time and accuracy of the next response was lost. The subject-paced nature of the task also provided participants with intrinsic knowledge of alignment accuracy as the more precise and faster they moved the faster the trials proceeded.

Similar to the original design of the task (Buck et al., 1981) participants were required to keep the pointer within 10 mickeys of the target for approximately 500 ms. A criterion alignment time of 500 ms was selected because it prevented rapid excursion of the pointer across the target from initiating the next target movement without allowing too long for the participant to question alignment accuracy (Buck et al., 1981). The positional criterion was set at 10 mickeys because this was approximately the diameter defining the target. Decision time terminated as the pointer left this area and alignment time commenced (or re-commenced) as the pointer entered (or re-entered) the area. The positional and temporal requirement thereby allowed each response to be considered as a discrete movement for each target presentation. Once successful alignment was achieved (i.e., staying on target for 500 ms) the light was extinguished and the next target was simultaneously illuminated.

Another basic feature of the experiment was that the directional probability of the target (i.e., left versus right movement) varied according to the position of the pointer on the display. For example, in Figure 2 with the pointer set at position 4, the probability that the next target would appear to the right was 25 per cent and 75 per cent to the left. Similarly, starting from position 3, there was a 50 per cent probability of moving either left or right and starting from either position 1 or 5, the directional probability was 100 per cent. The spatial display of the task made these four directional probabilities clear to the participants.

A stimulus block consisted of consecutive target presentations. Given the five LED positions on the task display there were 20 possible movements between pairs of positions (i.e., 12, 13, 14, 15, 21, 23, 24, 25, 31, 32, 34, 35, 41, 42, 43, 45, 51, 52, 53 and 54). Lists of targets were constructed by randomly selecting without replacement sequences of 20 between-target movements. A database of 72 unique sequences of 20 between-target movements was obtained. Within each stimulus block there were equal numbers of left and movements and each of the 20 possible between-target transitions occurred with equal frequency. A stimulus block always started and ended in the middle of the display (LED 3).

During the training phase low and high skill participants were exposed to 40 and 1680 (14 stimulus blocks each with a unique sequence of 120 targets) consecutive target presentations, respectively. During the testing phase, all participants performed one block of 120 consecutive target presentations under conditions of auditory distractions. A demonstration block of eight targets was presented before the training and testing phase: four without and four with the distraction stimuli, respectively. The demonstration list of eight targets was the same for all participants. The protocol included equal numbers of no distraction, begin-, mid- and end-subtask distraction.

3.3.6 Distraction task description

The distraction method used in the current research is commonly known as the "probe" technique (Posner & Boies, 1971) which involves asking participants to carry out some primary task and at various times during the performance of the primary task it is interrupted by presentation of a probe/distraction stimulus such as a brief tone. It is assumed that the probe requires or utilises some attentional capacity that should be devoted to the primary task. Responses to the probe reflect momentary attention away from the primary task.

In this study, two pure tones (600 and 700 Hz) were used. Simple auditory stimuli have been used effectively to distract participants in previous research (Alho et al., 1997; Hein, Alink, Kleinschmidts & Muller, 2007; Hochman & Meiran, 2005; Schumacher et al., 1997; Van Selst et al., 1999). The aim was to distract participants by evoking an orienting response by shifting attention away from the primary tasktowards the distracting stimuli in order to induce errors on the primary task. The orienting response is often elicited by novelty (Gati & Ben-Shakhar, 1990; Parmentier, 2008) and therefore with repeated exposure to distracting stimuli, the orienting response diminishes because participants learn to ignore it (Banbury & Berry, 1997; Kelly & Yantis, 2009; Reisbeg, Baron & Kemler, 1980).

To ensure that attention was captured by a tone every time it occurred (i.e., that it absorbed conscious attention) upon hearing a tone participants were required to decide whether it was high pitch (700 Hz) or low pitch (600 Hz) and to respond to only one of the tones by pressing the spacebar with their left hand. Participants were instructed to respond to an allocated tone as fast as possible. The purpose of using relatively close tones (600 and 700 Hz) compared to other tone-based distraction tasks that use disparities of over 500 Hz (Koch, 2009; Pashler & Johnson, 1989; Schumacher et al., 2001) was to increase the attentional demand so that participants had to pay attention to the tone in order to make this fine relative decision. The auditory nature of the distraction task meant that there was minimal sensory interference with the visual nature of the primary task (Wickens, 2002). The pilot study revealed no response conflict in relation to the use of the right and left hand to perform the primary and distraction task, respectively.

Distractions were presented randomly such that 60 trials had no tone and 60 had a tone (counterbalanced between 600 and 700 Hz tone). Within the 60 trials with a tone there were 20 begin-, 20 mid- and 20 end-subtask distractions. The timing of the distraction was based on a pseudo-random trial sequence protocol, established before the session and different for each participant. The protocol indicated, for each trial in the session: (1) whether a distraction should take place and if so, (2) whether it should take place at the beginning of a subtask, mid-subtask or end-subtask. The protocol allowed for consecutive distractions to occur but there were two restrictions. First, only one type of distraction could occur on each individual trial, and secondly begin-subtask could not follow a trial containing a mid- or end-subtask. This pseudo-randomisation procedure was necessary so that the causal effect of the distraction positions on the different performance variables could be distinguished.

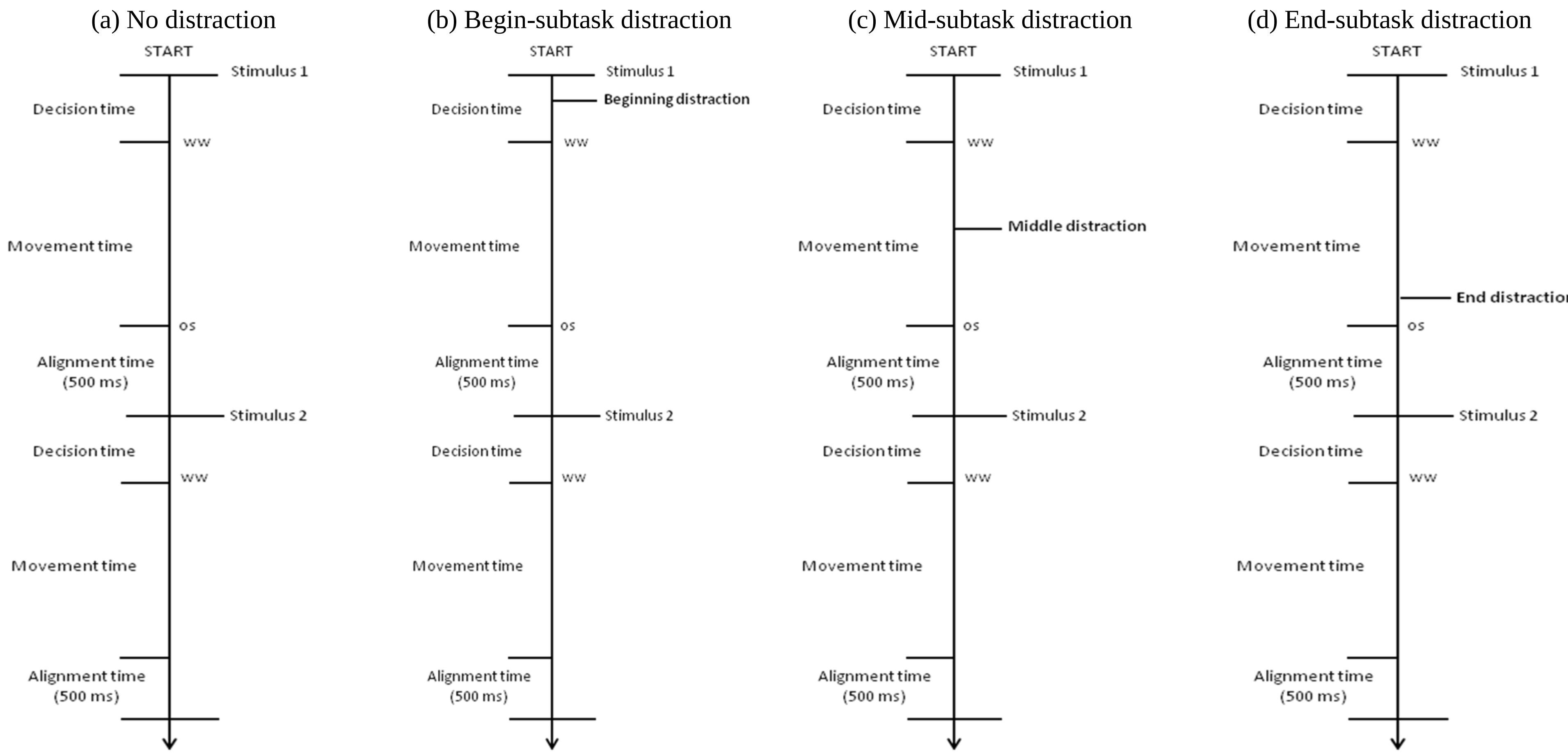


Figure 4. Sequence of events for the tracking movements under (a) no distraction; (b) a distraction at the beginning of a subtask; (c) a distraction in the middle of a subtask; and (d) a distraction toward the end of a subtask. The dependent variables were measured relative to the location of the distraction positions. Note that ww = wrong way error and os = overshoot error.

3.3.7 Procedures

The procedure for this experiment was approved by the local ethics committee. Participants were tested individually in a quiet room on campus. The procedure included a training phase (no distraction) and a testing phase (with distraction) with only the training phase differing between conditions. Participants were randomly assigned to low and high skill conditions according to a fixed rotation. All participants will be tested in the morning to avoid the post-lunch circadian downturn, limiting testing to one or two participants per day. Participation was voluntary and written consent was required.

At the start of the experiment, participants were asked to read a general information sheet about the experiment and to provide written consent for their participation. Participants were then given verbal instructions that described the task. The instructions were *"In this task, a pointer and five lights will appear on the screen. One of the lights will be lit. Move the pointer to that light and it will go out. Another one will light up, and you should move to that one. Note that the pointer moves in the opposite direction to the mouse. Keep moving the pointer to each light until the task is finished. Your task is to align the pointer with the target as it moves between different positions on the screen"***.** The experimenter then provided a practical demonstration of the task. Regarding performance instructions, participants were instructed to "*respond as quickly and as accurately as possible*". Participants were reminded of these instructions throughout the experiment at the beginning of each stimulus block.

Before exposure to the distracting stimuli, skill level was manipulated during an initial training phase by varying the amount of practice trials on the primary task. Distraction position was manipulated within trials during a testing phase where low and skill participants performed the primary task with distractions. Low skill participants completed 40 training trials, which were deemed sufficient for them to understand the task requirements without obtaining the same level of skill on the task. In contrast, high skill participants received 14 blocks of 120 training trials each (1680 training trials in total). The amount of training given to low and high skill participants was determined based on previous findings using similar tasks which found that most learning occurred over the first 800 trials and stabilised between 1200 and 1600 trials (Blais et al., 1993; Buck, 1974; Fazey & Fazey, 1989). Studies on skill acquisition more generally such as Logan et al. (1996) have also found that approximately 14-16 blocks of training trials is sufficient practice to produce the qualitative changes associated with skill automatisation in simple psychomotor tasks.

Figure 4 shows the sequence of events in the tracking task and how the dependent and independent variables were operationalised. Figure 4a shows two stimulus movements under no distraction. The trial starts when a stimulus light appears. Decision time was the time interval between the presentation of the target light and the initiation of a response. Wrong way errors (notated as ‘ww’ in the figure) was when a response was initiated in the wrong direction as defined by the location of the target. Movement time was the time interval between the initiation of a response and the successful alignment with the target light. Overshoot errors (notated as ‘os’ in the figure) was when the pointer moved passed the target. To be counted as a “wrong way error” or an “overshoot error”, the minimum number of mickeys moved beyond the boundaries of the starting position and target position, respectively, was set at 10 mickeys. This criterion reduced the chances of slight tremors and twitches in movement either from the participant's hand or electronically from the computer mouse to be counted as errors. Note participants were required to keep the pointer on target approximately 500 ms before the next stimulus light appeared and the same sequence of events were repeated.

Figure 4b, 4c, and 4d shows schematically how the position of begin-, mid- and end-subtask distraction were operationalised relative to each other. Begin-subtask was defined temporally as occurring approximately 165 ms following the presentation of the target light. Mid-subtask distraction occurred while movement was in progress. It was defined spatially in mickeys, that is, when the pointer was at the midpoint from the starting position to the target position. End-subtask was also defined spatially in mickeys, that is, when the pointer was within five mickeys of the target stimulus. As mentioned, the task program recorded the position of the blue pointer along the arc once every 55 ms and hence was able to systematically emit the tones according to pre-specified beginning, mid- and end-subtask distraction positions.

The effect of the different distraction positions on the dependent variables measured depended on where they occurred in relation to the sequence of events in the tracking movement. Specifically, the effect of a distraction at the beginning of a subtask on the dependent variables was evaluated on the same trial in which the distraction occurred. The effect of a distraction midway through a subtask on movement time and overshoot errors was also evaluated on the same trial in which the distraction occurred. Mid-subtask distraction could not be expected; however, to influence decision time and wrong way error on the same trial because the distraction occurred after a response to that trial was initiated. Hence the impact of mid-subtask distraction on decision time and wrong way error was evaluated in the next trial. The same logic applied to evaluating the effect of a distraction toward the end of a subtask on decision time, wrong way errors and movement time. The impact of end-subtask distraction on these variables was evaluated in the next trial. Only overshoot errors could be logically evaluated on the same trial in which the end-subtask distraction occurred. At the end of each block, participants received summarised feedback in the form of total time (in seconds) to complete that block. The task itself gave knowledge of directional accuracy because any errors had to be corrected before the next trial appeared. For the high skill condition, participants were instructed to take a short break (approximately one minute) at the end of each block before pressing the spacebar to proceed to the next block. At the start of each block, participants were reminded of the task instructions to try to move as quickly and as accurately as possible. Larger rest breaks (approximately five minutes) were imposed every four consecutive blocks to help avoid task fatigue.

Participants were instructed to press the space bar to begin the first block of training. At the beginning of the testing phase, the experimenter gave participants the instructions *"Once again, a pointer and five lights will appear on the screen. Move the pointer to follow the lights. This time, two tones will sound, first a low pitch and then a higher one. When the low* [high] *pitch sounds, you should press the space bar, when the high* [low] *pitch sounds, you should ignore it"*. The experimenter then provided a practical demonstration of the task. Participants heard two samples of the low and high pitch tone in order to familiarise themselves with the pitches and their labels.

Regarding performance instructions, participants were instructed to "*respond as quickly and as accurately as possible*" to the primary task and to respond as quickly as possible to the tone when it occurred by pressing the spacebar with their left hand. Responses to the tone were counterbalanced so that half of the participants were required to respond only to a high pitch tone (700 Hz) and half to respond only to a low pitch tone (600 Hz). Hence there were two types of tone trials: (1) respond and (2) ignore, depending on the low and high tone condition.

The testing phase did not begin until participants were clear on the task requirements. Low and high skill participants performed 120 trials of the primary task under conditions of auditory distraction. Unlike the training phase, participants did not receive feedback on their performance at the end of each block as they did during training. The aim was to avoid unnecessary influences on participants' performance which may confound or minimise the effects of the auditory distraction such as motivation and effort to do better as the result of the performance feedback. Knowledge of directional accuracy was, however, still available at the trial level because it was the nature of the task that any errors had to be corrected before the next trial appeared (i.e., the stimulus display did not change until the correct response was registered). Upon completion of the training and testing phase participants were debriefed and thanked for their participation.

3.3.8 Data analysis

Data was analysed using analysis of variance (ANOVA). Conservative Huynh-Feldt F-tests were considered but nominal degrees of freedom are reported. Consistent with previous research, trials with decision time shorter than 100 ms (1.6%) and longer than 2000 ms (<1%) were excluded from the analysis. Moreover, in analyses concerning latencies, a log-transformation was applied to improve the conformity of the data to the standard assumption of ANOVA. The significance criterion was set to $p < .05$, two-tailed for all analyses. For significant effects, partial eta-squared ($\eta_p^{2)}$ is reported as a measure of relative effect size (Cohen, 1988). All analyses were performed with the statistical software SPSS version 15.0. For all graphs, plus and minus one standard error bars are shown. Means displayed are the raw scores (not antilog converted ones).

3.4 Results

3.4.1 Correlations

To examine whether the four dependent variables measured in this study were providing unique information, a bivariate correlation analysis was conducted across the entire sample. The means and standard deviations and correlations for the variables measured in the study are shown in Table 1.

The only high correlation was between the two latency variables, decision time and movement time, ($r = .74$, $p < .01$) suggesting that the longer a person took to initiate a movement the longer they also took to execute the movement. There was evidence of a slight speed-accuracy trade-off effect as faster decision time was associated with more wrong way errors ($r = -.12$, $p < .01$) and faster movement time was associated with more

Table 1

Means, standard deviations, and correlation coefficients of dependent variables.

Dependent variables	*M*	*SD*	1.	2.	3.	4.
1. Decision time (ms)	312.21	83.34	-			
2. Movement time (ms)	759.59	159.42	$.74^{**}$	-		
3. Wrong way error rate (%)	13.58	5.53	$-.12^{**}$	.08	-	
4. Overshoot error rate (%)	23.47	7.82	.07	$-.22^{**}$	$.20^{**}$	-

$^{**} = p < .01$ (2-tailed).

overshoot errors ($r = -.22$, $p < .01$). There was also a significant relationship between the wrong ways and overshoots ($r = .20$, $p < .01$) indicating that the occurrence of these two error types were not completely distinct. In context, however, these correlations are very small and most likely significant because of the large amount of data collected (140 data points for each individual in the low skill condition and 1800 data points for each individual in the high skill condition). There was no significant relation between decision time and overshoot error ($r = .07$, n.s.) and there was no significant relation between movement time and wrong way error ($r = .08$, n.s.) suggesting differential associations between the type of latency and type of error.

3.4.2 Skill acquisition manipulation check

A fundamental part of the study's skill manipulation was to train participants in the high skill condition to an asymptotic level of performance on both speed and accuracy. The 14 training blocks of the high skill condition was analysed to provide an independent assessment of skill attainment in this condition. A within-subjects ANOVA with repeated measures on block (1 to 14, each with 120 trials) revealed a significant effect of block for decision time, $F(13, 377) = 110.97$, $p < .001$, $\eta_p^2 = .79$; movement time, $F(13, 377) = 74.21$, $p < .001$, $\eta_p^2 = .73$; and overshoot errors, $F(13, 377) = 6.73$, $p < .001$, $\eta_p^2 = .19$, but not for wrong way errors, $F(13, 377) = 1.81$, $p = .09$.

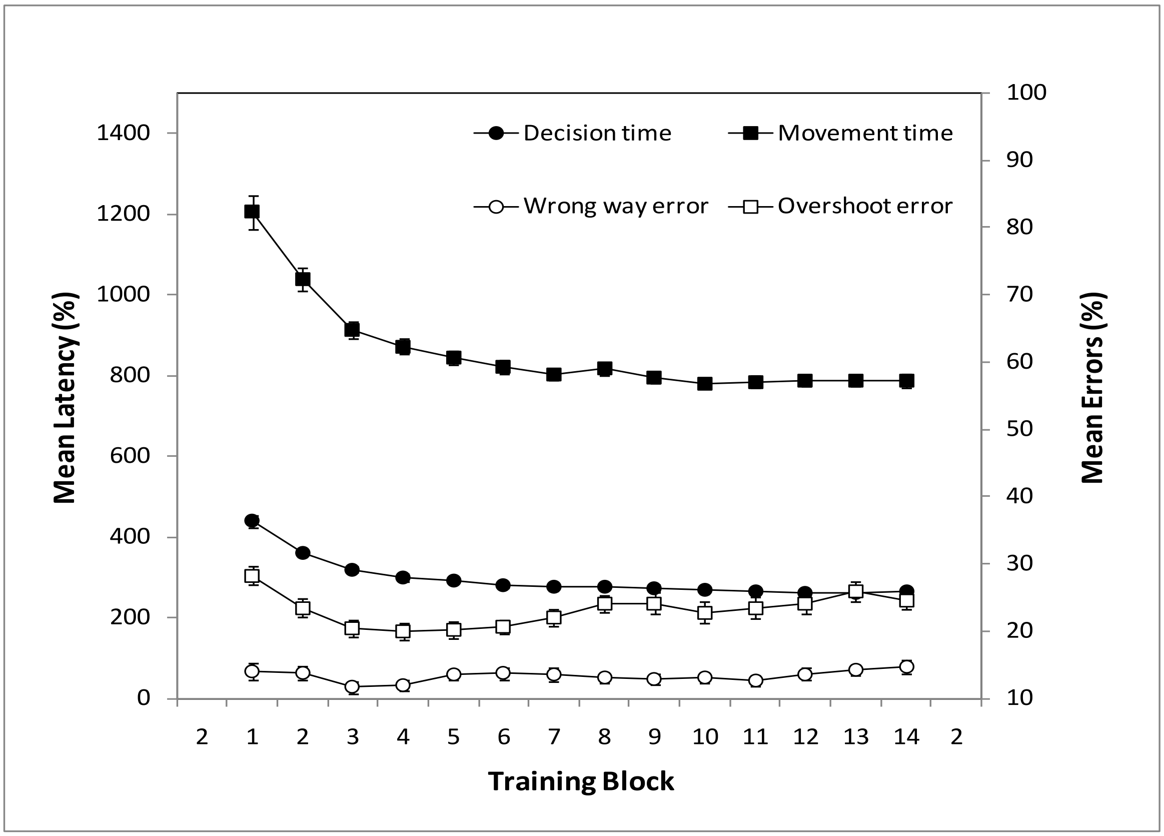


Figure 5. Training mean latency data (decision time and movement time) and mean percentage of error data (wrong way error and overshoot error) as a function of 14 blocks of practice (each with 120 trials).

As seen in Figure 5, there was a steady reduction in latency during the training blocks. Initial mean decision time was approximately 440 ms and was reduced to approximately 265 ms with 14 blocks of practice. Similarly, initial mean movement time was approximately 1200 ms at the start of practice and was reduced to approximately 800 ms by the end of practice. Most of the improvement occurred over the first 600 to 800 trials (Block 1 to 6) and stabilised between 1200 to 1600 trials (Block 7 to 14). Overshoot error rate reduced from approximately 28% (Block 1) to 20% (Block 6) and maintained at approximately 24% thereafter. In contrast, wrong way error rate remained essentially constant across the training blocks at approximately 13%.

To further understand the factors underlying wrong way errors, these errors were broken down into four types according to the directional probability of the target in terms of left versus right movement: 100%, 75%, 50% and 25%. A 4 × 14 (Probability × Block) ANOVA on proportion of wrong way errors with repeated measures on both factors showed a significant main effect of probability, $F(3, 87) = 229.59$, $p < .001$, $\eta_p^2 = .89$; block, $F(13, 377) = 4.77$, $p < .001$, $\eta_p^2 = .14$; and a significant interaction between probability and block, $F(39, 1131) = 8.22$, $p < .001$, $\eta_p^2 = .22$.

As seen in Figure 6, the majority of wrong way errors occurred on trials with 25% and 50% directional probability. In separate analyses that were conducted for each of the four trial types, wrong way errors decreased significantly with practice on trials with 100% directional probability (i.e., when the pointer was at the starting position 1 or 5) from approximately 4% to essentially zero errors by the end of training, $F(13, 377) = 4.70$, $p < .001$, $\eta_p^2 = .14$. Similarly, on trials with high directional probability (i.e., 75% - when the pointer was at the starting position 2 or 4 and the target appeared in the more probable direction) errors decreased significantly with practice from approximately 11% at the start of training to 6% by the end of training, $F(13, 377) = 4.50$, $p < .001$, $\eta_p^2 = .13$.

In contrast, on trials with equal directional probability (i.e., when the pointer was at the starting position 3, hence there was a 50-50 chance probability that the next target would appear left or right), wrong way errors remained relatively unchanged with practice at a constant rate of approximately 28%, $F(13, 377) = 1.08$, $p = .38$. The majority of errors occurred on trials with low directional probability (i.e., 25% - when the pointer was at the starting position 2 or 4 and the target appeared at position 1 or 5, respectively) and rather than decrease with practice as might be expected, errors on these trials nearly doubled, $F(13, 377) = 10.38$, $p < .001$, $\eta_p^2 = .26$ from approximately 35% at the start of practice to 60% by the end of practice. The finding that wrong way errors on trials with low directional probability *increased* significantly with practice which contrasts with the *decreased* in decision time with practice points to a speed-accuracy trade-off (SATO) (Pachella, 1974).

To investigate this issue, an additional analysis using a 4 × 14 (Probability × Block) ANOVA on mean decision time with repeated measures on both factors was performed. The results revealed a significant main effect of trial type, $F(1, 29) = 48.51$, $p < .001$, $\eta_p^2 = .63$; and probability,$F(3, 87) = 131.97$, $p < .001$, $\eta_p^2 = .82$; and block, $F(13, 377) = 105.46$, $p < .001$, $\eta_p^2 = .78$. The interaction between block and probability was not significant, $F(39, 1131) = 1.27$, $p = .23$. As shown in Figure 7, decision time improved significantly with practice for all trial types. There was an overall gradient effect of directional probability in that decision time increased as the uncertainty of directional probability increased except for mean decision time on trials with 25% directional probability which was found to be significantly shorter than mean decision time on trials with 50% directional probability, $F(1, 29) = 20.61$, $p < .001$, $\eta_p^2 = .42$.

