National Library of Canada
Canadian Theses Service

Ottawa, Canada
K1A 0N4

Bibliothèque nationale du Canada
Services des thèses canadiennes

CANADIAN THESES

THÈSES CANADIENNES

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30.

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

NL-339 (r.86/06)

Canada

THE UNIVERSITY OF ALBERTA

RATE OF VISUAL INFORMATION PROCESSING AND THE PREDICTION OF ATHLETIC SUCCESS

BY

JOS J. ADAM

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSICAL EDUCATION AND SPORT STUDIES

EDMONTON, ALBERTA
SPRING, 1987

Permission has been granted to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film.

The author (copyright owner) has reserved other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without his/her written permission.

L'autorisation a été accordée à la Bibliothèque nationale du Canada de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur (titulaire du droit d'auteur) se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation écrite.

ISBN 0-315-37603-1

THE UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR: JOS J. ADAM

TITLE OF THESIS: RATE OF VISUAL INFORMATION PROCESSING AND THE PREDICTION OF ATHLETIC SUCCESS

DEGREE: DOCTOR OF PHILOSOPHY

YEAR THIS DEGREE GRANTED: 1987

Permission is hereby granted to THE UNIVERSITY OF ALBERTA LIBRARY to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

(Student's signature)

HOUTHEMERWEG 39
(Student's permanent address)
6231 KS MEERSSEN, HOLLAND

Date: December 23, 1986

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled RATE OF VISUAL INFORMATION PROCESSING AND THE PREDICTION OF ATHLETIC SUCCESS submitted by JOS J. ADAM in partial fulfilment of the requirements for the degree of DOCTOR OF PHILOSOPHY.

R. B. Wilberg
(Supervisor)

Ed Bedingfield

F Allard

Date: December 15, 1986

DEDICATION

To my Mother and Father,

whose love and support are a continuous source of inspiration.

ABSTRACT

The main purpose of this study was to investigate whether the construct rate of visual information processing, operationally defined by the use of the backward masking technique, could separate "top-ranked" athletes from "bottom-ranked" athletes in fast action sports. Displays containing four letters were presented for stimulus durations ranging from 25 to 300 milliseconds. Following stimulus offset, a patterned masking stimulus was employed for 200 milliseconds. On a specially prepared response grid, subjects were instructed to write down as many letters as possible from the briefly presented array. Results indicated substantial individual differences in rate of visual information processing, defined as the total number of letters reported correctly over all exposure durations. That is, athletes could be classified differentially as "fast" visual information processors or as "slow" visual information processors. These individual differences in rate of visual information processing were interpreted as reflecting the operation of attentional factors. Importantly, it was found that the backward masking task could successfully differentiate between "top-ranked" university athletes and "bottom-ranked" university athletes in the sports of ice-hockey, basketball, and downhill skiing. On basis of these findings it was concluded that the concept rate of visual information processing, as indexed by the backward masking technique, has promising validity for predicting performance differences in fast action, open skill type sports.

In addition, an experiment was carried out to investigate the construct validity of the rate of visual information processing concept. Five laboratory tasks, expected to be reflective of speed of visual information processing, were administered to a large number of subjects (N=69). Correlations between derived scores of these tasks were

extremely low. The notion of a general speed of processing factor was therefore not supported. However, serious methodological problems were identified, leaving the status of a general, task independent speed of visual information processing ability undetermined.

ACKNOWLEDGEMENT

I would like to express my sincere thanks to Dr. R.B. Wilberg for creating an inspiring and productive work environment and for the friendly encouragement, guidance, and constructive criticism, which fundamentally contributed to both my academic and personal growth.

I would like to thank my committee members for their interest in my work and for their valuable comments.

Grateful acknowledgement is also extended to Ian Humphreys for his stimulating friendship.