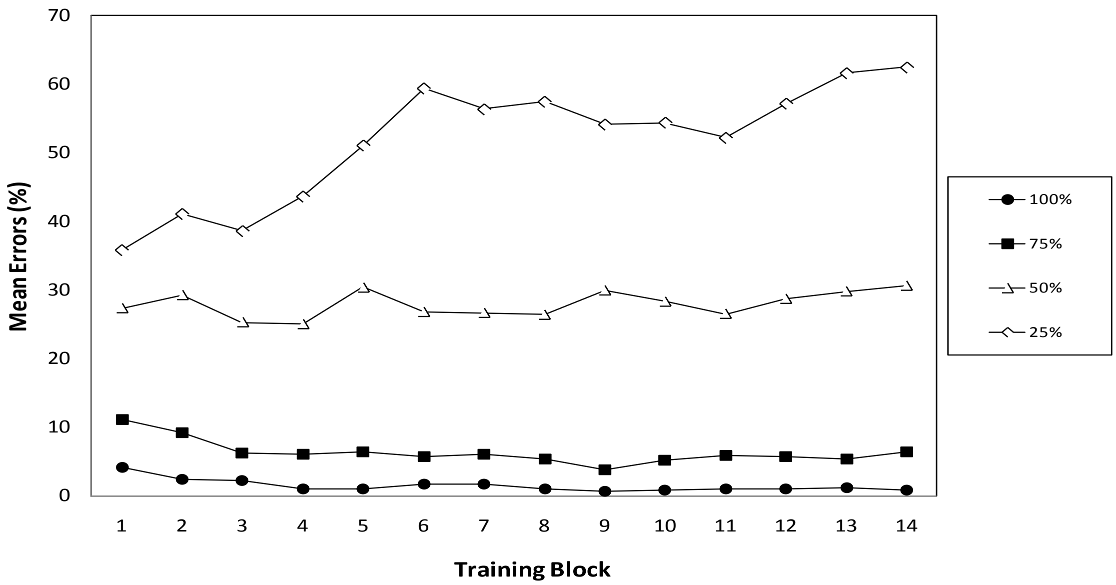


Figure 6. Training mean percentage of wrong way error data as a function of 14 blocks of practice (each with 120 trials) and directional probability.

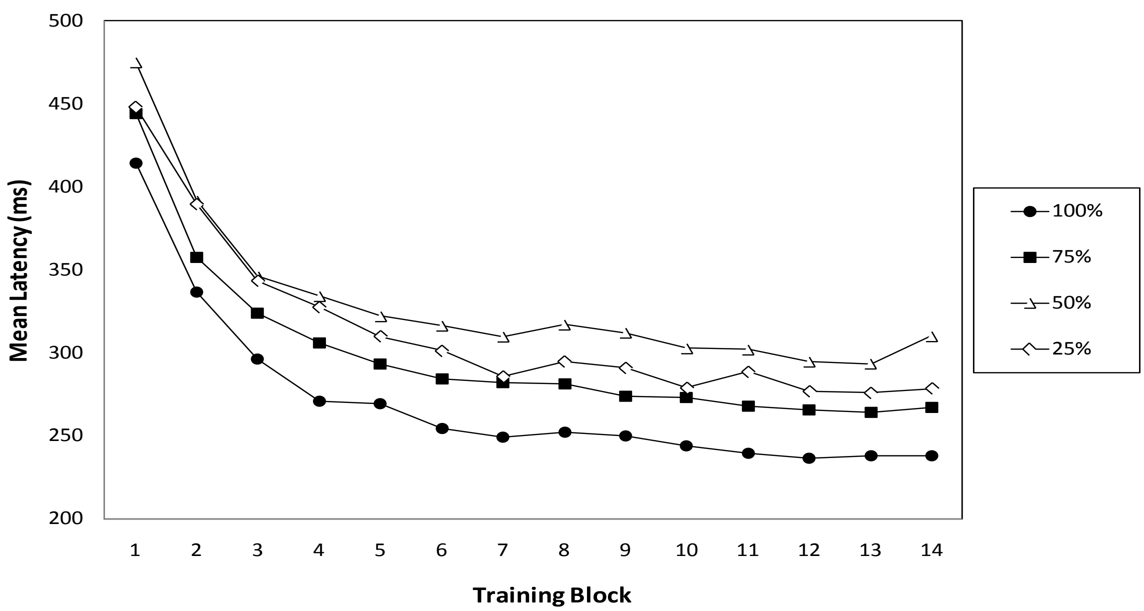


Figure 7. Training mean decision time data as a function of 14 blocks of practice (each with 120 trials) and directional probability.

3.4.3 Performance on the primary task under distraction

The data was first analysed to verify whether there were any differences in performance on the primary task depending on respond versus ignore tone trials. Results revealed no significant difference for the dependent variables measured, $t(59) < 1$ (p-value ranging from .72 to .14). Hence these two tone trials were combined and the data was analysed using a 2 x (4) mixed-model ANOVA with between-subjects factor variables, skill level (low skill versus high skill); and the within-subjects variable, distraction positions (begin, versus mid, versus end). ANOVA results for all the dependent variables measured are summarised in Table 2.

Wrong way error rate. Due to the finding that practice did not reduce wrong way on trials with 50% and 25% directional probability and evidence of an increasing SATO with practice on the latter trials it was necessary to consider the wrong way error data separately according to directional probability types. The effect of distraction on low (i.e., 25%) and equal (i.e., 50%) directional probability trials was not analysed because of insufficient sampling of trials to permit statistic analysis. Low and equal probability trials made up 10% and 20% of all trials in the distraction data, respectively. It was deemed inappropriate to combine wrong way error data for low and equal probability trials because the effects of practice on these trials were distinct. Hence only wrong way errors on high probability trials (i.e., 100% and 75%) were combined and analysed because these trials constituted the majority of trials and showed the expected pattern of learning improvement as a function of practice. For comparison purposes, Appendix A contains descriptive statistics for low, equal and high probability trials as a function of skill level and distraction positions.

As shown in Table 2, ANOVA results for wrong way errors on high probability trials revealed a significant main effect of skill and distraction positions. The interaction Distraction x Skill was not significant. Overall, as can be seen in Figure 8, high skill participants (*M* = 5.14, *SD* = 5.61) made significantly fewer wrong way errors than low skill participants (*M* = 8.62, *SD* = 8.65). Regarding the effect of distraction positions, contrast results revealed that wrong way errors were more frequent on distracted trials (*M* = 7.36, *SD* = 8.16) than on non-distracted trials (*M* = 5.44, *SD* = 4.66), $F(1, 58) = 10.11$, $p < .001$, $\eta_p^2 = 15$. Within distracted trials, wrong way errors were more frequent following end-subtask distraction (*M* = 9.11, *SD* = 9.82) compared to distraction at begin-subtask (*M* = 6.31, *SD* = 7.21), $F(1, 58) = 4.60$, $p < .05$, $\eta_p^2 = .07$; and mid-subtasks (*M* = 6.67, *SD* = 7.01), $F(1, 58) = 4.34$, $p < .05$, $\eta_p^2 = .07$. There was no significant difference between begin- and mid-subtask distractions, $F(1, 58) < 1$, $p = .74$.

Decision time. ANOVA results in Table 2 revealed a significant main effect of skill and distraction positions. There was no significant interaction. As evident in Figure 9, decision time was significantly faster in the high skill (*M* = 305.51, *SD* = 67.78) than in the low skill condition (*M* = 429.25, *SD* = 118.71). In terms of distraction effects, contrast results revealed that decision time was significantly faster on non-distracted trials (*M* = 342.83, *SD* = 86.36) than distracted trials (*M* = 375.56, *SD* = 121.77), $F(1, 58) = 22.03$, $p < .001$, $\eta_p^2 = .16$. Within distracted trials, decision time was significantly slower following distractions that occurred at end-subtasks (*M* = 393.90, *SD* = 113.00) than mid-subtasks

Table 2

ANOVA analysis results for the dependent variables measured according to skill level and distraction positions.

Source	**Wrong way error** [a]	**Decision time**	**Overshoot error**	**Movement time**
Main Effect				
Skill	$F_{(1, 58)} = 6.74$, $p <.05$, $\eta_p^2 = .10$	$F_{(1, 58)} = 41.12$, $p <.001$, $\eta_p^2 = .42$	n.s. ($p = .83$)	$F_{(1, 58)} = 74.41$, $p <.001$, $\eta_p^2 = .56$
Distraction positions	$F_{(3, 174)} = 4.36$, $p <.01$, $\eta_p^2 = .07$	$F_{(3, 174)} = 10.97$, $p <.001$, $\eta_p^2 = .16$	$F_{(3, 174)} = 8.72$, $p < .001$, $\eta_p^2 = .13$	$F_{(3, 174)} = 15.07$, $p < .001$, $\eta_p^2 = .21$
Two-way interaction				
Distraction positions × Skill	n.s. ($p = .99$)	n.s. ($p = .17$)	n.s. ($p = .45$)	n.s. ($p = .40$)

Note. [a] = trials with high directional probability (i.e., 100% and 75%).

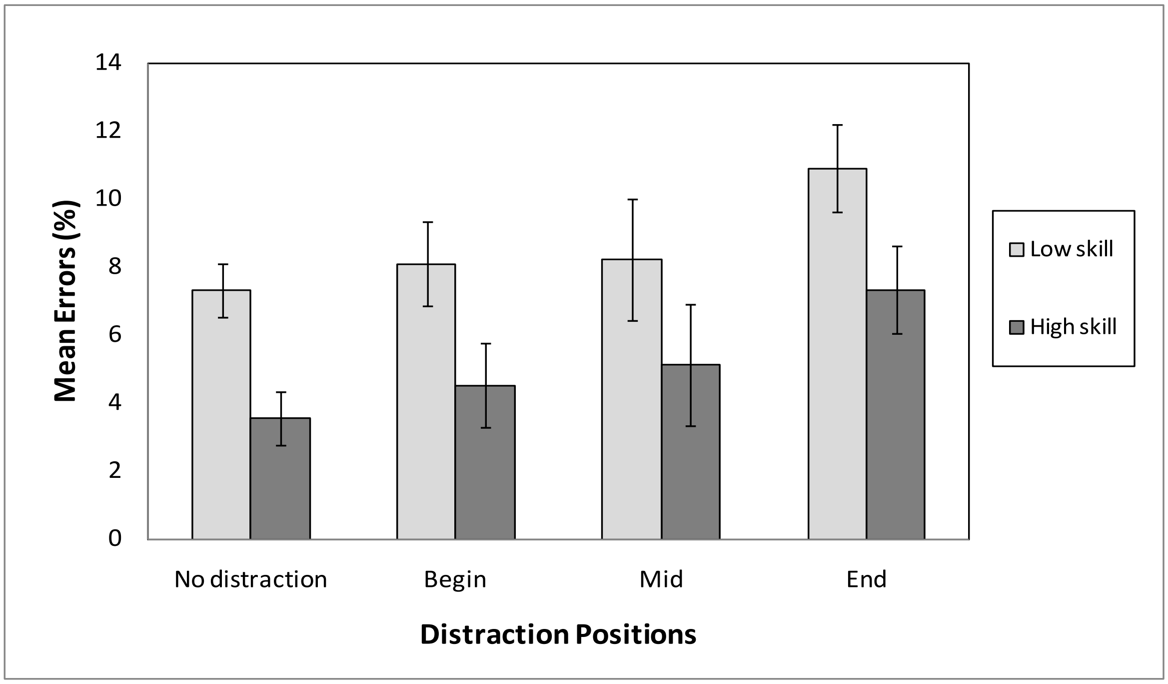


Figure 8. Mean percentage of wrong way errors on trials with high directional probability as a function of skill level and distraction positions.

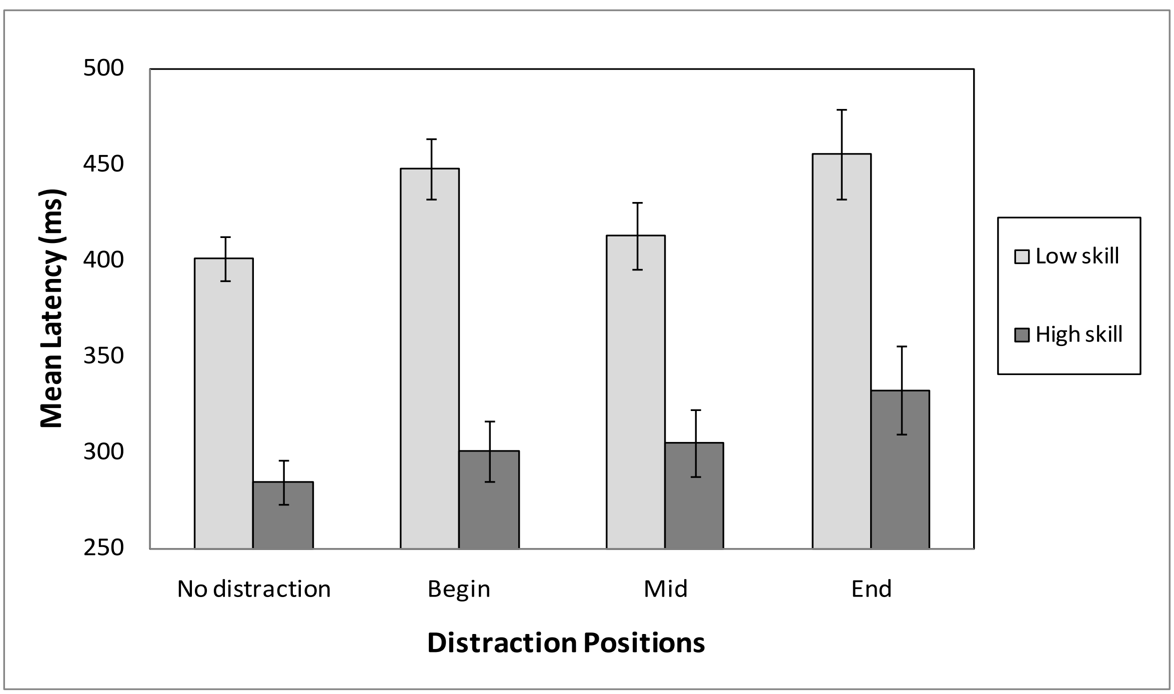


Figure 9. Mean decision time as a function of skill level and distraction positions.

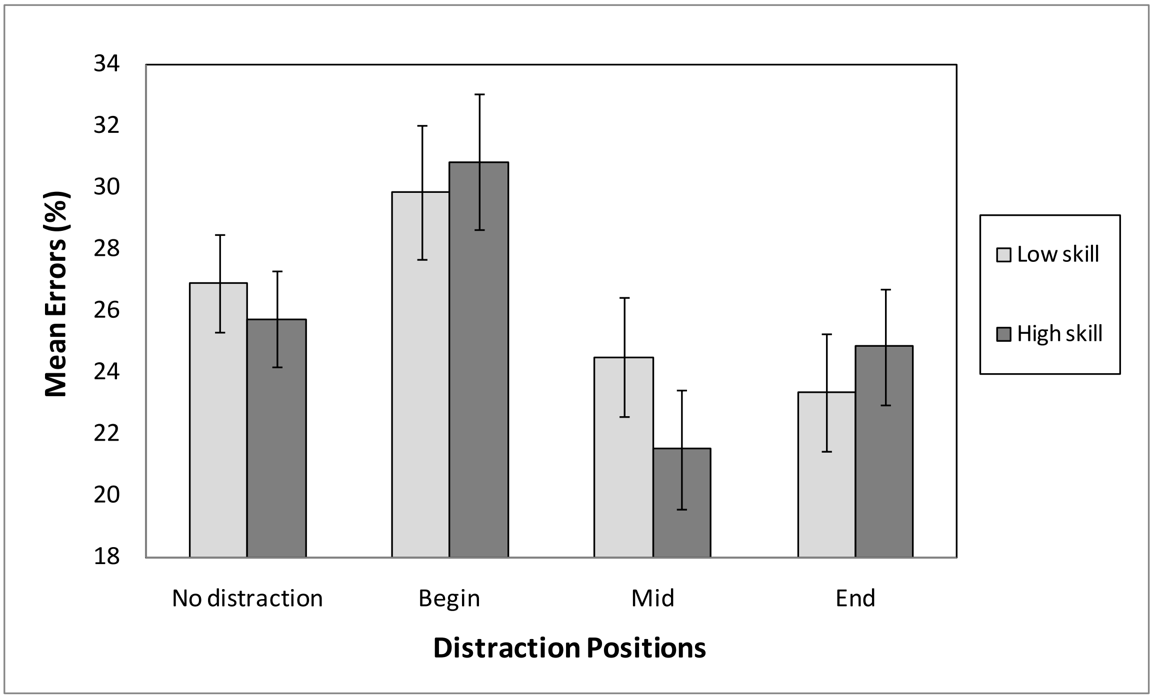


Figure 10. Mean percentage of overshoot errors as a function of skill level and distraction positions.

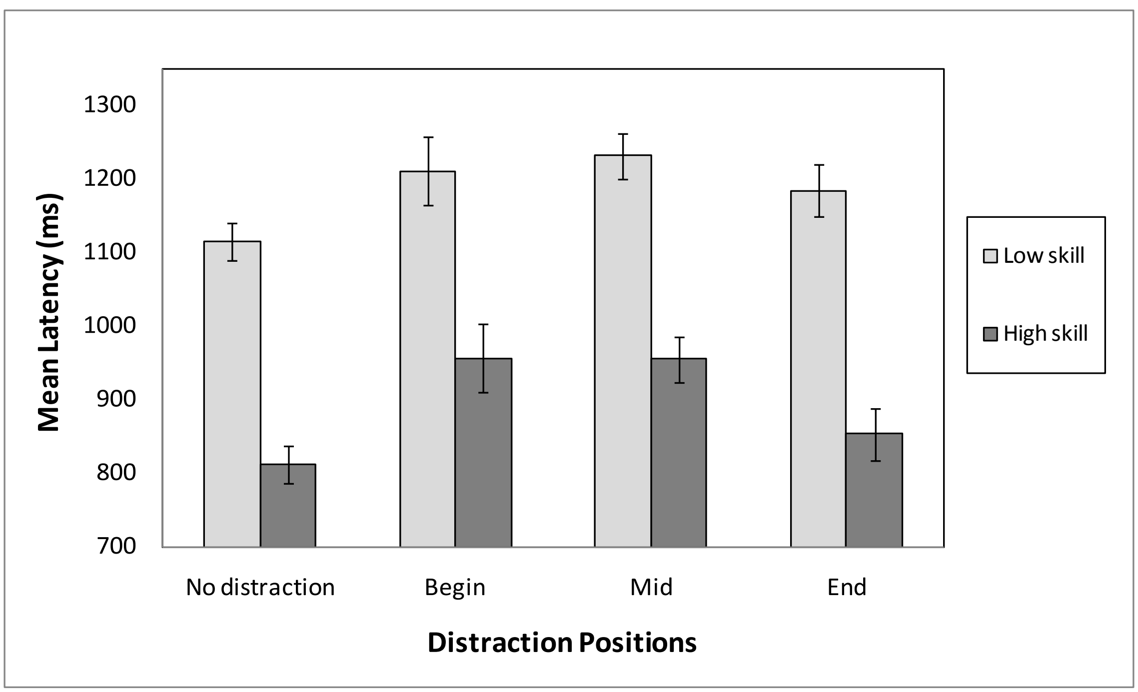


Figure 11. Mean movement time as a function of skill level and distraction positions.

(*M* = 358.68, *SD* = 100.50), $F(1, 58) = 13.26$, $p < .001$, $\eta_p^2 = .17$; and begin-subtasks (*M* = 374.10, *SD* = 146.57), $F(1, 58) = 10.38$, $p < .01$, $\eta_p^2 = .14$. There was no significant difference between begin- and mid-subtask distractions, $F(1, 58) < 1$, $p = .57$.

Overshoot error rate. As indicated in Table 2, the only significant effect was the main effect of distraction positions. As can be seen in Figure 10, begin-subtask distractions (*M* = 30.33, *SD* = 11.89) resulted in significantly more overshoot errors than any other conditions: no distraction (*M* = 26.31, *SD* = 8.49); mid-subtask distractions (*M* = 23.00, *SD* = 10.66), $F(1, 58) = 18.47$, $p < .001$, $\eta_p^2 = .24$; and end-subtask distractions (*M* = 24.08, *SD* = 10.21), $F(1, 58) = 14.42$, $p < .001$, $\eta_p^2 = .20$. Interestingly, mid-subtask distraction resulted in fewer overshoots errors compared to no distraction, $F(1, 58) = 4.82$, $p < .05$, $\eta_p^2 = .08$. There was no difference between distractions at end-subtask and no distraction, $F(1, 58) = 2.74$, $p = .10$.

Movement time. ANOVA results as seen in Table 2 revealed a significant main effect of skill and distraction positions. The interaction Distraction x Skill was not significant. As evident in Figure 11, movement time was significantly faster in the high skill (*M* = 894.00, *SD* = 157.36) than in the low skill condition (*M* = 1184.94, *SD* = 231.89). In terms of the main effect of distraction positions, movement time was significantly slower on distracted trials (*M* = 1065.01, *SD* = 252.90) than non-distracted trials (*M* = 962.84, *SD* = 206.12), $F(1, 58) = 64.25$, $p < .001$, $\eta_p^2 = .53$. Within distracted trials, begin-subtask (*M* = 1083.28, *SD* = 210.68) resulted in significantly slower movement time than end-subtask distractions (*M* = 1018.65, *SD* = 301.40), $F(1, 58) = 10.54$, $p < .01$, $\eta_p^2 = .15$. Similarly, mid-subtask distractions (*M* = 1093.12, *SD* = 235.55) resulted in significantly slower movement time than end-subtask distractions, $F(1, 58) = 8.73$, $p < .01$, $\eta_p^2 = .13$. There was no significant difference between begin- and mid-subtask distractions, $F(1, 58) < 1$, $p = .54$.

3.4.4 Performance on the distraction task

The tone accuracy data was first analysed to verify whether there was a difference between tone trials which required a key press response and tone trials which did not. Note that errors on the tone task were evaluated in terms of missed hits (not responding to a tone which required a response) and false hits (responding to a tone which did not require a response). There was no significant difference between respond and ignore trials (which occurred with equal frequency), $t(59) = 1.45$, $p = .15$ hence tone trials were combined and the data was analysed using the same factorial mixed-model ANOVA used to analyse performance on the primary task: a 2 x (4) mixed-model ANOVA with between-subjects factor variables, skill level (low skill versus high skill); and the within-subjects variable, distraction positions (begin, mid, end). Note that the 'no distraction' condition was not applicable to this analysis (i.e., tone task only relevant to trials with a distraction).

For tone accuracy (see Figure 12) although high skill participants ($M = 3.70$, $SD = 7.43$) made fewer errors than low skill participants on the tone task ($M = 6.60$, $SD = 10.86$), this main effect of skill was not significant, $F(1, 58) = 2.78$, $p = .10$. There was, however, a significant main effect of distraction positions, $F(2, 58) = 5.05$, $p < .01$, $\eta_p^2 = .08$. Errors on the tone task were significantly fewer when the tone occurred at mid-subtask ($M = 3.80$, $SD = 8.34$) than at end-subtask ($M = 6.4$, $SD = 10.87$), $F(1, 58) = 12.09$, $p < .001$, $\eta_p^2 = .17$. The Distraction x Skill interaction was not significant, $F(2, 116) <1$, $p = .44$.

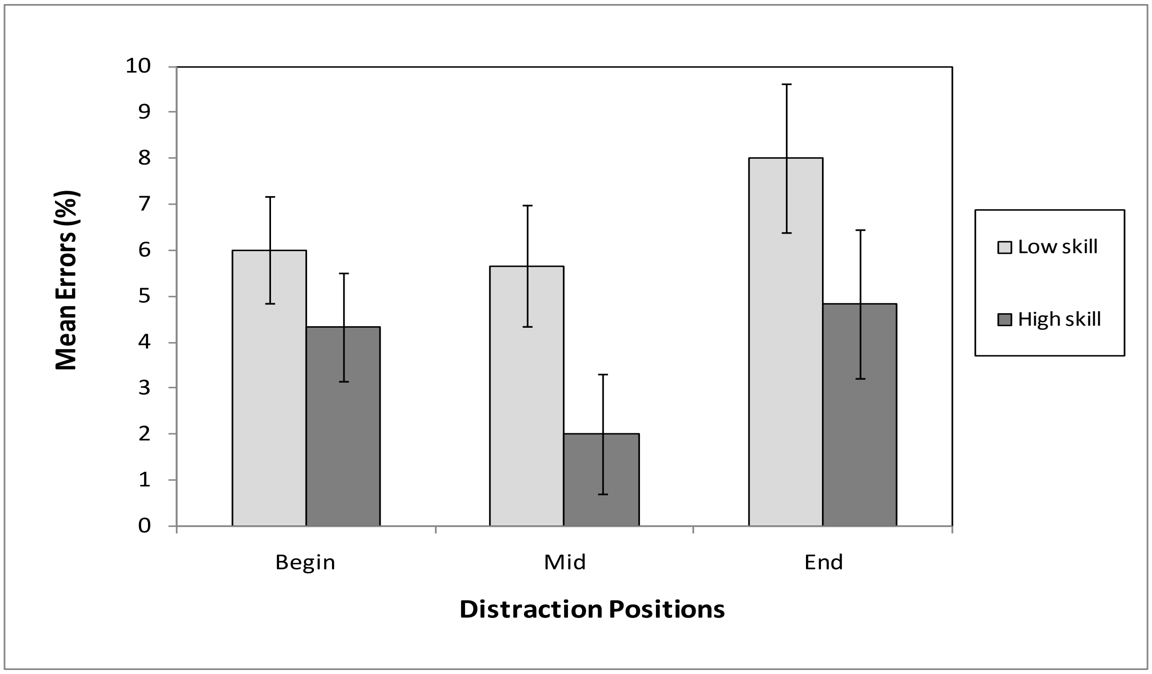


Figure 12. Mean percentage of errors on the tone task as a function of skill level and distraction positions.

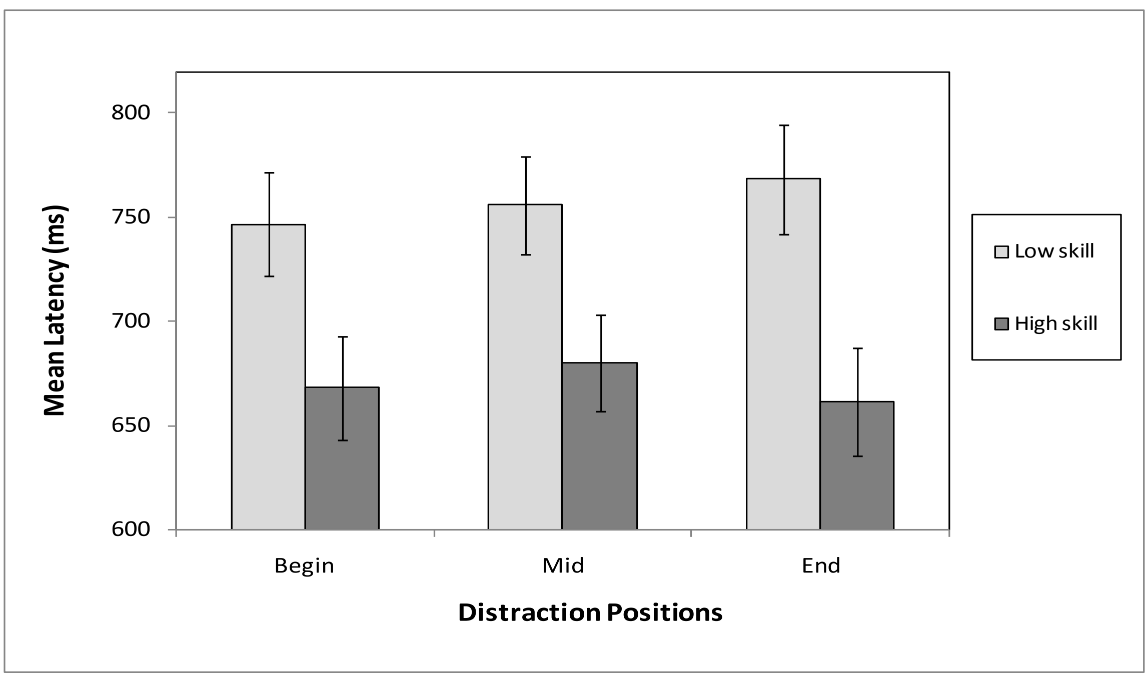


Figure 13. Mean latency on the tone task as a function of skill level and distraction positions.

For tone latency (see Figure 13), ANOVA results revealed a significant main effect of skill, $F(1, 58) = 7.36$, $p < .01$, $\eta_p^2 = .11$. Overall high skill participants ($M = 669.94$, $SD = 104.85$) were significantly faster to respond to the tone task than low skill ($M = 756.94$, $SD = 158.66$) participants. The main effect of distraction and the two-way interaction were not significant, $F(2, 58) < 1$, $p = .67$, and $F(2, 116) = 1.00$, $p = .37$, respectively.

3.5 Discussion

The present experiment investigated the nature of attention allocation at different points during task execution for low versus high skill performers. To summarise, there were four major findings relevant to this aim. The first finding was that high skill participants performed better than low skill participants on both the primary and secondary task. The second finding was that although the performance differential between low and high skill was maintained across distracted and non-distracted trials all participants' performance declined when they performed the tracking task under distraction. The third finding was that there were differential effects on performance depending on where distractions occurred during task execution. Finally, none of these effects were dependent on skill level. That is, the patterns of distraction timing on performance were the same for low and high skill individuals. These findings have important implications for our understanding of the role of attention during skilled performance.

In relation to the first finding, as expected, there was a consistent difference between the low and high skill group on accuracy and latency variables. On the primary task, high skill participants were faster to initiate (i.e., decision time) and execute a response (i.e., movement time) than low skill participants. High skill participants also made fewer directional errors (i.e., wrong way errors) than low skill participants on the trials analysed. Overshoot error rate was the only performance variable on the primary task that did not differ significantly between low and high skill participants but this is likely due to a trade-off effect with movement time. High skill participants were also significantly faster to responding to the secondary task (and made fewer errors, although not significantly). These results support the theoretical view that skill development on the primary task frees up more processing resources that can be used for the secondary task (Chen, 1985; Pashler, 1998). The results are consistent with previous studies demonstrating decreased attentional demands as a result of skill development (Beilock et al., 2002; Beilock et al., 2002; Leavitt, 1979; Parker, 1981; Smith & Chamberlin, 1992).

However, contrary to the prediction of automaticity theory (LaBerge & Samuels, 1974; Posner & Synder, 1975; Shiffrin & Schneider, 1977) well-practised performance was not immune to the negative effects of distraction. All participants' performance declined when they performed the tracking task under conditions of distraction. These results are consistent with the alternative theoretical view that although skill development frees up more resources it does not completely eliminate attentional demands (Chen, 1985; Pashler, 1998; Logan, 1988). A level of attention is still involved at a skilled level of performance and hence skilled performance is still vulnerable to the negative effects of distraction. This result contributes to a growing body of evidence of the particular susceptibility of skill performance under disruptive conditions (Allen, McGeorge, Pearson & Milne, 2004; Beilock, Kulp, Holt & Carr, 2004; Beede & Kass, 2006; Fick & Byrne, 2003; Kass et al., 2007). For example, Kass et al. found that in a driving simulation task both experienced and novice drivers suffered losses to driving performance (e.g., the number of pedestrians struck, speed limits obeyed or road departures) when using a mobile phone than when not using a phone.

A fundamental contribution of this study relates to the effects of distraction on performance at specific subtask points. The study investigated the processing limitations of two aspects of performance in one task paradigm: response selection and response programming which is lacking in previous research since most studies use tasks that do not permit the examination of both (Ketelaars et al., 1999; Netick & Klapp, 1994). Although there is evidence that both response selection and response programming are attention demanding processes (Buckolz & Hall, 1982; DeJong, 1993; Keele, 1973; Logan & Burkell, 1986) less is known about precisely where during task execution this occurs (i.e., the 'critical points') (Ketelaars et al., 1999) and even less is known about whether skill development modulates attentional requirements of these processes (Klein & Posner, 1974; Logan, 1982; Pashler et al., 2001).

This study found that the attentional critical point was different for response selection and response programming. Specifically, in relation to the effects of distraction on response programming both begin- and mid-subtask distraction increased movement time but interestingly had opposite effects on the frequency of overshoot errors. Mid-subtask distraction reduced overshoots errors suggesting a trade-off effect at this point with movement time. In contrast, begin-subtask distraction increased both movement time and overshoot errors. This result is consistent with previous findings in the motor control literature that distraction at the start of movement is most disruptive because this is where a response is programmed and triggered into action (Adams, 1971; Castiello & Umilta, 1988; Keele, 1973; Ketelaars et al., 1999; Netick & Klapp, 1994; Schmidt, 1975). For example, Castiello and Umilta examined how attentional demand alters during the performance of a return of serve in volleyball and tennis and found that distraction was most disruptive when it occurred at the initiation point of a return serve stroke. The authors attributed the effect of begin-subtask distraction to disruptions to attentional processes involved in the organisation of action programs at the start of a response.

Motor control theories differ in terms of the specific mechanisms proposed to account for the programming of different types of skilled movement. According to Adams's (1971) theory of slow-positioning movements, the memory trace which Adams termed as "a modest motor program" (p. 126) starts a movement by selecting the direction of movement and initiating it. The perceptual trace then takes over the control of the movement by determining the extent of movement to stop it at the final target location. Schmidt's (1975) theory distinguished between rapid-ballistic and slow-positioning movements and suggested that for rapid-ballistic movements the recall schema specifies the motor program and parameters and is structured in advance to carry out the movement with little peripheral feedback being utilised. In slow positioning movements, recall memory does not have such an important role. Rather, another schema called the recognition schema is used to evaluate the movement-produced feedback in slow positioning movements.

One of the difficulties with siding with either theory is that like many applied skills it is difficult to categorise the pointer movements involved in the current tracking task as either slow-positioning or rapid-ballistic. The pointer movement has characteristics typical of both categories. Depending upon the individual it took approximately one second from the beginning of the pointer movement until successful alignment which is well in excess of the 200 ms timeframe typically characterising rapid-ballistic movements. The duration of the pointer movement also included the time for feedback to be used to make adjustments to the movement which characterises slow-positioning movements. Moreover, the finding that a distraction midway through a movement slowed down its execution indicates that the tracking movement was to some degree controllable and thus was not completely ballistic. It also suggests that participants did not program the entire movement before its initiation and that some programming continued during movement execution. Several studies have found that some movements are programmed online during the execution of movement (Rosenbaum, Hindorff & Munroe, 1986; Smiley-Oyen & Worringham, 1996).

These factors seem to be more in favour of a slow-positioning interpretation of the pointer movements in the current task. However, the pointer movement also occurred at a speed not typical of slow-positioning movements (Adams, 1971). In addition, the finding that a distraction at the start of a movement was most disruptive to overshoot errors is inconsistent with slow-positioning movements where adjustments are made throughout the movement execution based on response-produced feedback. Several researchers have raised serious questions regarding the nature of timing invariance in motor skills that supposedly categorise particular classes of movements (Gentner, 1987; Shea & Wulf, 2005). This issue is one of the main criticisms of traditional motor skill theories such as Adams and Schmidt (1975).

The finding that skill level did not moderate programming effects is contrary to the prediction of motor skill theories (Adams, 1971; Keele, 1968; Schmidt, 1975). Motor skill theories typically assume that practice strengthens underlying mechanisms responsible for response programming as a function of stimulus-response contiguity, whether it is Adam's perceptual trace, Schmidt's schemas and Keele's motor programs. Assuming that low skill performers need to pay more constant attention during the execution of movement because they have not yet developed strong planning programs then distraction positions would have more equal negative effects as opposed to high skill performers where resources would be more centralised at the starting point. To the contrary, the results suggest that skill development does not change where attention is needed for the control and accurate execution of a movement which is mainly at the start of the movement.

In relation to the effects of distraction on response selection, this study found that a distraction toward the end of a response (just before the successful alignment with the target) was most disruptive to response selection in the next trial. Distraction at end-subtask points increased subsequent decision time and decision errors (i.e., wrong ways). Several studies have provided evidence of interference associated with response-selection processing (Buckolz & Hall, 1982; DeJong, 1993; Keele, 1973; Logan & Burkell, 1986) suggesting that like response programming, response selection is attention demanding. However, these studies have typically used discrete tasks (e.g., choice-RT type tasks involving a simple key press response) and therefore have not been concerned with whether the timing of a distraction during the movement interval has differential effects on response selection. One exception, however, is a study by Botvinick and Bylsma's (2005) study which found results in support of the particular susceptibility of mid-task distraction on the accuracy of action selection in a routine coffee making task.

In this study, the only impact of mid-subtask distraction on the primary task was as discussed to slow down movement execution and to reduce overshoot errors thus reflecting a trade-off effect at this point. Interestingly, performance on the secondary task was more accurate at mid-subtask suggesting that it was easier to handle a distraction when it occurred at mid-subtask compared to other subtask positions. These findings conflict with Botvinick and Plaut's (2003, 2004) theory which predicts that distraction should be most disruptive when it occurs midway through a subtask because distraction degrades information about the task context which is most susceptible to loss earlier in a subtask than near the completion of a subtask.

The results of this study are more consistent with Reason's (1990) prediction that distraction should be most disruptive when it occurs near the completion of a subtask because distraction at this point captures attention and leads to the omission of critical checking or monitoring operations that ordinarily would ensure the faultless execution of performance. In the context of the present task, this conscious check should have taken the form of a quick self-reminder that movement should be anti-stereotype when initiated. Moreover, the requirement to correct errors in this task may reflect the direct involvement of executive monitoring functions. The current results, however, do not completely support Reason's skill-based error theory because the disruptive effect of end-subtask distraction in the current study was not unique to the high skill performers. Low skill performers were also disrupted by end-subtask distraction suggesting that the development of skill does not change where attention needed for the efficient (i.e., fast and accurate) selection of actions.

The fact that the pattern of distraction timing was the same for low and high skill participants for all the performance variables measured is an important finding because it suggests that in general the development of skill does not change the distribution of attention during task execution. These results make a significant contribution to the literature because most skill acquisition theories from both cognitive and motor skill domains assume changes to the way attention is allocated as skill develops (Bernstein, 1967; Logan, 1992; Reason, 1990). For example, Logan suggested that when skill develops as a function of practice, attention is shifted (rather than reduced) to higher-level aspects of the skill that are concerned with integrating lower aspects of skill. Similarly, Schneider and Fisk (1983) suggested that once a skill is 'automatised' attention is redirected to strategic functions such as increasing the flexibility of the performer. Haider and Frensch (1999) proposed that skill acquisition may be accounted for in part by qualitative changes in attentional strategies with practice. Specifically, with practice, people learn to focus their attention on task-relevant subsets and increasingly reduce the processing of the task irrelevant. The current results suggest no such skill differential in the distribution of attention and/or attentional strategies. Where high skill performers needed to pay attention during task execution did not differ from those who were less skilled. The main effect of skill development in this study was to reduce overall attentional demands (as indexed by overall better performance on both the primary and secondary task by high skill performers). The development of skill appears not to change the nature of where attention is allocated during task execution.

Overall, the current results provide support for motor skill theories (e.g., Adams, 1971; Schmidt, 1975) and for Reason's (1990) attentional checking theory. No support was found for Botvinick and Plaut's (2003, 2004) prediction about the disruptive effects of mid-subtask distraction on errors during the performance of routine skilled tasks.

One possible explanation for the lack of disruptive effects of mid-subtask distraction in the current task maybe because this portion of the task was performed in a fairly ballistic mode. However, as discussed, it is difficult to categorise the pointer movements involved in the current tracking task as either slow-positioning or rapid-ballistic. One way to make this distinction more pronounced using the same task paradigm so that the effect of mid-subtask distraction can be clarified is to manipulate the speed and accuracy of performance effectively making movements in the task more (under speed stress) or less ballistic (under accuracy stress).

Another reason to manipulate task instructions is because there is some ambiguity in the current study as to whether participants were adhering to the task instruction to be optimise both speed and accuracy. This is a typical instruction used in most research to keep participants from unduly emphasising speed over accuracy or vice versa. Generally researchers have assumed that participants follow instructions and attempt to perform their instructed tasks as quickly and accurately as possible. Performance on the current task was definitely fast but in relation to accuracy there were some unexpected findings during the skill training phase with regard to wrong way errors. Specifically, the study found that when the probability of movement direction was not a factor (direction 100% probable) or was a factor of high probability (direction 75% probable) practice reduced wrong way errors and produced the expected skill learning curve (i.e., a decelerating trajectory, characterised by rapid improvement at the start of practice followed by diminishing improvements with further practice and asymptoted to a constant level). This pattern of improvement with practice was also found with decision time, movement time and overshoot errors.

However, when the probability of movement direction was equivocal (i.e., direction 50% probable) or was low (i.e., direction 25% probable) practice did not improve performance. Despite receiving over 1600 practice trials, wrong way errors remained essentially constant on equal probability trials and actually increased, in fact, nearly doubled on low probability trials. The strong influence of probability effects on the occurrence of wrong way errors suggest that participants were actively looking ahead and attempting to anticipate the direction of the next target often wrongly. The results suggest that participants chose the strategies of gambling in favour of higher frequency responses on low probability trials and guessed at chance level on equivocal probability trials even though these strategies resulted in error on a substantial number of occasions. Interestingly practice increased this tendency to frequency gamble which suggest a certain characteristic of skill, that is, a tendency towards taking greater risks perhaps reflecting an impulsiveness and/or over-confidence which leads to errors as has been reported in the driving literature (Svenson, 1981). There are several aspects about the study which may have biased participants toward the adoption of riskier response strategies.

The first relates to existing evidence that performance under noise alters the speed-accuracy trade-off (SATO) in favour of speed (Jones, 1984; Rabbitt, 1979). This effect is sometimes attributed to an increase in arousal level although it might equally reflect the disruption of control processes responsible for keeping the optimal balance between speed and accuracy (Rabbitt, 1979). Assuming that the balance between accuracy and speed has to be fairly precise and there is little margin for error, the tones presented in this study may have affected participants' ability to regulate SATO. Participants did, however, performed fast and accurately on trials with high directional probability (which constituted the majority of trials) suggesting at least on these trials, participants were able to effectively regulate SATO.

The second relates to the nature of the current task itself (i.e., involving speed and accuracy of motor movements). The task was a simple psychomotor task which had a large motor requirement. Accuracy rate on the task could be manipulated easily by speeding up or slowing down responding. The task was also self-paced instead of being experimenter-paced which meant that participants could go as fast as they wanted and the faster they moved the faster the trials proceeded. Hence participants could actively engage in the task by developing their own strategies task. The task was also unique in that it involved anti-stereotypical movement and due to the spatial display of the task it was possible for performers to look ahead and anticipate future responses in order to quicken task processing which was what the study found.

Another contributing feature of the task was that errors were not penalised in that no monetary or other loss was incurred. As there was no real consequence when errors were made on the task, participants may be more willing to make errors on the task. Participants also did not receive explicit summarised error feedback at the end of each block of trials. This was a technical limitation of the task software. Only summarised speed feedback was provided (i.e., time it took to complete each block of trials) which may have inadvertently emphasised speed over accuracy. This explanation is less likely however because participants had implicit feedback on errors every time they corrected them and were frequently reminded of the instruction to optimise both speed and accuracy at the start of each block.

Finally, for participants in the high skill condition, the experimental session was long (2.5 hr) which may have motivated some participants to finish the experiment quickly. The effects of task fatigue would have been minimal, however, because participants took rest breaks between stimulus blocks and importantly overall performance did not show decrements as would be expected if task performance was affected by fatigue. Nonetheless, given these issues, a systematic investigation of the separate effects of speed versus accuracy instructions is warranted.

CHAPTER 4

EXPERIMENT 2: THE EFFECT OF DISTRACTION ON SKILLED PERFORMANCE UNDER SPEED VERSUS ACCURACY INSTRUCTIONS

4.1 Overview of Chapter 4

The aim of Experiment 2 was to examine the separate effects of speed versus accuracy instructions in order to clarify the effects of distraction on low and high skill performance. Like the results of the previous study, this study found that skill development reduced capacity demands but a level of attention or self-regulation was still involved at critical points in order to avoid errors. These critical points were the same for low and high skill participants. This study extended the results of the previous study by showing that although skill development did not change where attention was needed it did reduce the amount of attention required at these critical points. There was also evidence that performance instructions moderated the amount of attention required at these critical points.

4.2 Introduction

An enduring challenge is to identify and explain the factors that influence skill learning and performance. Theories and models of skill acquisition generally converge on the view that practice is the primary determinant in the development of skill (Adams, 1987; Anderson, 1982; Logan, 1988; Newell & Rosenbloom, 1981; Procta & Dutta, 1995) particularly for tasks with significant motor requirements. With practice, performance becomes faster and less error prone. There is a limit, however, as to how fast a person can perform without compromising accuracy. This relation is called the speed and accuracy trade-off (SATO) which is the well-established finding that response time in any specific task situation is related to the number of errors that one is willing to make (Pachella, 1974; Pew, 1969; Wickelgren, 1977). A person can at will respond rapidly and make many errors or respond slowly and make few errors. In the context of SATO, ‘skill’ is defined as when performance is both fast and accurate. That is, when the balance between speed and accuracy is optimised or when performance is ‘efficient’ or ‘fluent’ (MacKay, 1982). The issue of SATO is important for both theoretical and applied reasons. Take for example a complex sport such as car racing. This is a sport where extreme errors cannot be tolerated and where it takes time and experience to find the balance that maximises speed and minimises error. The driver has to learn to recognise situations where maximum speed represents too great a risk so that they can allocate processing resources in advance to these situations. Only then can adjustments be made in order to finding the optimum speed that avoids the cost of error.

Ultimately, however, accuracy and speed are in conflict. The effect that speed leads to increased errors and accuracy leads to increased slowing has been demonstrated in numerous studies using a variety of tasks and experimental conditions (Dutilh et al., 2009; Hearly et al., 2004; Hick 1952; Sanders, 1998; Woodworth 1899). SATO has been found to influence the occurrence of errors from the lowest level errors in muscle movement to the highest level lexical and phonological errors (MacKay, 1971). However, although this principle has been repeatedly demonstrated across both cognitive and motor skill domains, it was discovered and has most often been studied in individuals possessing little previous exposure to the tasks they were performing (Beilock et al., 2004).

Although people's capacity for SATO has been known for a long time (Fitts, 1954; Hick, 1952; Wickelgren, 1977; Woodworth, 1899) surprisingly, it has received relatively little theoretical and empirical attention in the context of skill acquisition and skilled performance (Strayer & Kramer, 1994). Many prominent skill acquisition theories simply neglect any explanations regarding SATOs. For example, Crossman's (1959) early influential theory suggested that skill development involves the transition from random to more systematic selection of methods based on the time saved relative to other methods. Crossman's theory, however, focused on performance speed as the critical dependent variable and ignored any effects on accuracy. Similarly, Newell and Rosenbloom (1981) explained performance improvements with practice by claiming that information processing operations are gradually "chunked" to form increasingly efficient procedures. Like Crossman, Newell and Rosenbloom's theory made no acknowledgement of learners' capacity to vary their speed-accuracy criterion and the potential for practice to alter the compromises between speed and accuracy that individuals adopt (Rabbitt & Banerji, 1989).

Another well-known theory of the effects of extended practice in perceptual motor tasks is that of Schneider and Shiffrin (1977). Based on assumptions about the role of attention, Schneider and Shiffrin explained the difference between unskilled and skilled in terms of "controlled" and "automatic" processes whereby the latter was characterised as fast, efficient and not limited by short-term memory capacity or attention and the former as slow, error-prone and attention demanding. The theory provided no prediction as to how speed and accuracy change with practice and neglected any explanations regarding trade-off effects.

A notable exception, however, is MacKay's (1982) theory which was developed in the context of speed production and seeks to explain why there is a trade-off relation between speed and accuracy so that we can generate behaviour more rapidly only at the expense of a higher probability of error. The theory explains SATO through the effects of node activation and priming. In MacKay's theory, nodes are hierarchical cognitive units within the mental system responsible for controlling the movements making up an action sequence. Behaviour occurs only when nodes are activated. An activated node then "primes" all nodes connected directly to it. Correct action occurs whenever an "intended-to-be-activated" (p. 495) node has greater strength than any other node in the mental system. Errors occur whenever an extraneous node has greater strength than the intended-to-be-activated node. Nodes with extensive practice have greater strength which means that the time to reach activation to produce behaviour is shorter for more practised nodes as well as lower probability of error.

A different approach to explaining SATO is Ratcliff's (1978; Ratcliff & McKoon, 2008) diffusion model, which was developed to account for performance in speeded two-choice RT tasks. According to the diffusion model, upon stimulus presentation stimulus information accumulates gradually over time. Under speed instructions, the response criterion is moved closer to the starting point (i.e., where the accumulation of information begins) so that the amount of information that is needed to trigger a response is reduced, resulting in fast latencies but higher error rates. Under accuracy instructions, the response criterion is moved farther from the starting point so that amount of information necessary to trigger a response is increased which effectively slows down a response and increased its probability of being accurate.

The manipulation of speed versus accuracy instructions has been used extensively in past research to examine a range of different issues including the influence of SATO on performance. Consistent with the SATO principles, studies have typically found that participants under speed stress demonstrate faster latencies and higher error rates than participants under accuracy stress (Dutilh et al., 2009; Hearly et al., 2004; Pachella, 1974; Pachella & Pew, 1968; Rabbitt, 1989; Wickelgren, 1977). In relation to skilled tasks, however, the evidence is not entirely consistent with the SATO literature. There is some empirical evidence as well as theoretical speculation to suggest that speed stress benefits skill learning and performance more than accuracy stress.

For example, Ratcliff (1978) suggested that two components are necessary in order to obtain a highly skilled performance: increase efficiency in information processing which occurs as a result of consistent practice and strategic adjustment of the response criteria. Specifically, the adoption of a more liberal (i.e., speedier) set of response criteria to capitalise on the increased efficiency of information processing. LaBerge and Samuels (1974) in their theory on skill automaticity also suggested that speed stress increases the rate of automaticity. This was supported by a study by Fisk and Schneider (1983) who reported a substantial improvement in both the speed and accuracy performance during skill acquisition of a letter detection task when participants were instructed to “let go” and respond without thinking. Similarly, Schneider and Fisk (1982a, 1983) reported that automatic and controlled tasks can be carried out jointly without any additional cost only if participants are strongly instructed to focus on the controlled task. By contrast, performance reflected dual task costs if participants did not receive these particular instructions. The authors suggested that in dual-task situations participants may sub-optimally allocate resources to the automatic task even though these resources do not improve performance.