Finally, I would like to offer my thanks to my best friend Judy, whose love, understanding, and indulgence helped make the writing of this thesis less arduous; I could not have made it without her.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1. A: Amplitude or movement distance
2. ANOVA: Analysis of Variance
3. ID: Index of Difficulty
4. MT: Movement Time
5. SOA: Stimulus Onset Asynchrony
6. VIP: Visual Information Processing
7. W: Target Width

INTRODUCTION

Purpose

A common approach to the study of perceptual-motor skills is to view man as a processor of information (Fitts & Posner, 1967; Marteniuk, 1976; Schmidt, 1982; Magill, 1985). Central to this approach is the notion of various information processing stages and mechanisms that intervene between the presentation of a stimulus and the execution of a response. Even though there is no consensus among information processing theorists as to the mode of processing, serial or parallel, or about the nature of the mechanisms involved, the basic idea presented is a flow of information through several processing stages. The information processing approach to skilled behavior should therefore be considered more as a framework providing concepts, ~~principles~~, and metaphors, than as a fullblown theory (Mandler, 1985).

A general question of interest from the information processing perspective is how much information can be processed per unit of time. Speed of processing in this context is considered to be an intrinsic, biologically determined property of the central nervous system, and an important determinant of the quantity and quality of skilled behavior. The following quotations are typical of this perspective:

> "... consider that the speed-of-processing tests are measuring the efficiency with which persons can perform very basic cognitive operations which are themselves involved in, or which underlie, other kinds of cognitive and intellectual behavior ..... then the speed or efficiency with which individuals can execute

> the cognitive operations involved in a given task or problem might be expected to have a considerable effect on the success of their performance of the task." (Vernon, 1983, p. 54)

> "... even very small individual differences in *rates* of information processing, when multiplied by days, weeks, months, or years of interaction with the myriad opportunities for learning afforded by common experience, can result in easily noticeable differences in the amounts of acquired knowledge and developed intellectual skills. At a moment's glance there is scarcely a noticeable difference between the speed of a car averaging 50 and another 51 miles per hour, but after a few hours on the road they are completely out of sight of one another." (Jensen, 1980, p. 105; cited in Salthouse, 1985, p. 216)

This study is concerned with the limitations of the perceptual mechanisms involved in the processing of short duration visual information. In particular, the primary question is whether individual differences among university athletes in perceiving rapid visual displays is related to athletic performance effectiveness. That is, the studies reported here were designed to (1) determine the relative rates of visual information processing of athletes, (2) to determine the extent to which rate of visual information processing is predictive of general performer's excellence in athletic skills, and (3) to investigate the construct validity of the rate of visual information concept.

In short, the main hypothesis investigated in this study is that the rate at which an individual processes visual information has important implications for the quality of skilled behavior. The fundamental assumption underlying this hypothesis is that a faster speed of processing is advantageous, or, stated differently, that a subject's individual rate of information processing is a major limiting factor in the quality of his or her performance.

Skill and Ability

It has been argued that it is important in the study of individual differences to distinguish between the concept of ability and the notion of skill (Fleishman, 1966). In this view abilities are conceived of as relatively stable and enduring traits which are quite difficult to change. Skills, on the other hand, improve readily as a result of experience and are easy to modify through practice. Nevertheless, as Fleishman (1966) pointed out "many abilities are, of course, themselves a product of learning and develop at different rates, mainly during childhood and adolescence" (p. 148).

More importantly, abilities are usually general in nature, that is, they may underlie several skills and thus apply to several situations or environments, while skills are usually environment dependent or situation specific. In other words, abilities are somehow more *basic* than skills, since they are related to performance in a variety of human tasks. For example, evidence for a general ability of "attentional flexibility", reported by Keele and Hawkins (1982), could, they claim, be of use in predicting success in a variety of fast action skills.

The above differentiation between skill and ability provides two possible explanations for individual differences in performer's excellence. One account holds that task success largely results from practice. This notion of practice related improvement of skill is consistent with the idea of task specificity. That is, skill is specific to the task practiced (Fleisman, 1966, 1978; Marteniuk, 1973; Keele & Hawkins, 1982).