Similar findings are reported in studies comparing skill acquisition between younger and older adults. Older adults tend to show slower rates of skill learning even though there is no impairment in their ability to acquire a new skill (Rogers & Gilbert, 1997; Rogers, Hertzog & Fisk, 2000; Touron, Hoyer & Cerella, 2004). Some authors therefore assume that elderly participants show *behavioural inertia* (Mayr, 2001) that might be due to strong emphasis on accuracy (i.e., more conservative responding) (Strayer & Kramer, 1994).

In general, the notion that speed stress benefits skill learning and performance more than accuracy stress goes against the well-established SATO finding that the more rapidly a task is performed the less accurate it becomes. The reasons for the discrepancy between the findings in the literature are not clear. Based on the observation that most studies in support of the SATO effect used relatively unpractised tasks, Beilock et al. (2004) suggested that assuming control structures that govern performance differs as a function of skill level then it possible that the SATO does not generalise to well-practised skill. In direct contrast, MacKay (1982) argued that SATO is “one of the most reliable and pervasive phenomena in the study of skilled behaviour” (p. 495). It is likely that processes involved in the governing of performance speed and accuracy are rather complex involving numerous interacting factors such as the nature of the task, the level of practice, strategic bias and so forth. More research is required to understand better the particular circumstances in which skilled performance under speed versus accuracy stress leads to improvements.

The manipulation of speed versus accuracy instructions has also been used in past research to the role of attention during task performance (Beilock et al., 2004; Haider & Frensch, 1999; Meiser & Schult, 2008). The assumption underpinning this area of research is that accuracy instructions will increase the amount of attention paid to the task whilst speed instructions will do the opposite. For example, Beilock et al. used speed versus accuracy instructions to manipulate the degree of attentional focus on a golf putting task performed by novice and expert players. The study found that expert players performed better under speed than accuracy instructions whereas the reverse was found for novice players. These results corroborate the abovementioned studies and provide further evidence for the positive effects of speed stress on skilled performance.

In another study, Haider and Frensch (1999) used speed versus accuracy instructions to test the hypothesis that skill development involves a reduction in the amount of attention paid to task irrelevant information. The study manipulated speed versus accuracy instructions under the logic that participants who are instructed to optimise speed would decide on the basis of less evidence to ignore task redundant information and pay most attention to task-relevant information in order to quicken task processing thus resulting in a high rate of information reduction. In contrast, participants who are instructed to optimise accuracy would pay attention to both relevant and irrelevant task information and would ignore task-irrelevant information only if they are absolutely certain that the information is truly irrelevant resulting in a much smaller degree of information reduction. The study showed that the amount of information reduction was affected by instructions and suggested that one aspect of acquiring skill is the ability to limit task processing to task relevant information. The study's findings extend the view expressed by others that more liberal settings of respond criteria are one characteristic of advanced skill (Beilock et al., 2004; Ratcliff, 1981; Strayer & Kramer, 1994a; 1994b).

Although studies have used speed versus accuracy instructions to manipulate the *amount* of attention paid to a task at hand, no study has been found in the open literature which has investigated whether speed versus accuracy instructions changes *where* attention is allocated and whether these effects differ depending on skill level. The aim of this study was to extend our understanding of the role of attention during skilled performance by investigating the effect of distraction at different subtask points on low and high skill performance under conditions of speed (i.e., respond as fast as possible) versus accuracy (i.e., respond as accurately as possible) instructions.

The results of the current study will help to clarify to an unresolved issue in the initial study concerning the nature of the movements in the tracking task. Specifically, it was difficult to categorise with any certainty whether they were slow-positioning or rapid-ballistic movements. In this study, this distinction was made pronounced by manipulating the speed and accuracy of performance effectively making movements in the task more ballistic (under speed stress) and less ballistic (or more like slow-positioning movements under accuracy stress). By separating out the effects of speed versus accuracy instructions, the results of the current study will provide a clearer understanding of the effect of distraction at different subtask points on low and high skill performance.

Specifically, four effects were predicted. The first relates to the interaction between skill level and instructions. In accordance with the SATO literature, all participants should perform faster but less accurately under speed instructions; and perform slower but more accurately under accuracy instructions. Alternatively, if the principles of SATO do not generalise to well-practised skill, as proposed by Beilock et al. (2004) then high skill participants should perform better on both latency and error rate under speed instructions than accuracy instructions. Low skill participants should show the expected trade-off under speed versus accuracy instructions.

The second prediction relates to the interaction between performance instructions and distraction positions. Specifically, the lack of disruptive effects of mid-subtask distraction found in the initial study was due to the fact that this portion of the task was performed in a fairly ballistic mode then the disruptive effects of mid-subtask distraction (if there is any effect) should show under accuracy instructions because movements under this instruction is slower and less ballistic. Alternatively, assuming that performance under accuracy stress involves more frequent conscious monitoring of performance then Reason's (1990) theory about attentional checks at end-subtask points would still be a better fit. The third prediction relates to the interaction between distraction positions and skill level which is that the results in the previous study should replicate. Finally, assuming that performance instructions moderate these effects then a three-way interaction was expected.

4.3 Method

4.3.1 Participants

A total of 100 introductory psychology students (56 female, 44 male) aged 17 to 57 years (*M* = 22.63; *SD* = 7.37) from the University of New South Wales were tested individually in a single session lasting approximately 60 min for participants in the low skill condition and 180 min for participants in the high skill condition. Participants received course credit points for their participation. All were right-handed and had normal or corrected-to-normal vision.

4.3.2 Design

A 2 x 2 x (4) between-within subjects design with between subjects variables: skill level (high versus low) and instruction type (speed versus accuracy); and within-subjects variable, the timing of distraction (no distraction, begin, mid, end).

4.3.3 Primary task, distraction task, apparatus, materials & stimuli

These were identical to that used in Experiment 1.

4.3.4 Procedures

The procedure for this experiment was approved by the local ethics committee. The procedure was identical to Experiment 1 except for the manipulation of speed versus accuracy instructions. In the Accuracy condition, participants were instructed to respond as *accurately* as possible. The experimenter explained to participants that accuracy in this task meant moving in the direction of the target and not overshooting the target. In the Speed condition, participants were instructed to respond as *quickly* as possible. Participants were reminded of these instructions at the beginning of each stimulus block.

As in Experiment 1, participants were randomly assigned to experimental groups. Skill level was manipulated during the training phase of the experiment. Participants in the low skill condition received 40 training trials and high skill participants received 14 blocks of 120 training trials each (1680 training trials in total). In the testing phase, both low and high skill participants performed the primary task under conditions of auditory distraction. As in Experiment 1, the testing phase consisted of 120 trials of which 60 trials had no distraction and 60 trials had a distraction. Within distracted trials, the occurrence of beginning-, middle- and end-subtask distractions was countered balanced (20 trials in each condition). The same dependent variables in Experiment 1 were measured.

4.3.5 Data analysis

Consistent with Experiment 1, trials with decision time shorter than 100 ms (2.6%) and longer than 2000 ms (<1%) were excluded from the analysis. All other data analysis details were identical to Experiment 1.

4.4 Results

4.4.1 Correlations

Bivariate correlation analysis of the dependent variables measured across the entire sample. The means, standard deviations and correlations for the variables measured in the study are shown in Table 3. There was a high correlation between decision time and movement time

($r = .74$, $p < .01$) and between wrong way error rate and overshoot error rate ($r = .64$, $p < .01$) suggesting that the two types of latency and error variables shared a moderate amount of variance in the data. All other inter-correlations were low ($r < .30$) suggesting that the dependent variables measured relatively different aspects of performance. Separate correlation analysis was also conducted for Speed and Accuracy condition separately. These analyses yielded a similar set of correlation patterns. Because these analyses provided essentially no new information, the details are reported in Appendix B.

Table 3

Means, standard deviations, and correlation coefficients of dependent variables.

Dependent variables	***M***	***SD***	**1.**	**2.**	**3.**	**4.**
1. Decision time (ms)	365.43	105.15	-			
2. Movement time (ms)	929.70	232.40	.74**	-		
3. Wrong way error rate (%)	10.68	8.03	-.18**	-.21**	-	
4. Overshoot error rate (%)	18.07	11.24	-.12**	-.33**	.64**	-

** = $p < .01$ (2-tailed).

4.4.2 Skill acquisition manipulation check

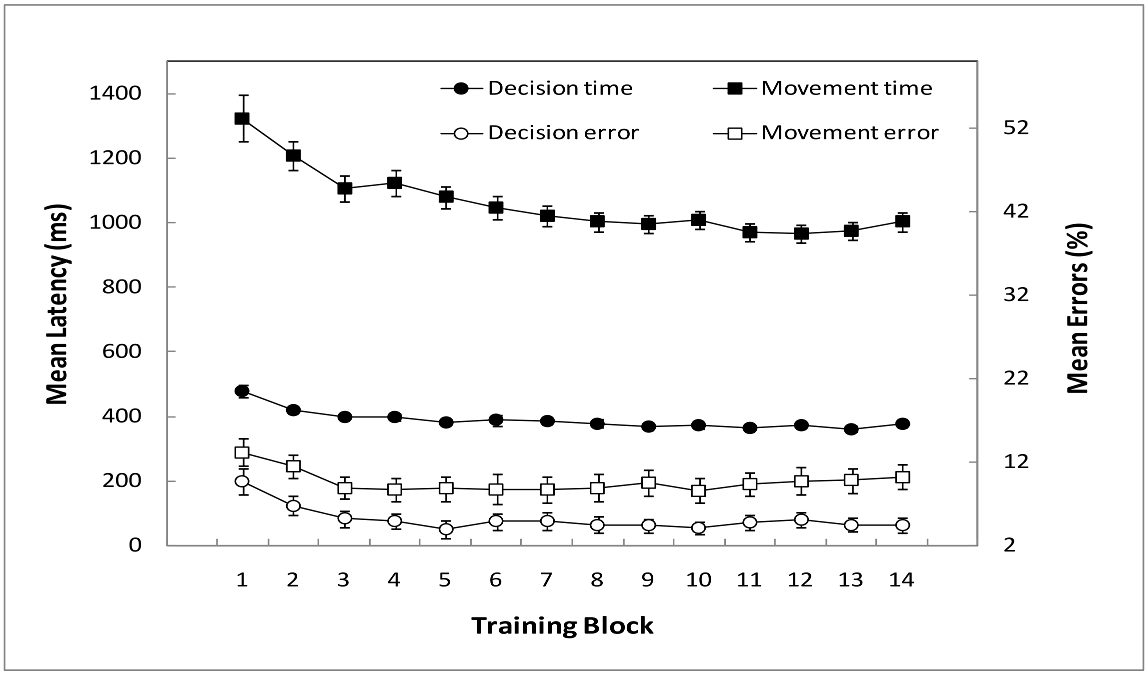
The training data was analysed to verify that skill acquisition occurred with practice in the high skill condition. The training data was analysed separately for the Speed and Accuracy group using a within-subjects ANOVA with repeated measures on block (one to 14, each with 120 trials).

For the Accuracy group, practice significantly improved performance for all variables measured: decision time, $F(13, 312) = 27.16$, $p < .001$, $\eta_p^2 = .53$; movement time, F(13,

312) = 25.84 , $p < .001$, $\eta_p^2 = .52$; wrong way error; $F(13, 312) = 10.01$, $p < .001$, $\eta_p^2 = .29$; and overshoot error; $F(13, 312) = 4.20$, $p < .001$, $\eta_p^2 = .15$. As seen in Panel A of Figure 14, at the start of training decision time was approximately 470 ms and was reduced to approximately 380 ms with 14 blocks of practice. Similarly, initial movement time was approximately 1300 ms at the start of practice and was reduced to approximately 1000 ms by the end of practice. Error rates also reduced with practice, from approximately 10% to 4% for wrong way error and from 13% to 9% for overshoot error.

For the Speed group, practice significantly reduced decision time, $F(13, 312) = 46.90$, $p < .001$, $\eta_p^2 = .66$, and movement time, $F(13, 312) = 42.81$, $p < .001$, $\eta_p^2 = .64$, and overshoot error, $F(13, 312) = 1.92$, $p < .05$, $\eta_p^2 = .07$, but not for wrong way error, $F<1$. As seen in Panel B of Figure 14, the latency data show a steady reduction during the training blocks from approximately 440 ms to 270 ms for decision time and from approximately 1380 ms to 870 ms for movement time. Overshoot errors also reduced from 29% (Block 1) to 23% (Block 5) and maintained at approximately 25% thereafter. In contrast, wrong way error rates remained essentially constant at approximately 15% throughout the 14 blocks of training.

A.



B.

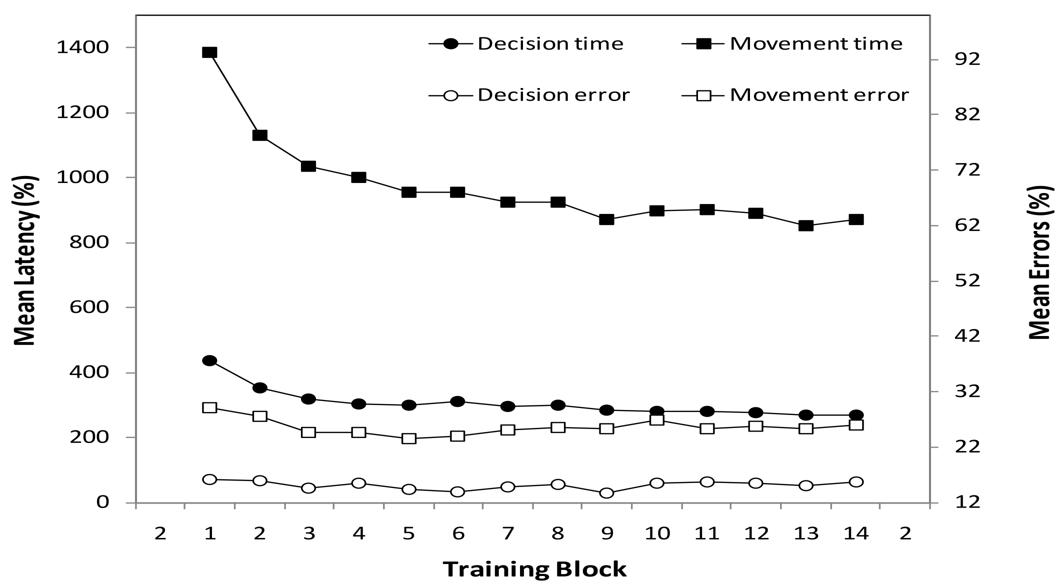
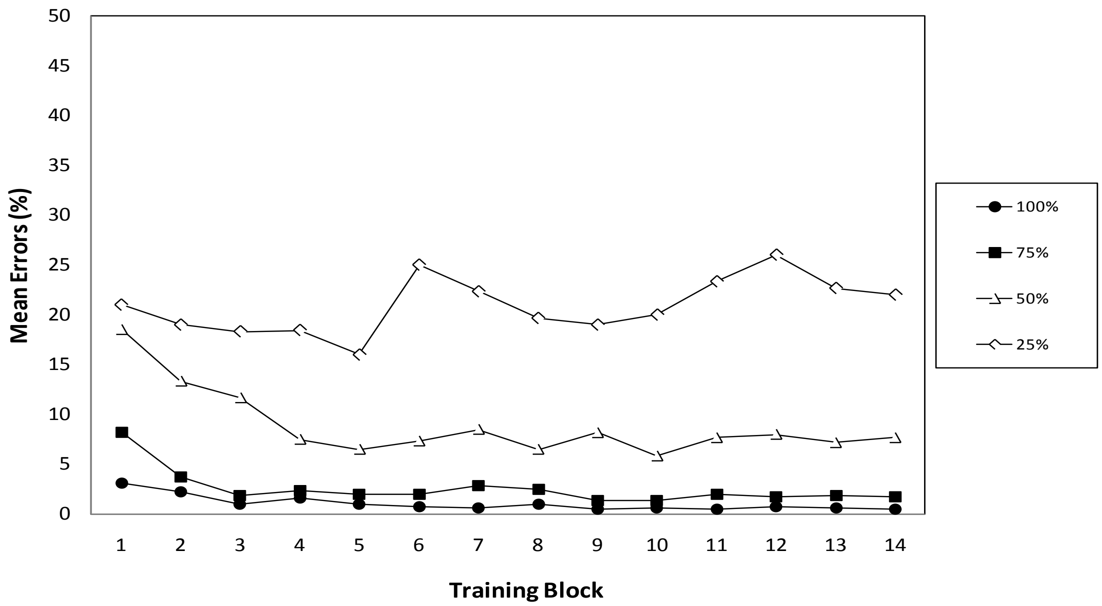


Figure 14. Training mean latency data (decision time and movement time) and mean percentage of error data (wrong way error and overshoot error) as a function of 14 blocks of practice (each with 120 trials) for the Accuracy group (Panel A) and for the Speed group (Panel B).

Wrong way errors were broken down into four types according to the directional probability of the target in terms of left versus right movement: 100%, 75%, 50% and 25%. A 4 × 14 (Probability × Block) ANOVA on proportion of wrong way errors with repeated measures on both factors was conducted separately for the two instruction conditions. For the Accuracy condition, there was a significant main effect of probability, $F(3, 75) = 41.13$, $p < .001$, $\eta_p^2 = .62$; block, $F(13, 325) = 4.84$, $p < .001$, $\eta_p^2 = .16$; and a significant interaction between probability and block, $F(39, 975) = 2.49$, $p < .01$, $\eta_p^2 = .09$. To understand better the significant interaction between block and probability, separate analyses were conducted for each of the four trial types. As seen in Panel A of Figure 15, practised significantly reduced wrong way errors for trials with 100%, 75% and 50% directional probability: $F(13, 325) = 3.03$, $p < .05$, $\eta_p^2 = .11$; $F(13, 325) = 10.44$, $p < .001$, $\eta_p^2 = .30$; and $F(13, 325) = 8.77$, $p < .001$, $\eta_p^2 = .26$, respectively. The majority of wrong way errors occurred on trials with 25% directional probability and on these trials wrong way errors remained at a constant rate of approximately 20% across practice, $F(13, 325) = 1.35$, $p = .19$.

For the Speed condition, there was a significant main effect of probability, $F(3, 75) = 198.41$, $p < .001$, $\eta_p^2 = .89$. The main effect of block was not significant, $F(13, 325) = 1.74$, $p = .08$ but there was a significant interaction between probability and block, $F(39, 975) = 6.10$, $p < .001$, $\eta_p^2 = .20$. Overall wrong way errors increased as target probability decreased. As seen in Panel B of Figure 15, the majority of errors occurred on trials with

A.



B.

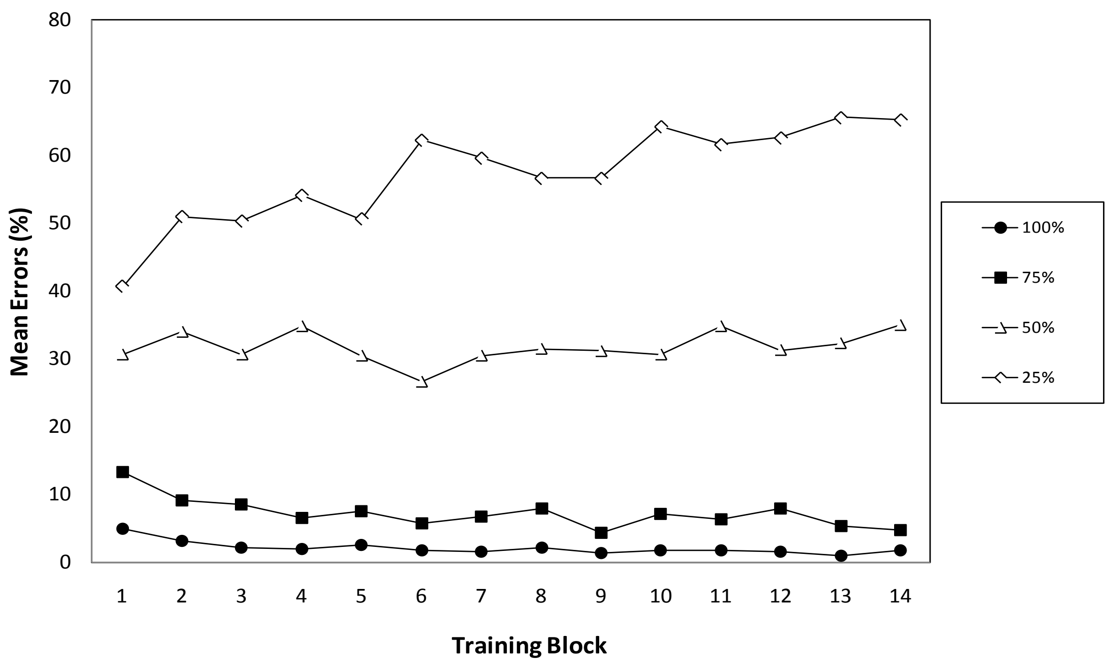
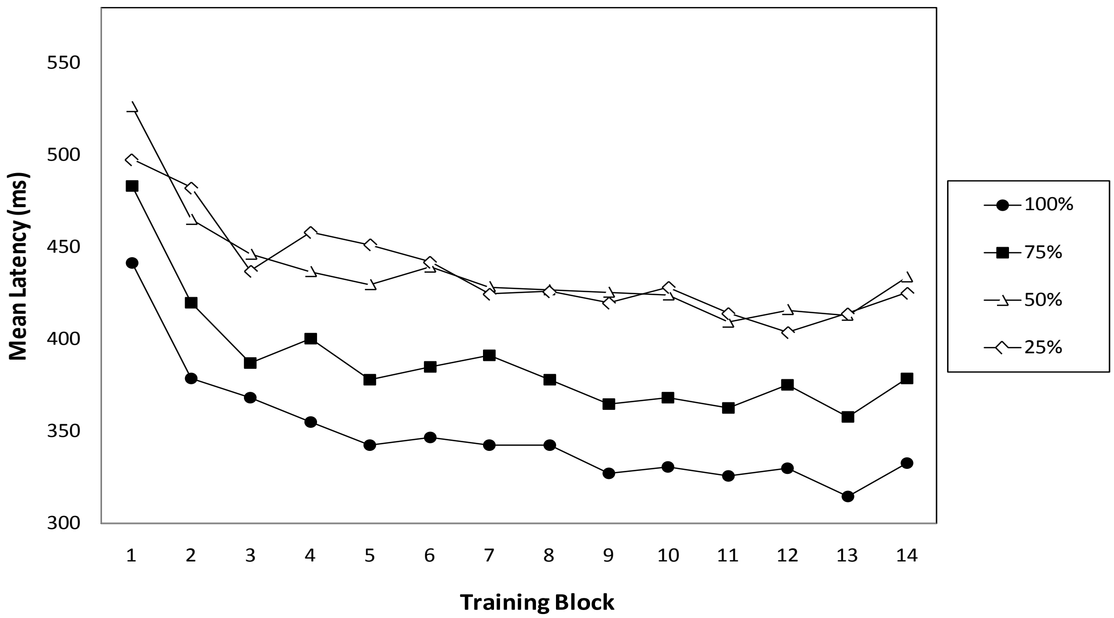


Figure 15. Training mean percentage of wrong way error data as a function of 14 blocks of practice (each with 120 trials) and directional probability for the Accuracy group (Panel A) and for the Speed group (Panel B).

25% directional probability and rather than decrease with practice as might be expected, errors on these trials increased, $F(13, 325) = 6.42$, $p < .001$, $\eta_p^2 = .21$ from approximately 41% at the start of practice to 65% by the end of practice. On trials with 50% directional probability, wrong way errors remained at a constant rate of approximately 32%, $F(13, 325) = 1.27$, $p = .29$. In contrast, on trials with high directional probability (i.e., 75%) errors decreased significantly with practice from approximately 13% at the start of training to 5% by the end of training, $F(13, 325) = 4.55$, $p < .001$, $\eta_p^2 = .16$. Similarly, on trials with 100% target probability wrong way errors decreased significantly with practice, from approximately 5% to essentially zero errors by the end of training, $F(13, 325) = 3.44$, $p < .01$, $\eta_p^2 = .13$.

As in Experiment 1, an additional analysis using a 4 × 14 (Probability × Block) ANOVA on mean decision time with repeated measures on both factors was performed. For the Accuracy group, there was a significant main effect of probability, $F(3, 72) = 153.57$, $p < .001$, $\eta_p^2 = .87$; and block, $F(13, 312) = 21.16$, $p < .001$, $\eta_p^2 = .47$. The interaction between block and probability was also significant, $F(39, 936) = 1.95$, $p < .05$, $\eta_p^2 = .08$. As shown in Panel A of Figure 16, decision time improved significantly with practice for all trial types but the improvements were generally larger at the start of practice and larger for trials with high directional probability (i.e., 100% and 75%). Overall decision time increased as the uncertainty of directional probability increased except for the finding that there was no significant difference between mean decision time on trials with 25% and 50% directional probability, $F(1, 24) < 1$, $p = .94$.

A.



B.