On the other hand, as Keele and Hawkins (1982) pointed out "the possibility remains that people differ in some general abilities that account in part for differences in skill" (p. 4). Although there is no strong evidence to suggest that rate of visual information processing is an ability as above defined, the findings that rate of visual information processing seems to be related to intelligence (Mosley, 1981; Baumeister, Runcie, & Gardepe, 1984), and age (Walsh, 1976; Di Lollo, Arnett, & Kruk, 1982) support its conceptualization as an ability. Therefore, for the purposes of this study, we tentatively assume that rate of visual information processing has the status of an ability.

Open and Closed Skills

The ability to process visual information quickly and accurately is a factor of crucial importance in many skills. Consider, for example, fast action motor skills such as batting in baseball, playing hockey and soccer, boxing and flying a jet plane. These skills are performed in rapidly changing environmental displays, and thus require maximal perceptual monitoring.

The importance of environmental information from a changing display in the control of performance has been widely recognized. Indeed, Poulton's (1957) classification of skills as "open" and "closed" is based on the type of environment they are performed in. Open skills, in Poulton's classification, involve continuously changing situations, and consequently, rely heavily on the ability to perceive quickly and accurately. Closed skills, like bowling and archery, are characterized by static, invariant, and highly predictable environmental cues, and hence need minimal perceptual interpretation.

Given acceptance of the idea that perception plays a pivotal role in open skills, it is conceivable that differences in perceptual ability are related to skill prowess. Generally, the rationale behind this speculation is that athletes who are able to process visual information at a fast rate have an advantage over slow processors in that they have more and quicker information available to them, before committing themselves to an action. Indeed, without an adequate initial representation of the environment, there is nothing to know, nothing to remember, and nothing to act upon (Baumeister, Runcie, & Gardepe, 1984). It is the explicit goal of this study to determine the extent to which rate of visual information processing contributes to general performer's excellence in team sports of the open skill variety.

Iconic Memory

There are three lines of evidence which suggest that individuals differ widely in their ability to process short duration visual displays. Rate of visual information processing in this context is operationally defined by the use of the visual backward masking paradigm in which a subject's recognition of a brief, informational target stimulus is impaired by a trailing, non-informational masking stimulus. Before discussing this evidence it seems useful to introduce briefly the concept of short-term visual storage or iconic memory, as Neisser (1967) termed it, since iconic memory is regarded by many theorists as a key component in theories of visual information processing.

In a classic study, Sperling (1960) demonstrated convincingly that following display offset, subjects had more information available than they could consciously report. Sperling was able to show this by comparing the results of two experimental techniques. In the Full Report technique, subjects were asked to report as many letters as possible from a briefly presented stimulus display. Subjects in this situation were typically able to report four or five items. Increasing stimulus duration did not result in improved performance, reflecting a fundamental limitation on human perception known as the Full Report Limitation.

In Sperling's (1960) innovative Partial Report technique, subjects were asked to report a *subset* of the items presented. To illustrate the Partial Report technique, a brief description of one of the experiments reported in Sperling's (1960) study follows. Sperling presented subjects with displays consisting of 3 rows of 4 letters for 50 milliseconds. Immediately after display offset, a tone was presented indicating which row to report. A high frequency tone signaled the report of the top row, a medium frequency tone, the report of the middle row, and a low frequency tone, the report of the bottom row. Even though the order of presentation of the tones was random, thereby precluding successful anticipation of the forthcoming tone, subjects were able to report virtually all the items in the row indicated by the tone. The inevitable conclusion of this finding was that all of the 12 items in the display must have been perceptually registered in a buffer store which Sperling (1960) initially called "visual information storage", and Neisser (1967) later coined "iconic memory". The difference between the number of letters *available* in iconic memory as indexed by the Partial Report procedure, and the number of letters *reported* in the Full Report condition, became known as the Partial Report Superiority effect (Coltheart, 1980).

In order to assess the functional lifetime of iconic memory, Sperling (1960) systematically delayed the onset of the tone, and found that the number of items reported from the display dropped accordingly (see Figure 1). After a delay of about 250 ms, the number of letters available in iconic memory equalled the number of letters reported in the Full Report condition. This finding indicated that the useful lifetime of iconic memory was about 250 ms. The finding of a Partial Report Superiority effect which diminishes with increasing cue delay is regarded by many theorists as the principal evidence for the existence of iconic memory (e.g., Averbach & Coriell, 1961; Coltheart, 1980, 1983).

Backward Masking and Rate of Visual Information Processing

Following his classic work on the experimental demonstration of iconic memory, Sperling (1967) proceeded to investigate the rate at which information from iconic memory, an unconscious buffer system, could be "read-out" to a more permanent system (often identified as working memory or short-term memory), in order to be reported. Sperling's (1967) approach was as follows. For different stimulus durations, he presented slides containing a number of letters, followed by a masking stimulus consisting of random black and white squares. This procedure is known as the backward masking technique. Sperling's basic finding was that the number of letters reported correctly increased consistently up to some value between 50 and 100 milliseconds, at which point about 3 or 4 items could be reported (see Figure 2). Beyond 100 milliseconds, the rate of acquiring letters was very low: at most, about one item per extra 100 milliseconds could be recalled (Coltheart, 1972). In other words, initially letters seem to be read-out from iconic memory at a high

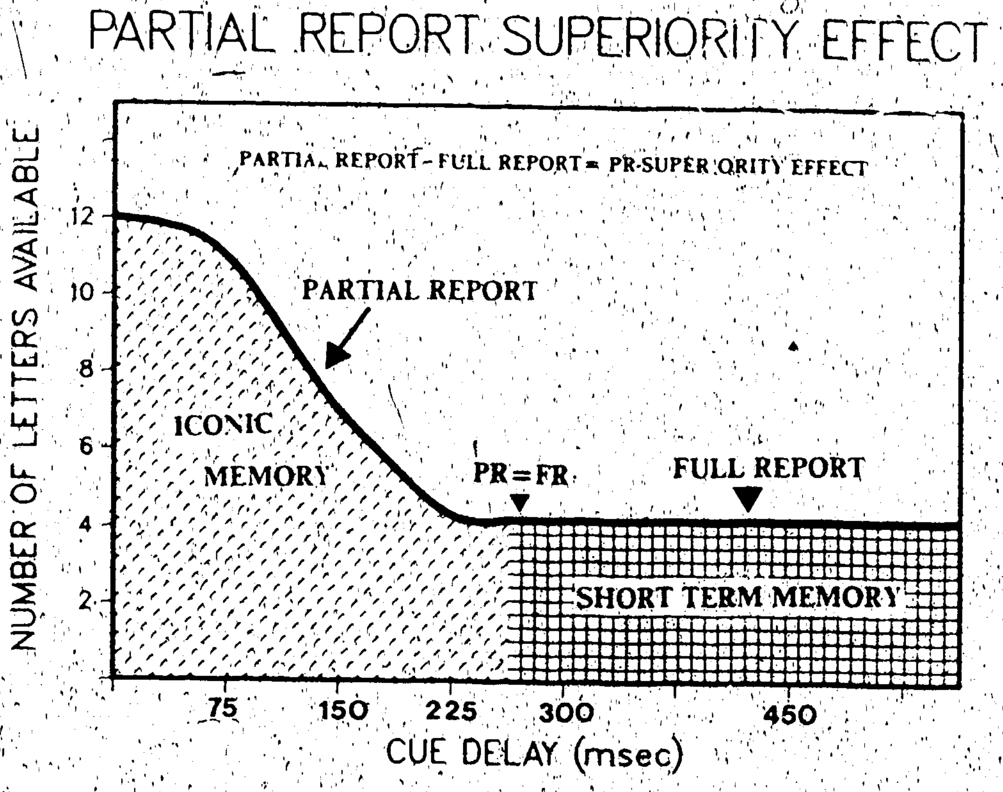

Figure 1. A schematic representation of the partial report superiority effect, showing the large difference between number of items available in iconic memory (Partial Peport) and short term memory (Full Report), which diminishes as a function of Partial Report cue delay. (PR = Partial Report; FR = Full Report). (After Haber, 1983).