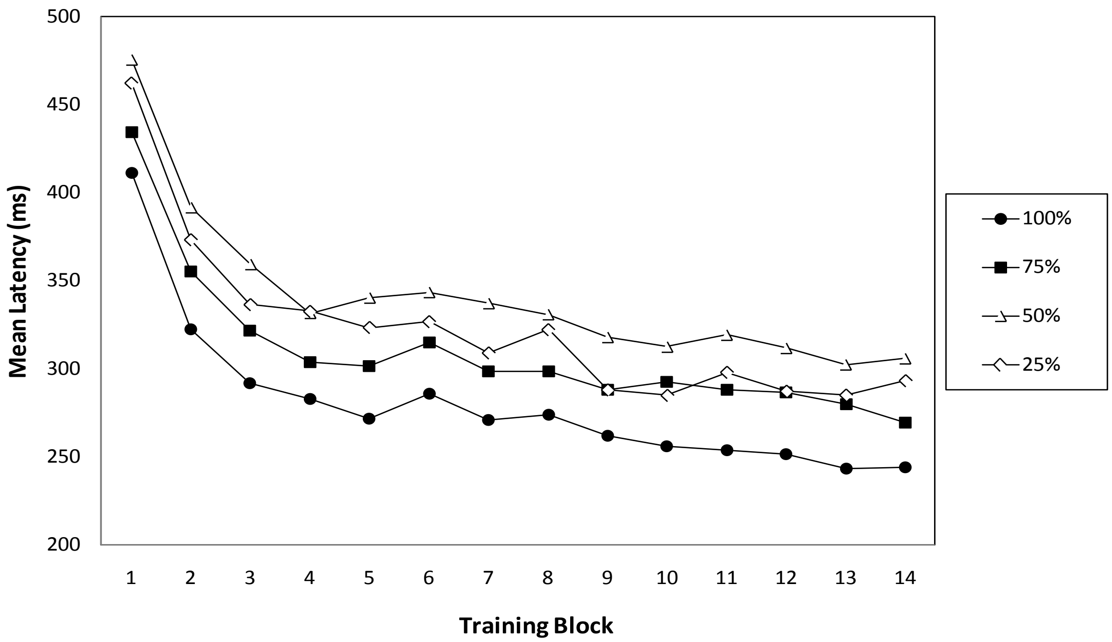


Figure 16. Training mean decision time data as a function of 14 blocks of practice (each with 120 trials) and directional probability for the Accuracy group (Panel A) and for the Speed group (Panel B).

A similar pattern of results was found for the Speed group. The results revealed a significant main effect of probability, $F(3, 72) = 85.21$, $p < .001$, $\eta_p^2 = .78$; and block, $F(13, 312) = 34.42$, $p < .001$, $\eta_p^2 = .59$. The interaction between block and probability was not significant, $F(39, 936) = 1.46$, $p = .06$. As shown in Panel B of Figure 16, decision time improved significantly with practice for all trial types. There was an overall gradient effect of directional probability in that decision time increased as the uncertainty of directional probability increased except for mean decision time on trials with 25% directional probability which was found to be significantly shorter than mean decision time on trials with 50% directional probability, $F(1, 24) =14.52$, $p < .001$, $\eta_p^2 = .38$.

4.4.3 Performance on the primary task under distraction

Performance on the primary task under conditions of distractions was analysed using a 2 x 2 x (4) mixed-model ANOVA with between-subjects factor variables: instruction groups (speed versus accuracy) and skill level (low skill versus high skill); and the within-subjects variable, distraction positions (begin, versus mid, versus end). ANOVA results for all the dependent variables measured are summarised in Table 4.

Wrong way error rate. Based on the finding that wrong way errors varied according to target probability the same approach was used as in Experiment 1 in limiting the analysis of wrong way errors on high probability trials (Appendix C contains descriptive statistics for all trials as a function of low, equal and high probability trials).

As seen in Table 4, ANOVA results for high probability trials revealed a significant main effect of skill, instructions and distraction positions. No interactions were significant.

Mean percentage of wrong way errors plotted as a function of skill level, distraction positions and instructions group is presented in Figure 17. Overall high skill participants (*M* = 3.81, *SD* = 6.71) made significantly fewer wrong way errors than low skill participants (*M* = 7.08, *SD* = 10.17) and the Accuracy group (*M* = 4.02, *SD* = 7.51) made significantly fewer wrong way errors than the Speed group (*M* = 6.87, *SD* = 9.66). In terms of the effects of distraction positions, contrast results revealed that wrong way errors were more frequent on distracted (*M* = 5.85, *SD* = 9.60) than no distracted trials (*M* = 4.16, *SD* = 5.30), $F(1, 96) = 5.88$, $p < .05$, $\eta_p^2 = .06$. Within distracted trials, end-subtask distraction (*M* = 8.35, *SD* = 11.28) resulted in significantly more wrong way errors than begin-subtask (*M* = 4.44, *SD* = 8.01), $F(1, 96) = 18.76$, $p < .001$, $\eta_p^2 = .17$; and mid-subtask distraction (*M* = 4.78, *SD* = 8.78), $F(1, 96) = 12.75$, $p < .001$, $\eta_p^2 = .12$. There was no significant difference between distractions at begin- and mid-subtasks, $F(1, 96) < 1$, $p = .63$.

Decision time. ANOVA results for decision time as seen in Table 4 revealed a significant main effect of skill, instructions and distraction positions. There were also two significant two-way interactions between instructions and skill and between instructions and distraction positions which qualifies the interpretation of these main effects. Mean decision time plotted as a function of skill level, distraction positions and instructions group is presented in Figure 18.

Table 4

ANOVA analysis results for the dependent variables measured according to skill level, distraction positions and instruction group.

Source	**Wrong way error**[a]	**Decision time**	**Overshoot error**	**Movement time**
Main Effect				
Skill	$F_{(1, 96)} = 5.98$, $p < .05$, $\eta_p^2 = .06$	$F_{(1, 96)} = 22.84$, $p < .001$, $\eta_p^2 = .19$	$F_{(1, 96)} = 4.00$, $p < .05$, $\eta_p^2 = .04$	$F_{(1, 96)} = 44.02$, $p < .001$, $\eta_p^2 = .32$
Distraction positions	$F_{(3, 288)} = 4.55$, $p < .05$, $\eta_p^2 = .05$	$F_{(3, 288)} = 19.80$, $p < .001$, $\eta_p^2 = .17$	$F_{(3, 288)} = 46.96$, $p < .001$, $\eta_p^2 = .33$	$F_{(3, 288)} = 10.12$, $p < .01$, $\eta_p^2 = .10$
Instructions	$F_{(1, 96)} = 10.97$, $p < .001$, $\eta_p^2 = .10$	$F_{(1, 96)} = 31.07$, $p < .001$, $\eta_p^2 = .25$	$F_{(1, 96)} = 6.80$, $p < .001$, $\eta_p^2 = .07$	$F_{(1, 96)} = 44.07$, $p < .001$, $\eta_p^2 = .32$
Two-way interaction				
Skill × Instructions	n.s. ($p = .92$)	$F_{(1, 96)} = 5.12$, $p < .05$, $\eta_p^2 = .05$	$F_{(1, 96)} = 3.96$, $p < .05$, $\eta_p^2 = .04$	n.s. ($p = .39$)
Distraction positions × Skill	n.s. ($p = .76$)	n.s. ($p = .06$)	n.s. ($p = .99$)	n.s. ($p = .85$)
Distraction positions × Instructions	n.s. ($p = .51$)	$F(_{(3, 288)} = 4.00$, $p < .01$, $\eta_p^2 = .04$	n.s. ($p = .99$)	n.s. ($p = .83$)
Three-way interaction	n.s. ($p = .87$)	n.s. ($p = .49$)	n.s. ($p = .57$)	n.s. ($p = .61$)

Note. [a] = trials with high directional probability (i.e., 100% and 75%).

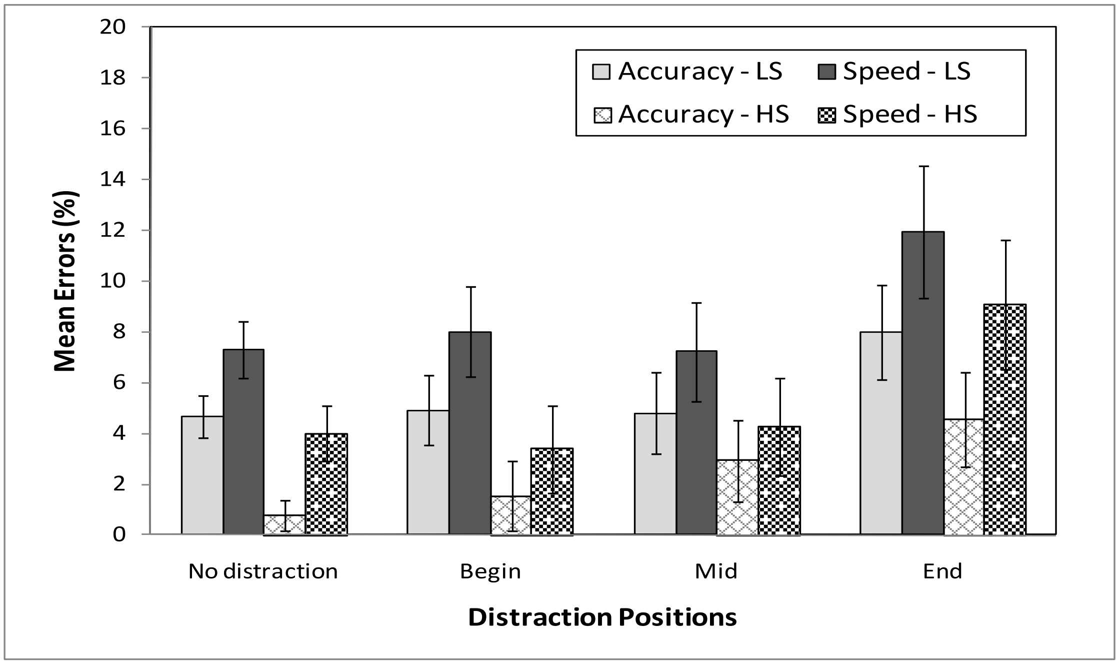


Figure 17. Mean percentage of wrong way errors on trials with high directional probability as a function of skill level, distraction positions and instruction group.

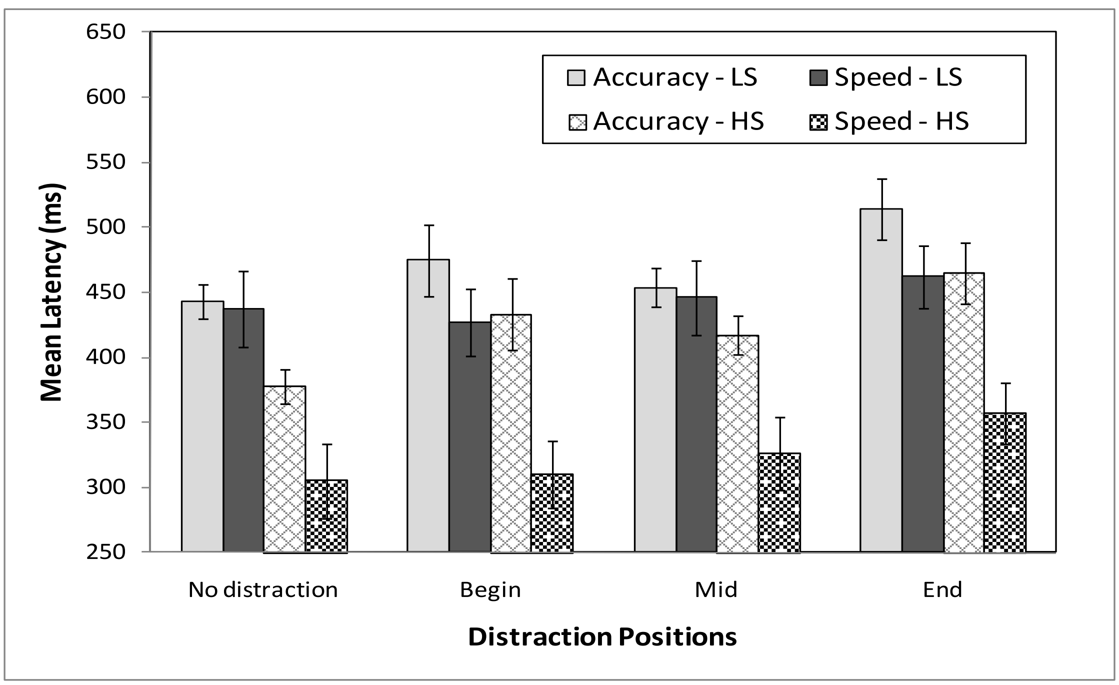


Figure 18. Mean decision time as a function of skill level, distraction positions and instruction group.

Overall decision time was significantly faster in high (*M* = 374.00, *SD* = 93.00) than low skill (*M* = 457.60, *SD* = 149.58) condition. This skill effect was larger under Speed (*M* = 382.69, *SD* = 144.14) than Accuracy instructions (*M* = 447.44, *SD* = 107.73). In relation to the main effect of distraction positions, overall decision time was significantly faster on non-distracted trials (*M* = 390.42, *SD* = 121.52) than distracted trials (*M* = 423.70, *SD* = 133.13), $F(1, 96) = 41.45$, $p < .001$, $\eta_p^2 = .30$. Within distracted trials, decision time was significantly slower when distractions occurred at end-subtasks (*M* = 449.44, *SD* = 130.02) compared to begin-subtasks (*M* = 411.18, *SD* = 144.19), $F(1, 96) = 40.72$, $p < .001$, $\eta_p^2 = .30$; and mid-subtasks (*M* = 410.47, *SD* = 121.80), $F(1, 96) = 41.28$, $p < .001$, $\eta_p^2 = .30$. There was no significant difference between begin- and mid-subtask distractions, $F(1, 96) < 1$, $p = .80$.

The significant interaction between instructions and distraction positions was between the mid- and end-subtask conditions. Specifically, the disruptive effect of end-subtask distraction compared to mid-subtask was significantly larger in the Accuracy than the Speed condition, $F(1, 96) = 6.25$, $p < .05$, $\eta_p^2 = .06$.

Overshoot error rate. . Mean percentage of overshoot errors plotted as a function of skill level, distraction positions and instructions group is presented in Figure 19. ANOVA results revealed a significant main effect of skill, instructions and distraction positions. The only significant interaction was between Instruction x Skill. Overall high skill participants (*M* = 19.47, *SD* = 13.09) made fewer overshoot errors than low skill participants (*M* = 22.75, *SD* = 11.98) and this skill effect was significantly larger in the Accuracy condition (*M* = 15.39, *SD* = 11.28) than in the Speed condition (*M* = 26.92, *SD* = 11.24). In terms of the significant main effect of distraction positions, overshoot errors were more frequent on distracted trials ($M = 21.79$, $SD = 13.16$) than non-distracted trials ($M = 19.00$, $SD = 10.73$), $F(1, 96) = 104.91$, $p < .001$, $\eta_p^2 = .52$. Within distracted trials, overshoot errors were more frequent following begin-subtask distractions ($M = 23.88$, $SD = 13.22$) than end-subtask distractions ($M = 19.83$, $SD =12.17$), $F(1, 96) = 9.54$, $p < .01$, $\eta_p^2 = .09$. Begin-subtask distractions also resulted in more frequent overshoot errors than mid-subtasks distractions, ($M = 21.67$, $SD = 13.85$) but this difference did not reach statistical significance, $F(1, 96) = 3.01$, $p =.09$. There was no significant difference between distractions at mid- and end-subtask, $F(1, 96) = 2.45$, $p =.12$.

Movement time. ANOVA results for movement time as seen in Table 4 revealed a significant main effect of skill, instructions and distraction positions. There were no significant interactions. Mean percentage of movement time plotted as a function of skill level, distraction positions and instructions group is presented in Figure 20. Overall, movement time was significantly faster in the high skill ($M = 1005.08$, $SD = 201.22$) than low skill condition ($M = 1339.21$, $SD = 380.52$). In terms of the main effect of instructions, movement time was significantly slower in the Accuracy ($M = 1209.74$, $SD = 311.90$) than Speed condition ($M = 1130.47$, $SD = 346.22$). For the main effect of distraction positions, contrast results revealed that movement time was significantly faster on non-distracted trials ($M = 1074.10$, $SD = 283.04$) compared to distracted trials ($M = 1202.64$, $SD = 359.58$), $F(1, 96) = 104.91$, $p < .001$, $\eta_p^2 = .52$. Within distracted trials, mid-subtask distraction ($M = 1295.61$, $SD = 370.95$) resulted in significantly slower movement time than distractions at begin-subtask ($M = 1207.36$, $SD = 382.06$), $F(1, 96) = 14.89$, $p < .001$,

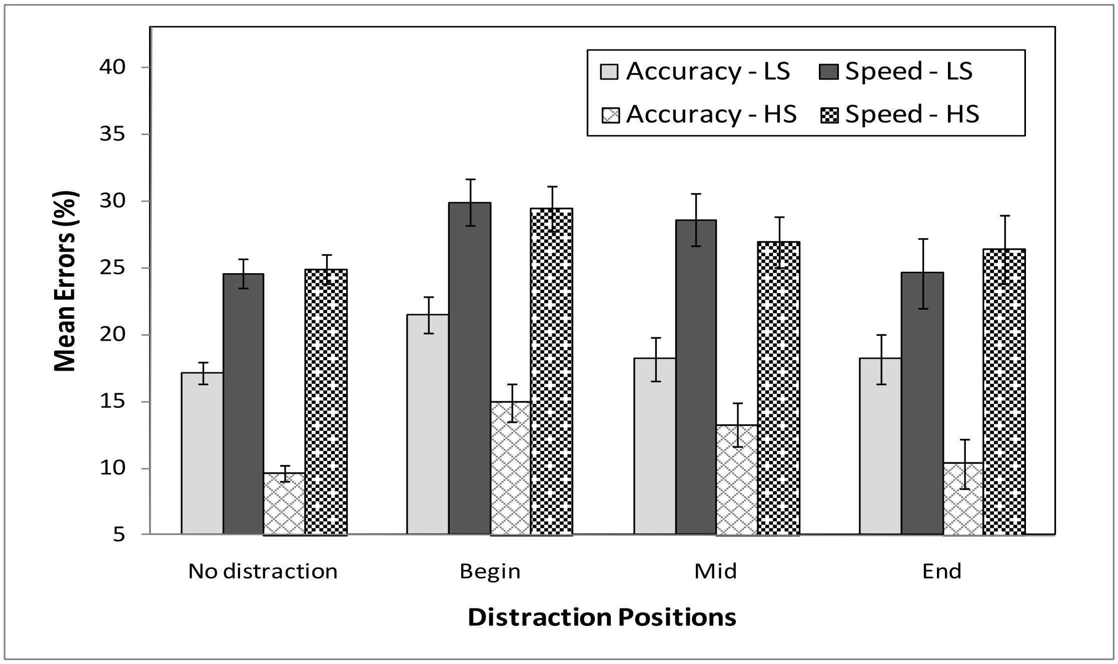


Figure 19. Mean percentage of overshoot errors as a function of skill level, distraction positions and instruction group.

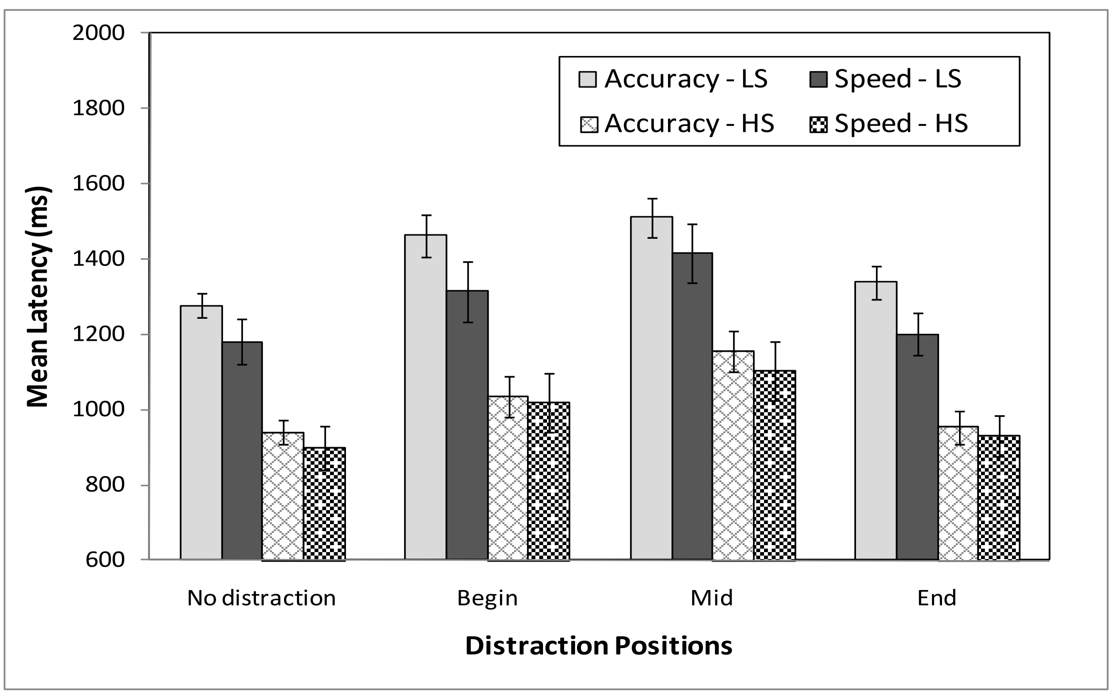


Figure 20. Mean movement time as a function of skill level, distraction positions and instruction group.

η_p^2 = .14; and end-subtask (*M* = 1104.97, *SD* = 297.60), $F(1, 96) = 52.48$, $p < .001$, η_p^2 = .36. Begin-subtask resulted in significantly slower movement time than end-subtask distractions, $F(1, 96) = 15.10$, $p < .001$, $\eta_p^2 = .14$.

4.4.4 Performance on the distraction task

As in Experiment 1, the tone accuracy data was first analysed to verify whether there was a difference between tone trials which required a key press response and tone trials which did not. Note that errors on the tone task were evaluated in terms of missed hits (not responding to a tone which required a response) and false hits (responding to a tone which did not require a response). There was no significant difference between respond and ignore trials (which occurred with equal frequency), $t(99) < 1$, $p = .42$ hence tone trials were combined and the data was analysed using the same factorial mixed-model ANOVA used to analyse performance on the primary task: 2 x 2 x (4) mixed-model ANOVA with between-subjects factor variables: instruction groups (speed, accuracy) and skill level (low skill, high skill); and the within-subjects variable, distraction positions (begin, mid, end). Note that the 'no distraction' condition was not applicable to this analysis (i.e., tone task only relevant to trials with a distraction).

For tone accuracy, ANOVA results revealed a significant main effect of instructions, $F(1, 96) = 9.73$, $p < .01$, $\eta_p^2 = .09$; and distraction positions, $F(2, 192) = 3.32$, $p < .05$, η_p^2 = .03. The main effect of skill was not significant, $F(1, 96) = 1.78$, $p = .19$ and none of the interactions were significant: Instruction x Skill, $F(1, 96) < 1$, $p = .38$; Distraction positions x Instructions, $F(2, 192) < 1$, $p = .75$; Distraction positions x Skill, $F(1, 96) = 1.02$, $p = .36$; and Distraction positions x Instructions x Skill, $F(2, 192) < 1$, $p = .47$.

In relation to the significant main effect of instructions, as seen in Figure 21, overall the Accuracy group (*M* = 3.40, *SD* = 5.96) made fewer errors on the tone task than the Speed group (*M* = 6.50, *SD* = 9.94). For the significant main effect of distraction positions, contrast results revealed that errors were significantly fewer when the tone occurred at mid-subtask (*M* = 4.10, *SD* = 7.81) than at end-subtask (*M* = 5.70, *SD* = 8.69), $F(1, 96) = 6.75$, $p < .05$, $\eta_p^2 = .07$.

For tone latency, there was a significant main effect of distraction positions, $F(2, 192) = 7.34$, $p < .001$, $\eta_p^2 = .07$ but a significant interaction with skill qualifies the interpretation of this main effect, $F(2, 192) = 4.20$, $p < .05$, $\eta_p^2 = .04$. As can be seen in Figure 22, low skill performers were significantly slower than high skill performers to respond to a tone when it occurred at begin-subtask compared to mid-subtask, $F(1, 96) = 5.77$, $p < .05$, $\eta_p^2 = .06$; and at end-subtask compared to mid-subtask, $F(1, 96) = 6.06$, $p < .05$, $\eta_p^2 = .06$. There was no significant difference between low and high skill performers at begin- and mid-subtask, $F < 1$, $p = .80$. No other effects were significant for tone latency: skill main effect, $F(1, 96) = 1.57$, $p = .21$; instructions main effect, $F(1, 96) < 1$, $p = .74$; Instruction x Skill, $F(1, 96) < 1$, $p = .67$; Distraction positions x Instructions, $F(2, 192) = 2.24$, $p = .11$; and Distraction positions x Instructions x Skill, $F(2, 192) = 2.20$, $p = .11$.