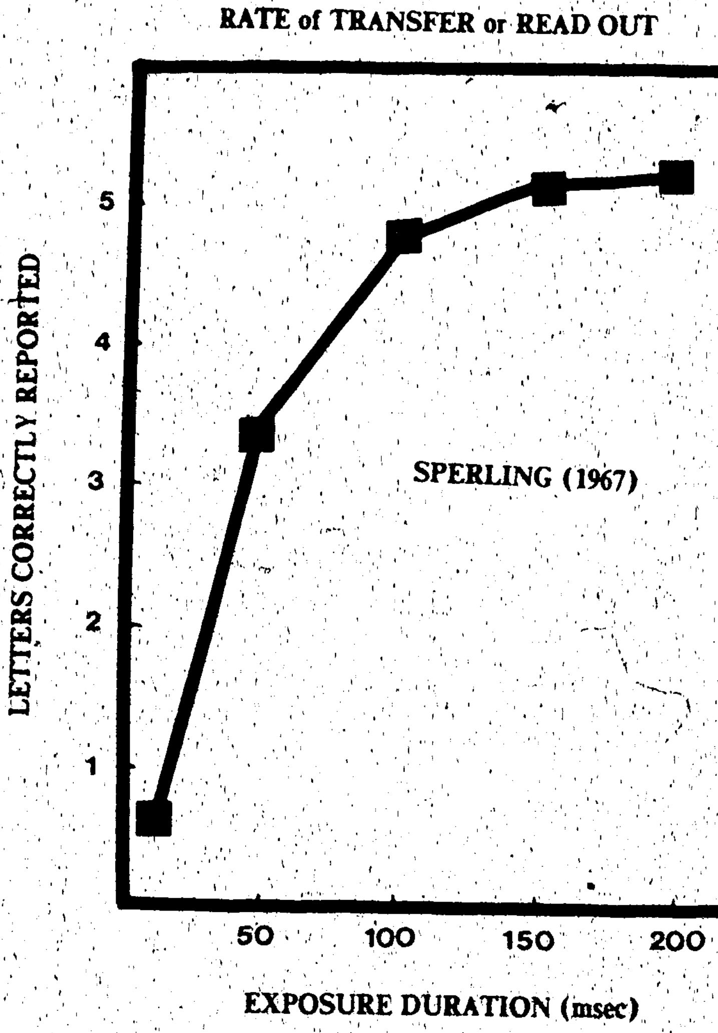

Figure 2. Number of letters reported correctly as a function of exposure duration in a backward masking paradigm. (After Sperling, 1967).

rate, and subsequently, at a low rate. This two-segmented read-out profile is a very robust phenomenon, as similar results have been reported by subsequent researchers (e.g., Mewhort, Merikle, & Bryden, 1969; Coltheart, 1972; Cerella, Poon, & Fozard, 1982).

It is not surprising, therefore, that many researchers have recognized the backward masking task as a useful tool to investigate individual differences in rate of visual information processing (e.g., Lovegrove & Brown, 1978; Cerella, Poon, & Fozard, 1982). The critical assumption underlying the use of the backward masking task has been well described by Di Lollo, Hanson, and McIntyre (1983).

> "Performance in backward masking is widely regarded as an index of the rate of visual information processing on the plausible assumption that the impairment in performance is the result of insufficient time to process the test stimulus before the arrival of the mask. Thus, a given brief SOA [1] may permit unimpaired perception of the test stimulus in a fast-acting visual system but may permit masking in a slower system." (Di Lollo, Hanson, & McIntyre, 1983, p. 924).

---

[1] SOA stands for "stimulus onset asynchrony" and refers to the time lag between the onset of the target stimulus and the onset of the masking stimulus which in effect denotes stimulus duration.

Individual Differences in Rate of Visual Information Processing

Having presented the concept of iconic memory, evidence in support of the existence of significant individual differences in rate of visual information processing, that is, rate of read-out from iconic memory, will now be discussed.

One line of evidence stems from the respective observations of Turvey (1973) and Marcel (1983). Both researchers reported that when a backward pattern mask was employed, a wide interindividual variance existed in the word-mask stimulus onset asynchrony (SOA) at which one was able to recognize a word or to detect the mere presence of a word.

A second line of evidence is based on studies which show slower processing rates as age increases (Kline & Szafran, 1975; Walsh, Till, & Williams, 1978; Di Lollo, Arnett, & Kruk, 1982).

A third line of evidence is offered by studies which demonstrate intelligence-related differences in rate of visual information processing (e.g., Galbraith & Gliddon, 1972; Mosley, 1981; Baumeister, Runcie, & Gardepe, 1984). That is, a basic information processing deficit observed among low-IQ subjects appeared be the result of relative slowness of iconic read-out. Additional support for this notion, as pointed out by Baumeister, Runcie, and Gardepe (1984), came from a series of studies, in which a derived index called "inspection time" was found to discriminate successfully between high and low IQ subjects (e.g., Hulme & Turnbull, 1983). Inspection time in this context referred to the rate at which information was sampled, and was operationally defined as the minimal exposure duration necessary to make a reliable discrimination between two briefly presented lines, which varied in length, and were followed by a masking stimulus. In this kind of task, low IQ subjects showed consistently longer inspection times, suggesting that they needed more time to process a given amount of information. This finding pointed to an IQ related speed of processing limitation (Baumeister, Runcie, & Gardepe, 1984).

In a similar vein , Di Lollo, Hanson, and McIntyre (1983) reported evidence that dyslexic children process visual information slower than a group of normal control subjects.

The importance of the concept of rate of information processing in characterizing individual differences has recently been emphasized by Salthouse (1982). Salthouse used the rate of information processing concept to account for age differences in performance. According to Salthouse (1982), the slowing of most behavioral activities with increased age can be attributed to a slower speed of nearly all elementary operations within the nervous system. Along these lines, it seems conceivable that individual differences in rate of information processing might not only account for differences in performance between age groups but also *within* age groups. Moreover, Salthouse (1982) argues that a basic advantage of the processing rate hypothesis is that "it might be operationally defined with fairly simple tasks such as choice reaction time or time to escape visual backward masking" (p. 192).

Sport Specific Perceptual Skills

Besides studies of the ability to process rapid visual displays, there have also been studies of sport specific perceptual skills. In general terms, the basic finding is that high level players have superior perceptual skills in situations particular to their sport only. For example, Allard, Graham, and Paarsalu (1980) compared the performance of basketball players and non-players on a task requiring the recall of slides containing structured and unstructured game information, after a four second view period. They found that basketball players were superior to the non-players in recall of structured slides only. As pointed out by Allard, Graham, and Paarsalu (1980) similar results have been established for the game of chess (deGroot, 1965; Chase & Simon, 1973), Go (Reitman, 1976), and bridge (Charness, 1979).

In essence, the paradigm used in these studies of perceptual skills consists of demonstrating an interaction between overall skill level (i.e., high versus low) and type of stimulus information (i.e., structured versus unstructured). The logic of this interaction paradigm is that when superior perception by skilled athletes is observed only for situations particular to their sport, evidence is obtained for the significance of "encoding of structure" as an important sport specific perceptual skill (Allard, Graham, & Paarsalu, 1980).

In summary, the interaction paradigm is important for demonstrating skill in perception relative to a particular stimulus environment, that is, relative to a sport specific context. Skilled perception, according to this paradigm, is only observed when a high level performer is required to encode information about his or her particular sport (Allard & Starkes, 1980). Studies employing the interaction paradigm have generally used relatively long duration displays (four or five second view periods) in combination with a recall or recognition task, and have provided robust evidence in support of the notion of important sport specific perception skills in terms of encoding accuracy.

Nevertheless, as Allard, Graham, and Paarsalu (1980) pointed out the successful athlete "must encode information *quickly* as well as accurately " (p. 20; italics added). In the following, evidence pertaining to the notion of speed of processing as an important element in skilled behavior will be discussed.