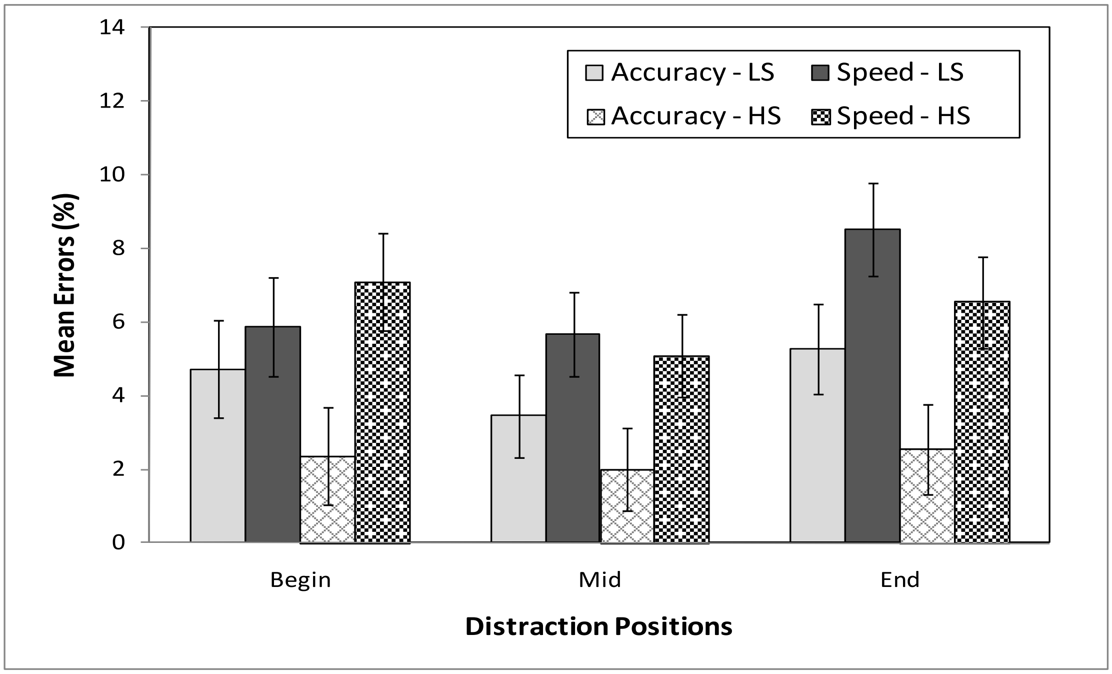


Figure 21. Mean percentage of errors on the tone task as a function of skill level, distraction positions and instruction group.

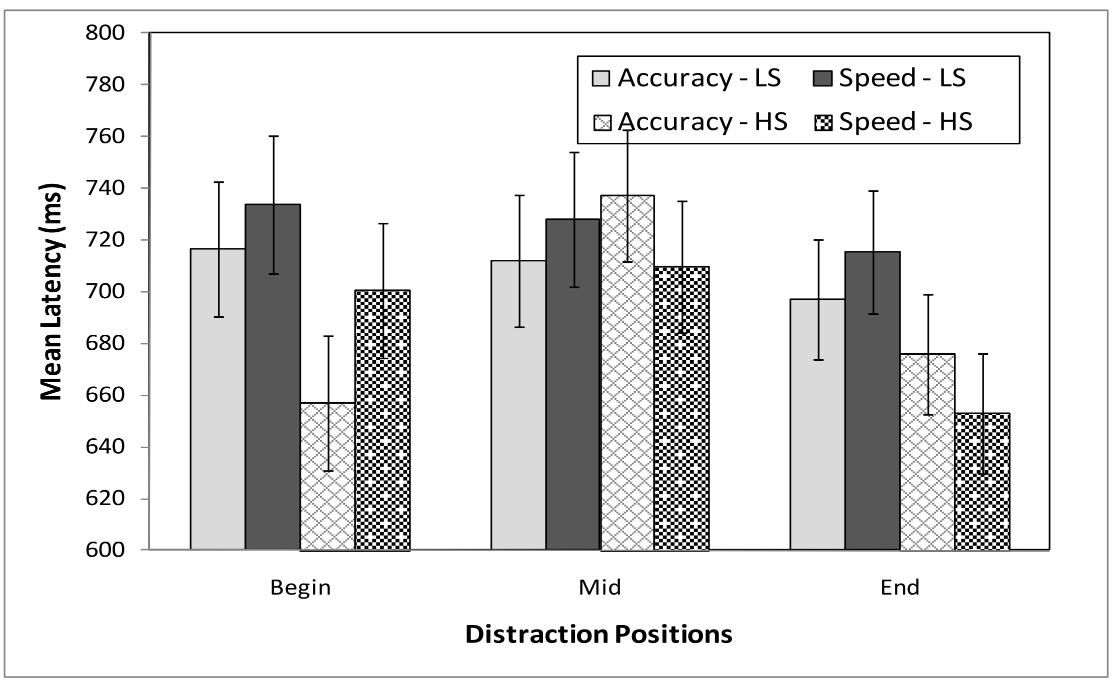


Figure 22. Mean latency on the tone task as a function of skill level, distraction positions and instruction group.

4.5 Discussion

Experiment 2 aimed to extend our understanding of the allocation of attention during skilled performance. Specifically, the study examined whether attention is allocated differently depending on the speed and accuracy with which a task is performed. Overall similar results were found to the first study but there were several extensions. To summarise, this study found that skill development reduced capacity demands but a level of attention or self-regulation was still involved at critical points in order to avoid errors. These critical points were the same for low and high skill participants. These results replicate the results of the previous study. There were also three additional findings in this study. First, although skill development does not change where attention is allocated there was evidence that it does reduce the amount of attention required at critical points. Secondly, there was evidence that performance instructions moderated the amount of attention required at these critical points. Thirdly, the instruction manipulation produced the expected trade-off effects in both low and high skill performance which is contrary to recent suggestions that the principles of SATO do not generalise to well-practised performance (e.g., Beilock et al., 2004). In general, these results suggest that control structures that govern performance do not differ greatly as a function of skill. The single dominant effect of skill development in this study was to reduce attentional demands but a level of attentional constraints remained.

One of the contributions of this study relates to the manipulation of speed versus accuracy in order to understand better the particular circumstances in which SATO influences skill learning and skilled performance. With regards to skill learning under speed versus accuracy instructions, the study found that practice under accuracy stress significantly improved performance for all variables measured. The pattern of improvement followed a power function of practice (i.e., rapid improvement at the start of practice, followed by diminishing improvements with further practice and asymptoted to a constant level). Practice under speed stress also resulted in marked reductions in decision time, movement time and overshoot errors but reduced wrong way errors only on trials with high target probability (i.e., 100% and 75%). Wrong way errors on trials with low target probability (i.e., 25%) increased with practice and wrong way errors on trials with equivocal target probability (i.e., 50%) remained essentially constant with practice. These results replicate those found in the previous study under the instruction to optimise both speed and accuracy which confirms the speculation that participants in that study were emphasising speed over accuracy despite frequent and explicit instructions to focus on both.

With regards to the skilled performance under speed versus accuracy instructions, as predicted by the large literature on SATO, all participants' performance showed the expected trade-off effects under speed versus accuracy instructions (Pachella, 1974; Pachella & Pew, 1968; Rabbitt, 1989; Sperling & Dosher, 1986; Wickelgren, 1977). Specifically, both low and high skill participants performed faster but less accurately under speed instructions and performed slower but more accurately under accuracy instructions. These results are inconsistent with Beilock's et al. (2004) finding that expert golfers' performed more accurately under speed stress than accuracy stress. The reason for this discrepancy may relate to the nature of the movements involved. A golf swing can be conceived to be more like a rapid-ballistic movement which may benefit from speed stress because conscious attention might interfere with a process that is best left to unfold on its own. The pointer swing in this study may be less ballistic and more attention-demanding than a golf swing. The finding that SATO influenced both low and high skill performance in this study suggests that the nature of movements may be a more influential factor in determining the generalisability of the principles of SATO than level of practice as suggested by Beilock et al.

Another fundamental contribution of this study relates to the manipulation of speed versus accuracy to understand better the attentional processes governing performance of low and high skill individuals. The results of this study suggest that skill level and performance instructions may be important factors in determining the *amount* of attention allocated during task execution but appear not to be important factors in determining *where* attention is allocated during task execution. Specifically, high skill participants were as susceptible to the negative effects of distraction as low skill participants at critical points during task execution which was at the beginning and toward the end of a subtask. These critical points were the same for low and high skill participants and the same for the speed and accuracy group. The finding that end-subtask distraction was more disruptive to subsequent decision time under accuracy than speed instructions provides evidence that performance instructions moderated the amount of attention required at this critical endpoint. As discussed in the previous study, the negative effect of end-subtask distraction can be attributed to disruptions to attentional processes involved in response selection (Buckolz & Hall, 1982; DeJong, 1993; Keele, 1973; Logan & Burkell, 1986) and is consistent with the prediction of Reason’s (1990) theory. Assuming that performance under accuracy stress involves more frequent conscious monitoring of performance, the finding that end-subtask distraction was more disruptive to subsequent decision time under accuracy than speed instructions provides further support for Reason’s checking hypothesis. Also consistent with the previous study, the negative effect of begin-subtask distraction can be attributed to disruptions to attentional processes involved in the organisation of action programs. These results support research in the motor control literature suggesting that distraction at the start of movement is most disruptive because this is where a response is programmed and triggered into action (Adams, 1971; Castiello & Umilta, 1988; Keele, 1973; Ketelaars et al., 1999; Netick & Klapp, 1994; Schmidt, 1975).

No support was found for Botvinick and Plaut’s (2003, 2004) alternative prediction about the disruptive effects of mid-subtask distraction on task performance. Even when performance on the task was significantly slowed down by requiring participants to focus only on being accurate no support was found for the disruptive effect of mid-subtask distraction on error rate which is contrary to Botvinick and Bylsma’s (2005) empirical findings. On the primary task, the main impact of mid-subtask distraction was to slow down movement which is not a surprising interference since the distraction occurred during the movement interval. Interestingly, on the secondary task, both low and high skill participants were more accurate at responding to a tone (i.e., fewer missed and false hits) when it occurred mid-subtask suggesting that it was easier for participants to process the tone when it occurred at this middle point. In addition to the finding that a distraction mid-subtask was also least disruptive to errors on the primary task, these results suggest that there was more spare attentional capacity during the middle of movement compared to other subtask points which is contrary to Botvinick and Plaut's conception of mid-subtask susceptibility.

Overall, high skill participants performed better on the primary task and were better at handling distractions than low skill participants. These results suggest that skill development results in the reduced need for attention but does not eliminate the need for attention especially at critical points during task execution. These results support suggestions that attention continues to play an important role in mediating the behaviour of skilled individuals (Chen, 1985; Ericsson, 1998; Haider & Frensch, 1999; Logan, 1988; Pashler, 1998). The current findings are in keeping with previous experiments showing persistent attentional constraints even after extensive practice (Ahissar et al., 2001; Dutta & Walker, 1995; Van Selst et al., 1999). These results are contrary to several experiments that found that skilled performers were unaffected by the addition of a secondary task compared to lesser skilled performers' whose performance showed significant decrements under dual-task conditions (Beilock et al., 2002; Leavitt, 1979; Parker, 1981; Smith & Chamberlin, 1992). These findings were used to support the argument that skilled performance is not subject to attentional limitations because it is associated with automatic processing which does not draw on attentional resources (Hasher & Zacks, 1979; LaBerge & Samuels, 1974; Posner & Synder, 1975; Shiffrin & Schneider, 1977). The reason for the discrepancy between the findings in the present experiments and these previous studies are not entirely clear but an important difference between the present study and previous studies concerns the nature of the tasks used.

Specifically, a commonly cited reason for potential discrepancy in results of dual-task studies is that the secondary task used may not be challenging enough to cause performance decrements in the primary task. Although the auditory discrimination task used in this study was a relatively simple task, it was sufficiently challenging to cause impairment to the tracking task. The task was simple in the sense that it involved only two auditory stimuli that varied only on one dimension (pitch). However, the tones used were relatively close in pitch (600 and 700 Hz) compared to other tone based distraction task used in previous research with disparities of over 500 Hz (Koch, 2009; Pashler & Johnson, 1989; Schumacher et al., 2001) and hence demanded greater attention resources in order to make this fine relative decision.

Although error rate on the tone task was relatively low for both the low (5.6%) and high skill group (4.3%) it took low skill participants on average 717 ms and high skill participants on average 689 ms to respond to the tone which is not a short amount of time in the context of typical RT data. This suggests that the tone discrimination task was cognitively taxing. One way to clarify this issue is to manipulate the cognitive load of the tone task between participants. For example, Hochman and Meiran (2005) tested three load conditions where pairs of tones differing in pitch were presented one immediately after the other and the task was to ignore the interference (low load). One of the tones within a pair was presented and the task was to decide whether the tone was high or low pitch (moderate load).Tone pairs differing in pitch were presented and the task was to decide whether the second tone in the pair was higher or lower than the first one (high load). By manipulating load the study was able to reveal how demanding a certain cognitive process was. Future research should assess the possibility of doing the same.

Another possibility for the observed interference in this study relates to the potential for structural interference. Although the primary and secondary task relied on two different response modalities (visuomotor and auditory) responses to the primary task were made using the left hand to control a computer mouse and responses to the secondary task was made using the right hand to tap the spacebar key. It is possible that the task interference observed in the present experiments arose from the need to coordinate the two manual responses. For example, McLeod (1980) showed that when the distraction and the primary task comprised different response modalities (manual or vocal) interference was significantly reduced relative to when the secondary task response was of the same modality as the primary task (manual response). However, if interference observed in the current studies is attributable to some aspect of concurrent responses then there should only be an interference effect on tone trials which required a key press response. The study found no performance difference between respond and ignore tone trials indicating that a response-based interpretation of the interference results is unlikely. Given that a tone must be perceived and processed/analysed for both respond and ignore trials a cognitive-based interpretation of the results is more likely.

Differences in the primary tasks used may account for the discrepancy between this and previous studies demonstrating no or minimal interference by a secondary task on skilled performance. The tracking task used in this research had several unique features which may have made it more attention-demanding and may account for its susceptibility to the negative effects of distraction. First, the fact that the task involved anti-stereotypical movement (i.e., tracking in reverse) may well account for why the task was attention demanding even for high skill participants. This novel feature of the task may have competed with a relatively innate tendency to move in a conventionally compatible way, although of note, high skill participants did receive over 1600 practice trials on the task and demonstrated an asymptotic level of performance on all the performance variables analysed during the skill training phase. Nonetheless, it is possible that distraction caused what Schmidt and Young (1987) referred to in their article on negative skill transfer as a temporary state of cognitive confusion which may have resulted in a ready reversion back to stereotypical movement. However, if distraction did produce temporary confusion in relation to the direction of movements its negative effects should have occurred across all distraction locations but this was not the case. A consistent finding across two experiments was that distraction had specific disruptive effects at the beginning of a subtask on response execution and toward the end of a subtask on subsequent response selection is more consistent with an explanation based on attentional resources. These results suggest that distraction drains limited attentional resources at critical points so performance is impaired only where attention is needed most.

In relation to the specific role played by attention in the maintenance of tracking proficiency in the present experiments, the current results suggest that attention plays a role in response preparation processes. In the present experiments, two aspects of response preparation were distinguished: selection and programming. Both were found to be attention demanding processes which is consistent with previous research (Fagot & Pashler, 1992; Ketelaars et al., 1999; Netick & Klapp, 1994; Pashler, 1989) but the locus of interference was different for the two processes: at the start of response for response programming and toward the end of a response for subsequent response selection.

In addition to the factors mentioned, the present experiments differed from many previous experiments on the feature that distraction in this research was presented systematically at defined points during task execution rather than presented randomly as is commonly the case in previous distraction studies. The presentation of distracting stimuli at random interval washes out any negative effects of distraction at critical points which may account for differences in the current results. The current results suggest that the timing of a distraction has an important influence on performance and that the mere presence or absence of a distraction alone may be insufficient to account for the complexities of human performance. These results corroborate and extend previous studies that have also manipulated the temporal interval by which the appearance of distracters precede a target response (Machado, Wyatt, Devine & Knight, 2007; Davids, 1988; Grice, Boroughs, & Canham, 1984; Li et al., 2008; Rose & Christina, 1990; Sanders & Lamers, 2002).

In terms of what caused the interference between the two tasks, the fact that interference occurred between two relatively separate modality tasks (visuomotor tracking and auditory discrimination) suggests that the limitations are likely to arise from some shared source that governs both tasks. This source may be a common limited processing capacity pool (Kahneman, 1973) but there are also other possible explanations. The finding that tracking performance was degraded at specific points during task execution suggests that the interference could involve a demand for a limited capacity response *stage*. These critical point results suggest that a processing stage interference may have played a greater role in determining time-sharing decrements than did a general capacity interference. There are many different theoretical approaches to explaining dual task interference (Pashler, 1994) but a more important implication of this research is that practice does not eliminate central interference. The results of this research suggest that practice simply reduces preparatory demands but there is no evidence that practice causes the central interference to disappear although this question needs to be investigated more thoroughly using different types of tasks and different means to induce distraction.

CHAPTER 5

EXPERIMENT 3: THE EFFECT OF DISTRACTION ON SKILLED PERFORMANCEIN A SIMULATED PILOT CHECKLIST TASK

5.1 Overview of Chapter 5

A primary aim of this thesis was to further our understanding of the role of attention during skill-based behaviour especially the role of distraction as a major source of skill-based errors. The results of the first two experiments provide support for Reason's (1990) original conception that distraction is most disruptive when it occurs at the end of a subtask over Botvinick and Plaut's (2003, 2004) more recent conception of the particular susceptibility of midway through a subtask. Admittedly, the novel psychomotor task used to obtain these results was quite different to Botvinick and Bylsma's (2005) coffee-making task. Hence it remains unclear as to whether the results obtained were due to the distinct nature of the novel task used (i.e., a task-specific phenomenon). The aim of Experiment 3 presented in this chapter was to clarify this issue by using a task more similar to Botvinick and Bylsma's coffee-making task. The task chosen was a simulated checklist task which pilots performed under conditions involving frequent distraction. The results of this study suggest that the nature of the task is an important factor in determining the precise effects distraction has on performance.

5.2 Introduction

The findings of the current research so far were contrary to Botvinick and Bylsma's (2005) study which found that decision point errors (i.e., errors at transition between subtask points) in a coffee making task were more frequent following a distraction occurring toward the middle of a subtask sequence than following a distraction at the end of a subtask. This research showed consistent results in two studies that errors (specifically defined as wrong way errors, which was the equivalent to Botvinick and Bylsma's decision point errors) were more frequent following a distraction occurring at the end of a subtask than following a distraction toward the middle of a subtask.

An important difference between the studies which may account for the discrepant results concerns the nature of the tasks used. The primary task used in this research was a tracking task which required participants to track a target light which moved between different positions on a computer screen. The appearance of the target light dictated where participants had to move next. Hence there was no requirement for participants to remember their place in the tracking sequence after they were distracted. The memory requirement of this task was to maintain task instructions (speed or accuracy or both) to remember how to respond the distraction task (low tone or high tone) and to remember that movement should be anti-stereotypical when initiated (left or right).

Botvinick and Bylsma's (2005) coffee making task relied on working memory in a different way. The skill was based on a sequentially dependent task representation in which initial steps and memory for their outcomes are used to generate subsequent steps to final task completion. In contrast, in the tracking task used in this research, task knowledge was not organised such that the execution of each element of performance was dependent on the maintenance of every prior step. Hence it may be the sequentially dependent interweaving of processing and information-storage demands that makes a skill task susceptible to a distraction mid-subtask.

The auditory distraction task used in the current research was also different to the mental subtraction task used by Botvinick and Bylsma (2005). As well as being different in modality, unlike Botvinick and Bylsma's study, participants were not required to stop what they were doing when a distraction occurred. The tracking task could still be continued while attending to the distraction task (participants controlled tracking movements with their right hand and responded to the auditory stimuli with their left hand). In this sense, attention was divided whereas in Botvinick and Bylsma's study participants had to completely disengage from the primary task at hand. Hence the process of reorientation in Botvinick and Bylsma's task involved not only a physical reorientation (i.e., visual re-acquisition of the primary task) but also a memory reorientation for important task information (e.g., where one left, what to do next). Hence it may be this more complete disengagement from the task which accounted for the study's finding of mid-subtask susceptibility.

Given that the tasks used were different across this research and Botvinick and Bylsma (2005) it remains unclear as to whether the discrepant results reflect task-specific phenomena or not. Hockey (1970) suggested that the type of task implemented plays a major role in determining the nature of distraction effects on performance. Indeed there is evidence that the nature of the primary task significantly alters both the likelihood of observing a disruptive effect of distractions (Beaman & Jones, 1997;

Henson, Hartley, Burgess, Hitch & Flude, 2003; Jones & Macken, 1993) and the nature of the effect observed (Buchner, Irmen & Erdfelder, 1996; Neely & LeCompte, 1999). In light of this evidence, the aim of the study presented in this chapter was to test the effect of distraction at different subtask points using a distinctly different task paradigm. The task chosen was a simulated checklist task which pilots performed under conditions involving frequent distraction. Pilots are expected to use checklists routinely, often from memory first and then crosschecked with the written checklist. The task is therefore working-memory intensive and based on a hierarchical and sequentially dependent task representation. The use of a checklist task also has several advantageous over Botvinick and Bylsma's (2005) coffee-making task such as the sequence of subtasks in checklists are longer and the actions required are more complex and therefore serve as a better task to test the effect of mid- and end-subtask distractions on skill-based errors. Moreover, unlike coffee making, flight checklists must be performed methodically, one item at a time in an unvarying sequence. There is a "right order" and a "right way to perform flight checklists (Degani & Wiener, 1990; NTSB, 1988b)..

Understanding the nature and causes of checklist errors is also important because they can have serious consequences for flight safety. There is widespread documentation that checklist omissions, incorrect use and simple non-use of flight checklists occur relatively frequently and contribute to a substantial number of aircraft accidents and incidents (Degani, 1992, 2002; Degani & Wiener, 1990; Diez, Boehm-Davis & Holtz, 2003; Helmreich, Wilhelm, Klinect & Merritt, 2001). Many investigations by the National Transportation Safety Board (NTSB) have revealed that the aircraft was not properly configured for flight as a result from improper checklist use (NTSB, 1969, 1975, 1982, 1988a, 1988b, 1989, 1990, 1997). For example, a review of the NTSB accident data revealed that during the period 1983 to 1993 approximately 279 aircraft accidents occurred where the checklist was not used or followed (FAA, 1995). The 279 accidents were responsible for approximately 215 fatalities and over 260 injuries. Similarly, data from the Flight Safety Foundation (FSF, 1998-1999) based on the analysis of 287 fatal approach-and-landing accidents that occurred in 1980 through to 1996 revealed that the omission of a required action or an inappropriate action is the most frequent (72%) causal factor in incidents and accidents.

There is also widespread evidence, although mostly anecdotal, that checklist omissions or inappropriate actions were often the result of an interruption or distraction. For example, in 1987 in Detroit, Michigan, pilots configuring a DC-9 for takeoff was interrupted by a request from ATC while performing the checklist guided preparation. Upon resuming, they missed the critical step of setting the flaps which were necessary to gain adequate lift on takeoff (Degani & Wiener, 1993). In the resulting crash more than 100 lives were lost. Similarly but more recently, in 2008, a SpanAir Flight JK 5022 crashed in Madrid just after takeoff, killing 153 of the 172 people aboard. An interim report was released on 17 August 2009 confirming preliminary reports that the crash was caused by an attempt to takeoff with the flaps and slats retracted. The cockpit recordings revealed that the pilots omitted the “set and check the flap/set lever and lights” item in the After Start checklist. In the Takeoff Imminent verification checklist the co-pilot just repeats the flaps and slats correct values without actually *checking* them, as shown by the physical evidence. The report found that the flight crew was distracted twice during their pre take-off checks and then there was a technical anomaly whereby tripping a circuit breaker to overcome a minor fault appears unbeknown to the crew to have disabled the takeoff configuration warning. These are just two of numerous reported cases of checklist errors resulting in serious injuries and loss of lives.

Besides evidence from accident reports, however, there is little systematic research investigating the role of distraction as a major source of checklist errors. Given that checklist errors occur relatively frequently and that the consequences of disrupted or interrupted checklists can be serious more research attention on this topic is needed. The primary goal of this study was to further our understanding of why skill-based errors occur by examining the effects of inattention on checklist errors due to distraction. Specifically, the aim was to investigate the effects of timing of distraction on checklist errors by testing Botvnick and Plaut's (2003, 2004) and Reason's (1990) theoretical predictions about the disruptive effects of mid- versus end-subtask distraction, respectively.

In the current study, pilots performed a skilled checklist task in a flight simulator and were distracted at mid and end points during the checklist procedure to disrupt performance and produce error. If skill-based errors occur because distraction degrades task context information then as predicted by Botvinick and Plaut's (2004) theory, and as demonstrated by Botvinick and Bylsma (2005) empirical study, checklist errors should be more frequent following a distraction toward the middle of a subtask. If, by contrast and in accord with Reason's (1990) prediction, skill-based errors are due to a failure to perform a conscious checking operation then there should be more checklist errors following a distraction occurring at the end of a subtask.

5.3 Method

5.3.1 Participants

A total of 30 general aviation student pilots (25 male, 5 female) aged 17 to 24 years (M = 20.31; SD = 1.44) from the University of New South Wales volunteered for the research. There were 15 participants in the second year of a three-year Bachelor of Aviation Flying degree and 15 participants were in the final year of the degree. Participants had an average flying experience of 128.23 hr (SD = 106.14) and had flown an average of 20.71 hr (SD = 20.72) in the last 90 days. Amongst the participants, 15 had a restricted pilot license, two held a private pilot license and 13 held a commercial pilot license. Participants were tested individually in a single session lasting approximately 90 min and received a double movie pass for their participation.

5.3.2 Design

A 2 × (3) between-within subjects design with one between-subjects variable, study year (second versus third) and one within-subjects variable, distraction positions (no distraction, mid, and end) was used.