Rate of Visual Information Processing as a Basic Ability

As just mentioned, besides a context dependent perceptual skill as a constituent factor of excellence in skilled behavior, there might also be a *general*, context independent perceptual ability as a correlate of skilled performance. As a factor of successful performance in open skills, this more *basic* perceptual ability is concerned with processing speed and is demonstrated experimentally by a significant main effect in the recognition speed of *non-specific* stimulus material between groups of athletes who differ in excellence.

Unfortunately, the few studies which have been concerned with speed of processing and how it relates to level of expertise have generally employed task specific stimulus material. Sloboda (1976) for example, examined the way in which experienced musicians differed from non-musicians in the perception of briefly exposed pitch notation. Sloboda (1976) found a distinct perceptual superiority for musicians over non-musicians.

Allard and Starkes (1980) studied the performance of volleyball players and non-players in a task involving the detection of a volleyball. Their experiments showed that volleyball players are much faster than non-players at detecting *volleyballs* in rapidly presented slides.

Finally, Fleury, Bard, and Carriere (1982), using a backward masking paradigm, presented slides for short durations, which depicted schematized offensive basketball situations. Their basic finding was that performance varied with level of expertise; the expert players outperforming the novices. They concluded that speed of processing is an important attribute of skill level.

The above studies do not, however, provide evidence for the existence of a *general* speed of processing factor, since they employed task specific or sport specific stimulus material. Their finding of superior performance for experts is consistent, therefore, with the notion of task specific perceptual skills, even though the results do not rule out the possibility of a more basic speed factor.

In order to demonstrate that speed of visual information processing, viewed more as a "hardware" ability than as a learned, "software" skill, is a correlate of successful performance, it is necessary to employ *non-specific* stimulus material. In this study, an attempt was made to satisfy the condition of non-specific stimulus material by presenting slides containing letters of the alphabet. The underlying assumption of this experimental manipulation was that university athletes would not differ from each other in their familiarity with alpha-numeric stimulus material.

EXPERIMENT ONE

Speed of visual information processing is an important factor in performance level in open skills. The approach used in the following study to support this contention differs from the interaction paradigm in several aspects. First, type of stimulus material is not systematically varied, but held constant and neutral (i.e., letters of the alphabet). Second, stimulus duration is not held constant at a relatively long duration, but systematically varied from 25 to 300 milliseconds. Moreover, following stimulus offset a masking stimulus is employed. Third, there are no profound differences between the athletes in the subject pool in terms of experience and general skill level, in that they are all varsity athletes. This latter requirement takes into account the fact that performance success is undoubtedly determined by a variety of factors. If the groups to be compared are not homogeneous in terms of other potentially important factors influencing performance level, the experiment will be confounded and the effect of rate of processing could be "swamped" by uncontrolled variance. Fourth, the subjects are differentiated into two groups (i.e.,"top-ranked" and "bottom-ranked") by the head coach, according to the criterion of general performer's excellence. Taken together, these experimental manipulations will make it possible to conclude that, when a significant main effect in recognition speed is found between "top-ranked" and "bottom-ranked" athletes, that rate of visual information processing is an important mediating variable in skilled behavior.

METHOD

Subjects

Twenty two male athletes from the University of Alberta served as subjects. Six were recruited from the varsity basketball team, six from the varsity football team, and ten from the varsity ice-hockey team. Subject selection was random, and proceeded on grounds of accessibility.

The basketball players (mean age 20.8 years; range 18 to 24) averaged 2.7 years of intercollegiate playing experience, the football players (mean age 19.8 years; range 18 to 23) averaged 2.0 years, and the hockey players (mean age 22.2 years; range 18 to 25) averaged 3.3 years.

All subjects were unpaid volunteers and had normal or corrected to normal vision.

Apparatus

The subjects stood in a normally lit room and viewed from above a 8.5 x 3.0 cm, horizontally placed, rectangular frosted/opaque rear projection glass screen at a distance of about 58 cm. Viewing distance was kept constant by requiring the subjects to rest their chins upon a supporting frame.