5.3.3 Apparatus & materials

Experiment 3 was performed using two IBM-compatible PCs that were linked via a network adaptor. One PC was located inside a mock cockpit and provided a display of the flight instruments of a PA 28/161 Piper Warrior II (see Figure 23). Another PC was connected to an LCD projector which displayed a 70 degree field of forward vision in front of the cockpit. The cockpit contained flight controls including a Precision Flight Controls Cirrus II yoke and rudder setup (see Figure 24). The flight simulator software used was X-Plane 8.60™ by the Laminar Research Corporation. The simulated aircraft was a single-engine fixed-gear aircraft used for flight training that was familiar to all the pilot participants. A Sony DCR SR85 digital camcorder was mounted directly above the flight simulator console.

Figure 23. Task display.

Figure 24. Flight simulator console.

Materials used in the experiment were a consent form, participation information sheet, debrief information sheet and a demographics questionnaire which included general background questions (i.e., age, gender, study year, license type, total flying hours and recency of flying hours) as well as three specific questions about checklist use: (1) “How often do you use the prestart checklist when flying?” (1 = never; 2 = seldom; 3 = sometimes; 4 = often; 5 = always); (2) “At this point in your training, how well do you know the prestart checklist?” (1 = not well at all – need to refer to the written checklist; 2 = slightly well; 3 = moderately well; 4 = well; 5 = very well); and (3) “How similar is the prestart checklist used in this research to the one you are trained on?” (1 = completely different; 2 = slightly similar; 3 = moderately similar; 4 = very similar; 5 = identical).

5.3.4 Checklist task description

The primary task was a prestart checklist procedure, which is one of ten ‘normal’ checklists used to configure an aircraft at different phases of flight, and are an integral part of standard operating procedures.. Note that participants were not required to do any flying in the simulator. The primary task was to perform the prestart checklist which is performed *before* starting the aircraft engine. The prestart checklist used in the current study was the same one used in the pilot training course at the University of New South Wales. As second- and third-year pilot students were trained using a different checklist, two versions of the prestart checklist were used in the current study (Table 5). Although using two versions of the prestart checklist was not methodologically ideal it was deemed necessary in order to keep the checklist memory skill intact for each study year.

As seen in Table 5, there were 15 items in both versions of the second- and third-year prestart checklist. There is a left-hand and a right-hand column to each checklist. In the left column is the switch or control that needs to be changed or confirmed. In the right column is the action that needs to be taken with the switch or control. The left column is referred to as the challenge and the right column is referred to as the response. They are called this because in completing checklists, pilots are “challenging” the checklist item to be changed to a predetermined “response”. The written checklists were laminated and printed on green paper.

The procedure used in the current study for completing the checklist was identical to that taught in the training course at the University of New South Wales. Specifically,

Table 5

The checklist task used by second- and third-year pilot participants.

	Second-year checklist		Third-year checklist	
	Challenge	Response	Challenge	Response
1	Seats and harnesses	Adjusted and secured	Seats and harnesses	Adjusted and secured
2	All switches and avionics	Off	Trims	Set
3	Master switch	On	Flaps	Zero
4	Park brake	Pressure checked/set on	Fuel	On – left or least
5	Trims	Checked/set for takeoff	Flight controls	Full, free and correct sense
6	Fuel selectors	Left or least	Avionics and electrics (beacon remains on)	Off
7	Clock	Functioning and correct time	Carburettor heat	Cold
8	Throttle	Set	Mixture	Rich
9	Mixture	Rich	Throttle	Set
10	Carburettor heat	Cold	Master switch	On
11	Circuit breakers	Checked	Fuel pumps	On/pressure checked
12	Fuel pumps	On/pressure checked/off	Beacon	On
13	Audio selector panel	Set	Circuit breakers	Checked
14	Assigned altitude indicator	Set zero	Primer	As required and locked
15	Anti collision light	On	Engine	Cleared and start

participants were required to complete the checklist entirely from memory first and then cross-checked with the written checklist as a confirmation that everything was done correctly and nothing omitted. The procedure commenced when the pilot stated the name of the checklist to be completed “Commencing Prestart checklist”. Each challenge was spoken aloud (e.g., ‘Flaps’), the specified task then performed (e.g., set flaps to zero) and the response was then concluded out loud (e.g., ‘Flaps zero’). This is called the “say-do-conclude” method and is widely considered as the best approach for completing checklists because everything is verbalised out loud and each item in the checklist is to be carried out methodically, one item at a time in an unvarying sequence (Degani & Wiener, 1990). The checklist was complete when the pilot announced “Checklist complete”.

5.3.5 Distraction task description

The distraction task was a simple mental addition task. This task was chosen because it was similar to the distraction task used in the study by Botvinick and Bylsma (2005). The task was to add one to every digit of a spoken four-digit number (e.g., 4236 = 5347). As in Botvinick and Bylsma’s study, when a distraction occurred participants were required to stop what they were doing, to place both hands on the flight wheel and to state the answer to the problem aloud. The requirement to place both hands on the flight wheel as soon as a distraction occurred was designed to minimise demands that might elicit the application of control strategies (e.g., physically placing a finger as a marker on the last completed item). After the distraction, participants resumed the checklist task from where they left off. The aim of the distraction task was to momentarily shift attention away from the checklist task towards the distracting stimuli in order to induce errors on the checklist task.

Simple mental addition is advantageous as a laboratory distraction task because it is relatively novel and hence its learning history can be controlled (Geary & Wiley, 1991). Simple mental addition has been used in numerous previous studies to manipulate cognitive engagement and has been shown to be an effective distraction task (Botvinick & Bylsma, 2005; Geary & Wiley, 1991; Harbluk, Noy, Trbovich & Eizenman, 2007). Moreover, because it is based on common arithmetic operations carried out in a particular order it is also similar to the kinds of situations pilots encountered in the real world. For example, it mimics pilot communication with ATC calls. The task is also simple enough so that all participants could perform it without training (Geary & Wiley, 1991; Harbluk et al., 2007).

5.3.6 Procedure

The procedure for this experiment was approved by the local ethics committee. Participants were tested individually in a quiet room on campus. The procedure included a revision phase (no distraction) and a testing phase (with distraction). At the start of the experiment, participants were informed that the experiment session was videotaped and that participation was voluntary and written consent was required. Participants then read a general information sheet about the study, provided written consent for their participation and filled in a general demographics sheet. Participants were then given verbal instructions that described the checklist task and the experimenter provided a practical demonstration of the say-do-conclude checklist method.

Each checklist item was defined as a subtask. Mid-subtask distractions occurred during the “do” phase of the say-do-conclude method. To be more precise, the participant was distracted just as the hand touched the required switch or control. End-subtask distractions occurred during the “conclude” phase of each checklist item, that is, just as the hand began to withdraw from the switch or control. An initial pilot study using three participants also included items with begin-subtask distractions which occurred during the “say” phase. The pilot study revealed a strong tendency for participants to simultaneously initiate the required action while verbalising the name of the checklist item out loud (e.g., while saying the word ‘Flaps’ participants would simultaneously reach for the flaps). Participants found it difficult to inhibit this reaching action. Given the difficulty associated with operationalising the beginning of a subtask it was decided to exclude begin-subtask distractions from the main study’s design.

Performance of the checklist task was interrupted on approximately 50% of the items. Each repetition of the checklist procedure consisted of 15 items of which four items had a mid-subtask distraction, four items had an end-subtask distraction, and seven items with no interruption. Participants performed 15 repetitions of the checklist procedure in a session lasting approximately 1.5 hr. The timing of the distraction was based on a pseudorandom item sequence protocol established before the session and different for each participant. The protocol indicated for each item in the session whether a distraction should occur and if so whether the distraction should occur at mid-subtask or end-subtask.

Two broad types of checklist errors were measured in this study: action slips and verbal slips. Verbal slips were associated with cases where call outs were wrong. Wrong call outs were possible during the ‘say’ phase (of the ‘say-do-conclude’ method) when the challenge was spoken aloud (e.g., touching the flaps and wrongly saying something like ‘fuel’) and during the ‘conclude’ phase when the response was concluded aloud (e.g., instead of saying ‘flaps zero’, wrongly saying something like ‘flaps off’).

Action slips were associated with errors in physical movement which included not carrying out a checklist item that should have been carried out (omitting an item, e.g., forgetting set flaps to zero); carrying out an inappropriate action (e.g., erroneously setting flaps to a non-zero status) and carrying out an action in the wrong order (e.g., performing the set flaps actions in the wrong sequence order). Because the primary aim of this study was to examine errors in routine actions this necessarily meant that errors in the experiment would be relatively few. In view of this and in order to maximise the sensitivity of error detection the study adopted the same method used by Botvinick and Bylsma (2005) by also measuring '*micro slips'* (Schwartz, Reed, Montgomery, Palmer & Mayer, 1991) which were cases which an erroneous action is initiated but aborted (e.g., reaching for the wrong switch and quickly retrieving). The analysis proceeded on the assumption shared by Schwartz et al. that such partial errors stem from the same factors as completed errors and were counted as commission errors.

Revision phase. The main purpose of the first part of the experiment was to give participants the opportunity to familarise themselves with the flight console and to revise the checklist task in the simulated environment. Participants were given the printed checklist and were encouraged to use the printed checklist to help revise the items. Participants performed five repetitions of the checklist task entirely from memory. At the end of each repetition participants were required to cross check with the written checklist to ensure that no items were missed. The revision phase took approximately 15 min to complete.

Distraction phase. At the beginning of the distraction phase, participants were given two examples of the mental addition task. Participants were instructed to respond to the 4 digit problem as soon as they heard it by stopping what they were doing and placing both hands on the flight wheel. Participants were asked to state their answer to the problem aloud. Immediately after this they were to return to the checklist task picking up where they had left off. Testing did not begin until participants were clear with all task requirements. All participants performed 15 repetitions of the checklist task with distraction which took approximately 90 min. As with the revision phase, at the end of each repetition participants were required to cross-check with the written checklist. Participants were allowed to complete the checklist at their own pace. As would occur in real-life settings no specific instructions were provided regarding speed or accuracy. Upon completion participants were then debriefed and thanked for their participation.

5.3.7 Data analysis

Videotapes of the simulated checklist task were viewed by the researcher and errors were coded according to the classification of action slips and verbal slips. Data was analysed using a within-subjects ANOVA with repeated measures on distraction position (no distraction, mid and end) and Bonferroni tests were applied for post-hoc comparisons. In addition, participants' self-report data was analysed using independent *t*-tests to examine whether there were any group differences between second- and third-year student pilots in their checklist use. All other data analysis details were identical to Experiment 1 and 2.

5.4 Results

5.4.1 Self-report of checklist data

Overall 87% of participants reported that they always use a checklist when flying, 90% of participants reported that they knew the checklist well enough to perform it from memory and 93% agreed that the checklist used in the current research was identical or very similar to the one they are formally trained on. There was no difference between second-year and third-year students on the frequency of their checklist use, $t(28) = 1.41$, $p = .23$; familiarity with the checklist, $t(28) = 1.50$, $p = .15$; and similarity of the checklist used in the current experiment to the one used in formal training, $t<1$, $p = .67$. The means and standard deviations for these variables are shown in Table 6.

Table 6

Means and standard deviations of self-report checklist data for frequency of checklist use, familiarity with the checklist and similarity of the checklist used in the current experiment to the one used in formal training according to study year.

	Frequency of checklist use		***Familiarity with checklist***		***Similarity of the checklist***	
	M	***SD***	***M***	***SD***	***M***	***SD***
Second year	4.94	.25	4.69	.48	4.76	.19
Third year	4.46	1.33	4.23	1.01	4.85	.10

5.4.2 Performance on the checklist task under distraction

Performance on the simulated checklist task was first analysed using a 2 × (15) mixed-model ANOVA with between-subjects factor variables, study year (second versus third year); and the within-subjects variable, block (15 repetitions of checklist). The ANOVA results for action slips revealed no task repetition effects, $F<1$, $p = .15$, and no significant difference between second and third-year pilot participants and $F<1$, $p = .84$, and no significant interaction, $F<1$, $p = .73$. The same pattern of results was found for verbal slips. The data were therefore combined across the two study year and analysed using a within-subjects ANOVA with repeated measures on distraction position (no distraction, mid and end).

Action slips. As was anticipated, overall performance was highly accurate with 5.1% ($SD = 4.94$) of items containing an action slip of which 2.9% were micro slips ($SD = 3.21$). Mean percentage of action slips plotted as a function of distraction positions is presented in Figure 25. ANOVA results revealed a significant effect of distraction positions, $F(2, 58) = 10.16$, $p < .001$, $\eta_p^2 = .26$. Contrast results revealed that action slips were more frequent on distracted items ($M = 12.52$, $SD = 9.37$) than on non-distracted items ($M = 2.84$, $SD = 2.72$), $F(1, 29) = 33.92$, $p < .001$, $\eta_p^2 = .55$. There was no significant difference between mid- and end-subtask distraction, $F(1, 29) < 1$, $p = .82$.

Verbal slips. Mean percentage of verbal slips plotted as a function of distraction positions is presented in Figure 26. Overall 3.3% ($SD = 4.04$) of items contained a verbal slip. ANOVA results revealed a significant effect of distraction positions, $F(2, 58) = 18.46$, $p < .001$, $\eta_p^2 = .39$. Contrast results revealed that verbal slips were more frequent on distracted items ($M = 8.80$, $SD = 6.59$) than on non-distracted items ($M = 1.04$, $SD = 1.01$),

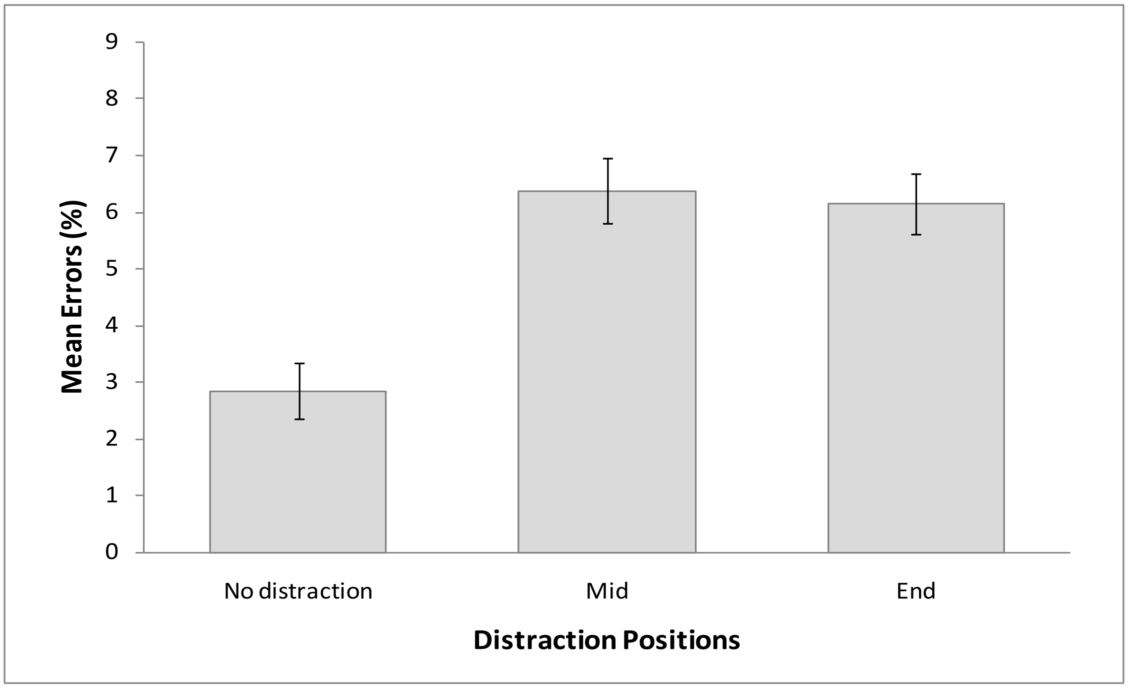


Figure 25. Mean percentage of action slips occurring on the current and next item as a function of distraction positions.

Figure 26. Mean percentage of verbal slips occurring on the current and next item as a function of distraction positions.

$F(1, 29) = 31.32$, $p < .001$, $\eta_p^2 = .53$. Within distracted trials, verbal slips occurred more frequently following a distraction at mid-subtask than at end-subtask, $F(1, 29) = 11.49$, $p < .01$, $\eta_p^2 = .28$.

5.4.3 Performance on the distraction task

Overall performance on the simple mental addition task was fairly accurate with 12% (*SD* = 11.65) of trials containing at least one error in the four digit problem. There was no significant difference between second-year (*M* = 9.81, *SD* = 8.05) and third-year (*M* = 14.29, *SD* = 14.17) students, $F(1, 28) = 1.22$, $p = .28$; and there was no difference in accuracy between mid-subtask (*M* = 11.64, *SD* = 10.15) and end-subtask (*M* = 12.46, *SD* = 13.14) distractions, $F<1$, $p = .55$.

5.5 Discussion

Experiment 3 aimed to further our understanding of the nature of attention allocation during the execution of routine skilled tasks. Specifically, the study tested Botvinick and Plaut's (2003, 2004) and Reason's (1990) differential theoretical predictions regarding the effect of distraction at mid- and end-subtask points on skill-based errors. In an experiment involving repeated performance of a routine checklist task under conditions involving frequent distractions the study found that student pilots made more checklist errors (action slips and verbal slips) when distracted than when not distracted. Although the occurrence of action slips did not differ depending on where a distraction occurred during the checklist task (mid- and end-subtask distraction were equally disruptive) verbal slips occurred more frequently following distractions that occurred midway through a subtask than following distractions that occurred toward the end a subtask. The latter result is consistent with Botvinick and Bylsma's (2005) empirical finding and provides support for Botvinick and Plaut's theory which predicts that distraction should be most disruptive when it occurs midway through a task.

According to Botvinick and Plaut's (2003, 2004) theory, distraction degrades task context information which relates to past, current and future steps in an action sequence (held internally) which is most susceptible to loss at mid-subtask. When the internal representation of a task context is distorted it occupies the wrong task space leading to confusion about the task context and therefore setting the scene for errors to occur. The finding that participants in this study were more likely to say the wrong things (i.e., to call out a wrong challenge or to conclude a wrong action status) when they were distracted mid-subtask provides support for this account of the way temporal task information are represented internally. The increase in verbal slips in this study when distracted at mid-subtask compared to no distraction was substantial (six-fold increase). Botvinick and Plaut's theory is supported by research on task structure (Boehm-Davis & Remington, 2009; Monk et al., 2004) showing that it is better to interrupt just after someone has completed a task or subtask rather than prior to the completion of the subtask because the latter adds to memory the state to the interrupted task in addition to what has already been stored.

The findings, however, do not completely support Botvinick and Plaut's (2003, 2004) theory because *actual errors*, that is, disruption to the physical skill (action slips) occurred equally frequently following a distraction at mid- and end-subtask. There are two possible reasons for the lack of differential effects of mid- versus end-subtask distraction in this study which is contrary to Botvinick and Bylsma's (2005) study.

First, it is possible that the difference might be due to the information-processing requirements of the checklist task which made larger demands on working memory than Botvinick and Bylsma's coffee making task. Although the checklist task has common elements with coffee making, at least in terms of the need to remember the order of subtask sequences they are distinct in several ways such as the fact that the sequence of subtasks involved in the checklist task was much longer (15 distinct checklist actions versus the three simple actions of adding coffee, cream and sugar) and the specific actions involved (i.e., configuring an aircraft) were more complex than the actions involved in making a cup of coffee. More than twice as many action slips were made in the present study (5.1%) than in Botvinick and Bylsma's study (1.9%) suggesting that indeed the checklist task was more challenging.

The finding that action slips occurred equally frequently following a distraction at mid- and end-subtask suggests that there may be two mechanisms at play, specifically, task context degradation as proposed by Botvinick and Plaut's (2003, 2004) and executive function failures such as a failure to execute an attentional check at end-subtask as proposed by Reason (1990). Indeed the micro slips observed in the present experiment may very well reflect the role that checking or monitoring operations play in routine skilled actions. Assuming that checking or monitoring of performance occurs more frequently when a task is more challenging and where errors are consequential as in the case of checklist errors and assuming that distraction also degrades task context then this may explain why there was no difference between distractions at mid- and end-subtasks for action slips in the current task. The resultant effect was an overall main effect of distraction.

Alternatively, action slips did not differ depending on where a distraction occurred during the checklist task because of the way mid- and end-subtasks were defined in this study. Specifically, mid-subtask distraction occurred just as the hand touched the required switch or control and end-subtask distractions occurred just as the hand began to withdraw from the switch or control. These two distraction points were temporally very close to one another, particularly on items which only required a simple switch or press of a button or control (e.g., turning the master on, setting the carburettor to cold, turning on the beacon, setting the throttle). Hence the lack of differential effect of distraction position on action slips in this study may be an artefact of the way mid- and end-subtask was defined. In contrast, verbal behaviour in this study was clearer (i.e., more well-defined) and hence may be a more reliable test of the effect of distraction positions. Assuming this is the case, the results are supportive of Botvinick and Plaut's (2003, 2004) task degradation theory. One way this study can be adapted to allow a better test of the two predictions is to use a simulated flying task such as a routine take-off and landing procedure instead of a manual checklist task. A simulator program will provide more precision both in terms of scheduling distractions and the measurement of dependent variables.

Given that no support was found for the particular susceptibility of mid-subtask distraction in the first two studies of this research using a primary tracking task, the results of this study suggest that it may be the sequentially dependent interweaving of processing and information-storage demands that makes a skill task more susceptible to a distraction mid-subtask. Specifically, unlike the tracking task, the checklist task used in this study was based on a sequentially dependent task representation, much like Botvinick and Bylsma's (2005) coffee making task. This meant that participants had to remember their place in the checklist sequence after they were distracted by finding the place where the task was left off (i.e., the specific step in the checklist) and then to recall what to say and do next. Across three experimental studies, the difference in the nature of the tasks used and the difference in the results obtained suggest that the nature of the task is an important factor in determining the precise effects distraction has on performance.

In general, these results provide further support for the role of distraction as a major source of skill-based errors. In particular, the results provide systematic evidence that distraction is a major source of pilot checklist errors which up until now has mainly been based on anecdotal evidence and accident reports (Degani, 2002; Degani & Wiener, 1990; Diez et al., 2003; Helmreich et al., 2001; NTSB, 1969, 1975, 1982, 1988a, 1988b, 1989, 1990, 1997). In this study, student pilots made over four times as many action slips and over eight times as many verbal slips when distracted compared to when they were not distracted. These rates are higher than typically reported effects of distraction on performance in immediate recall tasks, such as a mean increase in errors of up to 30% (Jones et al., 1996) or 50% (Ellermeier & Zimmer, 1997). The tasks used in these previous studies, however, were very simple in nature (as is typical of most experimental laboratory tasks) .They were not as working-memory intensive as the checklist task used in the present experiment and the actions involved were much simpler (key press response) compared to the actions involved in configuring an aircraft for flight.

These findings have important implications for practices and policies surrounding the use of checklists and flight safety in general by reducing errors associated with checklist completion. There are several strategies that pilots can use to minimise the negative effects of distraction during the performance of checklist tasks. For example, the Federal Aviation Administration (FAA, 1995) recommended distraction coping strategies such as advising pilots to stop and hold the checklist at the item where a distraction and or interruption occurred and when the checklist resumes to repeat the last completed item and continue with the rest of the checklist or to start the checklist over again. Indeed backtracking through previous steps was observed in this study on approximately 3% of distracted trials.

It has also been strongly recommended that anytime a checklist flow has been interrupted or an item placed on hold the checklist should not be stowed. It should be kept in hand or placed in a conspicuous area as a reminder that the list has not been completed. Operators should also ensure that company ground support personnel who communicate directly with flight crews are familiar with the procedures used on the flight deck and the need to avoid interrupting the crew during a checklist flow. Persons entering the flight deck to talk to the crew should make their presence known and unless an emergency exists to refrain from interrupting any flight deck activity or talking to the crew until the crew indicates that they have completed their task and acknowledges their presence. An example is the "sterile cockpit" rule which is an FAA regulation requiring pilots to refrain from non-essential activities during critical phases of flight normally below 10,000 feet.

The results of this study also extend the literature on checklist errors because much of the literature focuses only action slips (i.e., omitting an item or carrying out an inappropriate action). Research on checklist errors typically ignore the phenomenon of wrong call outs during the completion of a checklist and as a result relatively little is known about the circumstances in which such verbal errors occur, their implications and relationship with action slips. Although verbal slips (i.e., saying the wrong thing) may have less detrimental effects than action slips (i.e., doing the wrong thing) minimising their occurrence is still of practical significance (Billings & Cheaney, 1981; Degani & Wiener, 1990). Errors associated with wrong call outs are potentially dangerous because they are indicative of a degraded internal representation of the task context. As proposed by Botvinick and Plaut's (2003, 2004) theory, when the internal representation of a task context is distorted it occupies the wrong task space leading to confusion about the task context. Verbal slips can therefore affect the probability of subsequent errors. Although there was a low correlation between verbal slips and action slips in the current study (r = .35) nevertheless aviation is a field where even a minor slip can lead to disastrous consequences and hence all precautions should be taken.

The results of this study, however, must be considered in light of some limitations. The first limitation relates to the lack of differential effect of distraction position on action slips in this study which may be an artefact of the way mid- and end-subtask was defined. Because experimental control over the timing of a distraction relative to performance of a task is notoriously difficult to achieve (Altman & Trafton, 2002; Li et al., 2008) verbal slips might be a better test of distraction positions. Future research is required to establish whether the current results can be replicated reliably.

A second limitation of this study was that like Botvinick and Bylsma's (2005) study the current study did not measure latency which is important information for understanding potential speed-accuracy trade-off (SATO) functions (Pachella, 1974; Rabbitt & Banerji, 1989; Wickelgren, 1977). This study was aimed to confirm the results of the previous laboratory studies which measured speed and manipulated speed versus accuracy, therefore, the measurement of latency in this study was considered less important. Moreover, from a safety perspective, accuracy is a more paramount goal than speed when performing a flight checklist task. Pilots are, however, often under time pressure (e.g., time pressure from ground personnel to open a gate for another aircraft, pressure from ATC to expedite taxi or takeoff or to meet a restriction in clearance time, the pressure to keep on schedule when delays have occurred due to maintenance or weather, the inclination to hurry to avoid exceeding duty time regulations) and hence future research should attempt to assess both speed and accuracy measures.

Another limitation of this study was the use of second- and third-year student pilots who were trained on two different versions of the prestart checklist. The study found no difference, however, between study year on the frequency of checklist use and familiarity with the checklist. It is possible, however, that because participants were trainee pilots the results may not generalise to more experienced pilots. Nonetheless, all participants in the current study were licensed pilots had an average of 128 hr total flying experience, had flown an average of 20 hr recently (in the last 90 days) and were competent in relation to completing checklists which is one of the basic skills that pilots must demonstrate in order to pass licensing requirements.

In summary, from a theoretical perspective, the results of this study support Botvinick and Plaut’s (2003, 2004) model as a useful theoretical framework allowing predictions to be made the representation of task context information and the effect of interruption. The generalisation of Botvinick and Plaut’s theory, however, appears to be constrained to sequentially dependent memory-based skilled tasks**.** Naturally further experimental work is called for to establish that the pattern observed in this study and in Botvinick and Bylsma’s (2005) study can be replicated reliably and that it generalises to other task paradigms. From an applied perspective, given the practical significance of checklist errors further research is required in order to further our understanding of their nature and causes. Anecdotal evidence suggests that there are numerous sources of checklist interruptions such as communications, head down activities, system/equipment malfunction and time pressure which opens up many interesting opportunities for future investigation (Degani & Wiener, 1990). In this regard, the findings reported here open up immense interesting opportunities for further investigation.

CHAPTER 6

GENERAL DISCUSSION

6.1 Overview of Chapter 6

This final chapter deals with key theoretical and practical issues. The chapter begins with a summary of the major findings. The theoretical implications are then discussed, broadly in relation to the role of attention during skilled performance. Following this is a discussion of the practical implications pertaining to the reduction of and skill-based error. The chapter concludes with an overall summary of this research.

6.2 Summary of key findings

The fact that errors occur even in the most highly skilled or habitual behaviour is testament that error is intrinsic to human behaviour. The systematic study of error per se is relatively new in psychology and the study of the most infrequent types of error, those occurring in skilled behaviour has lagged even further behind. This is a significant gap in the literature. The overall objective of this research was to add to current knowledge about the nature, timing and sources of human error, specifically, errors that occur in skilled, well-practised behaviour. Three empirical studies were conducted in this research each with the specific aim to further our understanding of the role of attention during skill-based behaviour, in particular, the role of distraction as a major source of skill-based errors.

The results of Experiment 1 reported in Chapter 3 suggested that although skill development frees up more processing resources that can be used for a secondary task it does not completely eliminate attentional demands as indicated by the finding that distraction disrupted both low and high skill performance. This is consistent with previous research (Cheng, 1985; Logan, 1988; Pashler, 1994, 1998). In relation to the role played by attention in the maintenance of task performance, there was evidence to suggest that attention played a key role in response preparation processes. Two aspects of response preparation were distinguished: selection and programming. Both were found to be attention demanding processes which is consistent with previous research (Fagot & Pashler, 1992; Ketelaars et al., 1999; Netick & Klapp, 1994; Pashler, 1989) but the locus of interference was different for the two processes. The attentional critical points were at the start of response for response programming (i.e., begin-subtask) and toward the end of a response (i.e., end-subtask) for subsequent response selection. These critical points were the same for low and high skill performers.

Experiment 2 reported in Chapter 4 examined whether attention is allocated differently depending on the speed and accuracy with which a task is performed. This study extended the first study by demonstrating that although skill development does not change where attention is allocated, it reduced the amount of attention required at specific critical points (begin- and end-subtask points). There was also evidence that performance instructions moderated the amount of attention required at these critical points, specifically, at end-subtask, where a distraction at this point was more disruptive to subsequent decision time under accuracy than speed instruction. In general, the results across the two studies suggested that attentional structures that govern performance do not differ greatly as a function of skill. Practice appeared to reduce attentional demands but a level of attention was still involved in response preparation at critical points.

Experiment 3 reported in Chapter 5 was conducted using a simulated checklist task which pilots performed under conditions involving frequent distraction. The results provided further evidence of the negative effects of distraction on pilot checklist errors which up until now has mainly been based on anecdotal evidence and accident reports (Degani, 1992, 2002; Degani & Wiener, 1990; Diez et al., 2003; Helmreich et al., 2001; NTSB, 1969, 1975, 1982, 1988a, 1988b, 1989, 1990, 1997). The study also extended previous results by examining the effects of distraction on two different types of checklist errors (action slips and verbal slips). Whilst the occurrence of action slips did not differ depending on where a distraction occurred during the checklist task (mid- and end-subtask distraction were equally disruptive) possibly due to a design artefact, verbal slips occurred more frequently following distractions that occurred midway through a subtask than following distractions that occurred toward the end a subtask. Overall the results of the three studies suggest that the nature of the task as well as the nature of the errors is important factors in determining the precise effects distraction have on performance.

6.3 Theoretical implications of the current findings

The results of this research have important implications for our understanding of the phenomenon of skill, in particular, the specific role of attention in producing successful skilled behaviour. The results of the first two studies confirm the well-documented finding that the acquisition of skill leads to improved performance whether that is reflected in accuracy, speed, the efficiency of movement or another performance measure (Anderson & Fincham, 1994; Crossman, 1959; Logan, 1988; Newell & Rosenbloom, 1981). High skill participants demonstrated superior performance in both speed and accuracy compared to low skill participants. Practice was a key factor in improving performance which is consistent with the large literature on the positive effects of training on skill development (Anderson, 1982; Logan, 1988; Newell & Rosenbloom, 1981; Shiffrin & Schneider, 1977).

Where the results do cast doubt is on the widely held assumption that skilled performance is associated with effortless, attention-free performance (Hasher & Zacks, 1979; Posner & Synder, 1975; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Although practice improved performance in several ways and reduced capacity demands (Beilock et al., 2002; Leavitt, 1979; Parker, 1991; Smith & Chamberlin, 1992) there was no evidence to suggest that it eliminated attentional demands. Both low and high skilled participants showed clear decrements in performance when carrying out the tracking task under conditions of distraction and where distraction was most disruptive was the same for low and high skill individuals. These results are important because they suggests that although practice might change the *amount* of attention required to execute a skill it does not change *where* attention is allocated during task execution.

A level of attention or self-regulation is still involved at critical points during skill performance rather than entirely ‘automatic’ behaviour. The results contribute to the growing body of evidence in direct challenge to the view that practised operations are performed ‘automatically’ and no longer involve capacity demands (Ahissar et al., 2001; Cave & Wolfe, 1990; Chen, 1985; Dutter & Walker, 1995; Francolini & Egeth, 1980;

Joseph et al., 1997; Kahneman & Chajzyck, 1983; Kahneman & Henik, 1981; Logan, 1980; Moretti et al., 2003; Van Selst et al., 1999). These results challenge in particular Shiffrin and Schneider's (1977; Schneider & Shiffrin, 1977) theory that two distinct modes of processing underlie skilled (automatic) and unskilled (controlled) performance. As several researchers have argued, this dual-mode model may be an oversimplified conceptualisation of human performance (Bargh, 1992; Logan, 1985; Logan & Cowan, 1984; Pashler, 1998).

Although it has become increasingly clear that a literal interpretation of automaticity as requiring no conscious attention at all may not be an accurate description of skilled behaviour (Moors & Houwer, 2005) the distinction between automatic and controlled processes is featured in most introductory textbooks as the main theory to understanding skilled performance and has become part of contemporary jargon.

The current findings also have important implications for our understanding of the nature of attention allocation during task performance. Across three studies, the results suggest that where attention is allocated during task performance depends on the nature of the task and the aspect of performance under consideration. These task-related factors appeared to be more important than actual skill level in determining the effects of distraction on performance. Specifically, in a task with significant motor requirements (e.g., a tracking task) this research found that attention was needed at two critical points. First, at the start of a response for the accurate execution of that response (i.e., response programming) and secondly, toward the end of a response for the accurate selection of the next response (i.e., response selection). In a task with significant working memory requirements (e.g., a checklist task) this research found attention to be more important midway through a task.

The role played by attention at these critical points is consistent with several theoretical predictions. For example, according to the motor control literature, attention is important at the start of a response because this is where movement is programmed and triggered into action (Adams, 1971; Castiello & Umilta, 1988; Keele, 1973; Ketelaars et al., 1999; Netick & Klapp, 1994; Schmidt, 1975). According to Reason's (1990) theory, attention is important toward the end of a response because this is where the monitoring and checking of actions occur before proceeding onto the next response. According to Botvinick and Plaut's (2003, 2004) theory, attention is important midway through a response because this is where task context information is most susceptible to loss as a result of a distraction during task execution. The results of this research suggest that there is merit to each of these theoretical accounts depending on the nature of the task in question and the aspect of performance being measured.

Previous studies have found ample evidence for interference effects at different stages during task execution (Bundesen, 1990; Hochman, & Meiran, 2005; Ketelaars et al., 1999; Netick & Klapp, 1994). An example is the literature on the psychological refractory period (PRP) effect (Pashler 1994; Welford, 1967). The PRP effect is attributed to a processing stage that cannot handle two tasks simultaneously. Within this framework, a great deal of debate has been devoted to finding *where* the attentional bottleneck is located in the information processing system. Most of the early debate was about the issue of whether the single-channel limit is associated with making a response (i.e., late selection) rather than with other processes such as perceptual analysis (i.e., early selection) (Logan & Burkell, 1986; Pashler, 1989, 1994; Pashler & Johnston, 1989; Welford, 1967). Recent evidence suggests that interference can occur at early, intermediate and late stages during the information processing chain (Cowan, 1988; Posner & DiGilrolam, 2000) suggesting that the location of the attentional bottleneck is flexible rather than fixed. Indeed several researchers have argued against mutually exclusive early versus late selection views of attention (Allport, 1993; Lambert, 1985). For example, Lambert (1985) noted that despite evidence that attention selectivity may operate at several different levels and stages of information processing, there has been a relatively persistent tendency to try to pin it down to a single level/stage. More recent evidence supports a multilevel view in which attentional bottlenecks can affect processes at various points in the course of information processing (Luck & Hillyard, 2000). A major challenge for the future is to determine how these multiple attentional mechanisms operate in a coordinated manner to maintain unity of behaviour. Moreover, as Styles (1997) noted, however, “discovering precisely *where* selection occurs is only one small part of the issues surrounding attention, and finding where selection takes place may not help us to under *why* or *how* this happens” (p. 28). An important area for future research is to explicate further when and why attention is needed at critical points during task execution.

At present, what is becoming increasingly apparent in the empirical literature is that the existence of a sharp dichotomy in information processing between automatic, capacity-free processing and attentive, controllable, capacity-demanding processing or the equivalent, between "early" perceptual level and “late” response selection now seems doubtful. As argued by Lambert (1985) “attempts to shore up revised versions of either automatic or controlled processing, or early or late selection seem unlikely to produce theoretical progress” (p. 254). These dichotomous conceptualisations of human performance now seem outmoded and inadequate. In a critical review of attention research, Allport (1993) argued “there can be no simple theory of attention, any more than there can be a simple theory of thought. A humbler but also a more ambitious task for the next twenty-five years will be to characterise, in cognitive neurobiological terms, as much as possible of this greater diversity of attention functions” (p. 206). As in the current research, one way to tap into this greater diversity of attentional functions is to isolate the different aspects of task performance and measure attentional limitations and functions in each component rather than combining all aspects of the task together.

In general, attention is not a unitary construct (Allport, 1993; Pashler et al., 2001) and hence it is possible that some secondary tasks may have different effects on performance depending on the nature of the attentional resources they require and the involvement of these resources during performance. Future progress is likely to come from a systematic exploration of the nature of the different types of primary and secondary tasks to determine the contributing factors of attentional demands on task performance. One product of such research will be a taxonomy of tasks based on a clear understanding of the nature and representation of their control structures at different levels of skill.

Finally, in terms of resolving the disagreement and inconsistencies between Reason’s (1990) and Botvinick and Plaut’s (2003, 2004) theoretical positions, as mentioned in Chapter 1, the theories are clearly very different which makes it difficult to reconcile their differences theoretically. Given that the results providing conflicting support, sometimes favouring one and sometimes the other, one way to try to resolve the disagreement between the two theoretical positions is to test their differential predictions in a broad range skill contexts. A variety of different tasks should be tested and like the studies in this research programme, different types of error should be measured. If results are robust across these different factors and in support of one theory then this will help to resolve the theoretical inconsistencies between the two theories. If, however, the results providing conflicting support, sometimes favouring one and sometimes the other depending on these different factors then this would suggest the need for a more comprehensive, overarching theory than Reason's and Botvinick and Plaut's theory.

There are a few generic, "context-free" theories which may be suitable candidates such as (a) Hockey's (1997) compensatory control model which consists of two hierarchical levels of control. A lower level which describes normal, routine and skill-based task performance and an upper level which describes compensatory control and includes elements relating to task goal setting, effort monitoring and supervisory control; (b) Norman and Shallice's (1986) contention scheduling system which controls routine, skilled behaviour and a second system referred to as the supervisory attentional system which is capable of interacting with the routine system in situations requiring attention to detail (e.g., checking, monitoring, trouble shooting, planning, decision making, suppression of a habitual response); (c) Hollnagel's (2005) general theory of performance systems involving different but simultaneous layers of control (e.g., concurrent open and closed control loops); and (d) Stein and Glickstein's (1992) theory that for most voluntary movements some sort of feed-forward control is combined with online correction based on intermittent feedback sampling.

Given the many different theoretical alternatives, the present research in itself is not able to resolve the competing accounts. At best, the current results suggest that the nature of the task and task context are important factors in determining the specific effects of distraction on performance. Admittedly, this conclusion is not robust because of a possible design flaw in Experiment 3. Further work is clearly needed.

6.4 Applied implications of the current findings

In addition to theoretical implications, the current findings also present a number of applied implications. First, the finding that skilled performance is capacity limited de-mythologieses the widely endorsed notion that skilled behaviour is effortless, that it does not consume attentional resources and therefore cannot be disrupted by distraction. The cost of distraction even for skilled operators has profound implications for those operating in environments where even a minor slip can lead to serious injury or loss of life (e.g., air traffic controllers, pilots, nuclear plant operators, medical staff, military personnel, automobile drivers). The finding that skill does not lead to immunity from error reinforces the view that error is a normal part of human behaviour. This decreased performance is a normal result of limitations in the information processing system rather than an indictment of personal skill.

The current results also have implications for practical recommendations relating to the appropriate focus of attention during the performance of skills such as in the sporting environment. Based on the theoretical account of automaticity many authors have proposed an "attention-free" approach to optimising the performance of motor skills such as the five step strategy by Singer et al. (1993). This strategy is based on the idea that automaticity is an ideal performance state (Bouchard & Singer, 1998; Singer et al., 1993) and therefore motor skills are best performed in the absence of conscious control. Advocates of this approach often cite evidence that conscious attention to well-learned sequences can disrupt performance (Baumeister, 1984; Beilock et al., 2002; Langer & Imber, 1979; Singer et al., 1993). However, evidence suggesting that conscious attention to the step-by-step components can disrupt well-learned movement sequence does not necessarily require that skills are best performed using a completely attention-free approach. Rather, all these results indicate is that *too* much conscious attention to movement details can hinder performance or that attention was misplaced. It does not imply that *any* level of conscious attention will disrupt performance.

Not only is the concept of automaticity inadequately supported by empirical evidence (Bargh, 1992; Kahneman & Treisman, 1984; Logan & Cowan, 1984; Logan, 1985, 1988, 1989) but also arguments based on the automatic quality of sporting performance neglect an essential characteristic of skill, that it is dynamic in nature and is continually developing rather than reflecting a static entity that can be developed and repeated robotically as required. For instance, after winning all four golf majors within a twelve-month period, Tiger Woods spent a considerable amount of time making technical corrections to his golf swing. If skill is conceived as something that continually develops as proposed by several prominent researchers such as Adams (1971), Fitts and Posner (1967), Ericsson (2003) and

Logan (1985) then there will almost always be an appropriate attentional focus that is not "unawareness' or "automatic".

The results from the current series of experiments suggest that an attention-free/unawareness approach may not be the ideal strategy for producing optimal performance. Considering the finding that the nature of the task and the aspect of performance under consideration are important factors in determining the precise effects distraction has on performance it may be necessary to devote attention to specific requirements of the task or particular aspects of performance. Further research is required to examine if there is any general attentional strategy that can be identified or whether this will be dependent upon the nature of the task as suggested by the current series of studies or whether attentional focus will need to be adapted for characteristics of the individual (Ackerman, 2007).

Another significant practical implication of this research is in the new insights it provides on a serious and often overlooked problem for safety and prevention of injury, that isskill-based error. Although there is no doubt that skill has immense benefits (Anderson, 1982; Logan, 1988; Newell & Rosenbloom, 1981; Shiffrin & Schneider, 1977) and is an attribute sought after in most settings, it is often overlooked, however, that skilled performance does not imply completely error-free performance. Reason (2008) recently argued that, "one of the best rules of error management is that the best people can make the worst errors" (p. 37). One of the reasons he outlined was because "the best", most skilled people in occupational settings are often in a supervisory capacity they often must multi-task and are thus easily distracted or preoccupied.

Errors are less frequent in skilled performance (Hobbs & Williamson, 2002) but they do occur often leading to injury or death (Edkins & Pollock, 1997; Pape et al., 2001; Rothschild et al., 2005; Salminen & Tallberg, 1996; Wiegmann et al., 2005; Williamson & Feyer, 1990). Evidence from the first Work-related Fatalities Study indicated that skill-based error was a most direct cause of around 44% of workplace deaths accounting for close to 200 deaths per year. Current estimates place the total cost of workplace fatalities at around $1.1 billion per year (NHSC, 2004) so the cost of fatalities due to skill-based errors is around $484 million per year all of which are borne by the worker and the community. If the same estimate is used for the role of skill-based error in workplace injury, the estimated total costs are nearly $28 billion annual (based on total estimated injury costs of $64.1 billion). Clearly, prevention of error in skilled behaviour in the workplace would lead to a significant reduction in costs to the health system and to the community. It is notable that this analysis only focused on occupational injury. Skilled-based errors also contribute to injury in a wide range of other settings including road and other transport, sports and home settings. No data is available on the incidence of skill-based errors in these settings so it is not possible to calculate even estimated costs. Nevertheless, they will certainly be high.

One of the problems for our understanding of skilled performance is that operators appear to commit errors in apparently unpredictable ways and at unexpected times. The series of studies presented in this research shed light onto this issue by demonstrating that distraction is one major source of skill-based errors that taps disparate cognitive operations, from movement preparation/execution, decision making to memory and that the occurrence of skill-based errors can be affected by manipulating where distractions occur during task executions. These findings suggest that a key to remediation is in how distractions/interruptions are managed. As distractions and interruptions are ubiquitous, it has been argued that the only way to combat the problem of human error in high risk technologies is to try to mitigate the consequences so that even if errors do occur as result of distractions the consequences are contained. Some researchers having suggested the design of "prevention" systems (Ash, Berg & Coiera, 2004) or error "traps" (Loukopoulos, Dismukes & Barshi, 2003) that do not allow you to proceed until an error has been corrected. For example, Reason (1990) suggested that designers of machines should build in system responses to error. These can be in the form of warning (to alert operators that a mistake has been made); locking (to prevent further use until the error has been corrected); do nothing (not responding until the correct response has been made); self correction; or dialogue (asking whether the proposed action is the correct one). However, the problem with fail safe mechanisms as a number of inquiries into major accidents have shown is that they can be switched off or overridden. Reason suggested that another way of reducing the impact of errors is to build in procedures or mechanisms so that other people detect them.

Whatever the strategy, what is clear is that if we are to prevent error from turning into injury we need to understand more about how and why errors occur in skilled behaviour. Whilst cognitive theory in itself cannot offer specific solutions, especially in the absence of situational details, nonetheless, an understanding of the underlying cognitive processes can begin to focus on identifying amelioration approaches that are both effective and usable.

6.5 Conclusion

Whilst there is no question that skill has immense benefits namely reduced effort with improved speed and accuracy, there is also mounting evidence that errors in skilled behaviour occur and can be serious. Despite this evidence there has been comparatively little research on the nature and causes of skill-based error. This series of studies addressed a gap in the psychological literature on attention and skilled performance that have received relatively little empirical attention. Overall this research questioned automaticity's theory core proposition that skilled performance is not subject to attentional limitations and therefore cannot be disrupted by distraction. To the contrary, the results suggest a level of attention or self-regulation is still involved at critical points during execution. Across three experiments, the results suggest that where attention is allocated during task performance depends on the nature of the task and the aspect of performance under consideration. These task-related factors appear to be more important than actual skill level in determining the effects of distraction on performance. Overall continued exploration of the skill-based error phenomenon across diverse skill domains will help to further our understanding of the specific reasons why attention may be necessary at certain points under some conditions but not at others. In this regard, there are numerous interesting opportunities for further investigation.

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APPENDIX A

Table 1

Mean percentage of wrong way errors, standard deviations and number of trials (for each individual)l contributing to the mean in each cell of the factorial design: Skill level × Probability × Distraction positions.

Probability	***Distraction Positions***		**Low Skill**		**High Skill**	
		n	***M***	***SD***	***M***	***SD***
High (100% + 75%)	No distraction	21	7.30	5.38	3.57	2.85
	Begin	21	8.10	8.33	4.52	5.46
	Mid	21	8.21	8.06	5.13	5.47
	End	21	10.89	11.68	7.33	7.29
Equal (50%)	No distraction	6	33.74	18.69	30.00	18.99
	Begin	6	25.00	20.76	26.67	19.62
	Mid	6	31.67	28.57	26.67	22.68
	End	6	26.67	25.37	26.67	25.37
Low (25%)	No distraction	3	42.78	25.78	55.56	25.65
	Begin	3	35.00	37.49	43.33	38.80
	Mid	3	48.89	29.99	60.00	30.83
	End	3	33.33	47.95	63.33	49.01

APPENDIX B

Table 2

Means, standard deviations, and correlation coefficients of dependent variable measures in the Accuracy group.

Dependent variables	***M***	***SD***	**1.**	**2.**	**3.**	**4.**
1. Decision time (ms)	312.21	83.34	-			
2. Movement time (ms)	759.59	159.42	.66**	-		
3. Wrong way error rate (%)	.14	.06	.11*	.01	-	
4. Overshoot error rate (%)	.23	.08	.03	-.21**	.63**	-

* = $p < .05$ (2-tailed). ** = $p < .01$ (2-tailed).

Table 3

Means, standard deviations, and correlation coefficients of dependent variable measures in the Speed group.

Dependent variables	***M***	***SD***	**1.**	**2.**	**3.**	**4.**
1. Decision time (ms)	312.21	83.34	-			
2. Movement time (ms)	759.59	159.42	.75**	-		
3. Wrong way error rate (%)	.14	.06	.03	.17**	-	
4. Overshoot error rate (%)	.23	.08	.31**	.15**	.21**	-

* = $p < .05$ (2-tailed). ** = $p < .01$ (2-tailed).

APPENDIX C

Table 4

Mean percentage of wrong way errors, standard deviations and number of trials (for each individual) contributing to the mean in each cell of the factorial design: Instructions × Skill level × Probability × Distraction positions.

			Accuracy				**Speed**			
Probability	***Distraction Positions***		**Low Skill**		**High Skill**		**Low Skill**		**High Skill**	
		n	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
High (100% + 75%)	No distraction	21	4.68	5.67	.78	1.83	7.32	6.90	4.00	3.37
	Begin	21	4.92	8.85	1.54	3.85	8.01	10.99	3.38	5.48
	Mid	21	4.80	8.93	2.93	6.96	7.22	11.95	4.27	6.35
	End	21	8.00	9.62	4.53	8.97	11.94	15.10	9.07	10.00
Equal (50%)	No distraction	6	20.62	18.00	10.15	11.48	25.96	13.58	28.31	17.02
	Begin	6	23.00	22.73	13.00	20.57	28.13	25.87	38.00	27.12
	Mid	6	25.33	25.96	16.00	21.77	34.72	23.01	32.00	24.50
	End	6	17.00	27.69	19.00	20.77	27.08	20.74	26.00	25.50
Low (25%)	No distraction	3	20.00	18.32	14.00	17.80	24.31	14.31	53.33	24.30
	Begin	3	28.80	20.07	19.20	23.44	40.00	24.32	63.20	23.58
	Mid	3	26.00	18.37	24.00	22.22	32.29	23.87	55.00	22.82
	End	3	26.67	31.91	38.67	24.87	38.89	27.22	53.33	25.50