Test and masking stimulus were rear-projected upon the screen via a mirror. They were projected tachistoscopically by two identical sets of apparatus, each consisting of a Kodak slide projector (Ektagraph), an Opticon Uniblitz electro-programmable shutter (Model 262), and an Opticon Uniblitz shutter driver and timing unit (Model SD-10). Control of display parameters was established by a PDP-11/10 computer in conjunction with the Uniblitz SD-10 shutter control units.

Stimuli

The target stimuli consisted of 35 mm slides of four different letters arranged in a linear array. The letters for each array were randomly selected from all consonants (except for the letter "y"), to minimize the possibility of subjects interpreting the arrays as words. A total of 100 target arrays was constructed.

Two different sizes of letters were used for the elements within the target arrays. The two outer elements were 1.0 degree of visual angle in height and 0.8 degree in width, while the two inner elements were 0.5 degree in height and 0.4 degree in width. The inner letters were spaced 0.5 degree apart while there was a distance of 1.5 degree between the inner and outer letters. These values were chosen from the guidelines established by Anstis (1974), to keep letter resolution above threshold at both retinal locations. The outer letters were printed in upper case Helvetica Medium script, and the inner letters were printed in upper case Helvetica Small script.

The masking stimulus consisted of a pattern of randomly superimposed letters of both sizes, and it covered the entire field.

Target stimuli were presented for six different stimulus durations: 25, 50, 75, 100, 150 and 300 milliseconds. Following target offset, the masking stimulus was displayed for 200 milliseconds.

Procedure

Subjects were tested individually in a session lasting approximately 20 minutes. After entering the room, the subjects were informed about the nature of the experimental task. Each subject was then shown a random sample of ten target arrays at several stimulus durations in order to orient them to the task. Following these orienting trials, the subjects received a block of 15 trials for each stimulus duration. The first five trials of each block were considered practice trials, and were not included in the analysis. Each subject received the same order of presentation of the stimulus durations, which started with the longest (300 ms) and ended with the shortest (25 ms). Prior to the experiment all slides were randomly mixed and arranged into 1 block of 10 trials (the orienting trials) and 6 blocks of 15 trials (the test trials).

For each trial, subjects were instructed to fixate on the center of the screen and to give a verbal ready signal. Then the experimenter pressed a button, which initiated a warning tone of 50 ms. After a delay of one second, the target stimulus appeared, which was followed at its offset by the masking stimulus. The subjects were instructed to write down as many letters as possible from the briefly presented array on a specially prepared response grid. While the subject wrote down his response, the experimenter advanced the slide projector by a remote control. It was emphasized that letters had to be reported in the correct location and that guessing was allowed if one was uncertain.

After testing was completed, the head coaches of the respective sports were asked to rank order all their athletes who had participated in the experiment according to the criterion of "general excellence", with players of equal ability being given tied or equal ranks. Based on these evaluations, "top-ranked" and "bottom-ranked" groups were formed for each sport. That is, athletes in the top 30 percent of the rankings were categorized as "top-ranked" athletes, and athletes in the bottom 30 percent of the rankings were categorized as "bottom-ranked" athletes.

RESULTS AND DISCUSSION

Figure 3 displays the principal results of this experiment. Mean number of letters reported in the correct position is shown for each individual in his respective type of sport, as a function of stimulus duration. No inferential statistical analysis were performed on these data. Visual inspection of Figure 3 reveals, for all three sports, consistent performance differences between athletes on the backward masking task. Athletes seem to differ both in rate of information gain and in final amount gained, at least for the stimulus durations employed in the present experiment. The overall shape of the functions relating amount reported to stimulus duration, that is, an initial steep slope followed by a relatively shallow slope, seems to hold for each individual and resembles closely those reported by other investigators (Coltheart, 1972).

To present the experimental results more effectively, the individual performance curves were dichotimized into two groups based on the criterion of total number of letters reported correctly. This resulted in the following two groups: a "fast" group, consisting of the athletes with the higher total number of letters reported correctly, and a "slow" group, consisting of the athletes with the lower total number of letters reported correctly. The application of this categorization scheme to the individual performance curves shown in Figure 3, resulted in the group curves

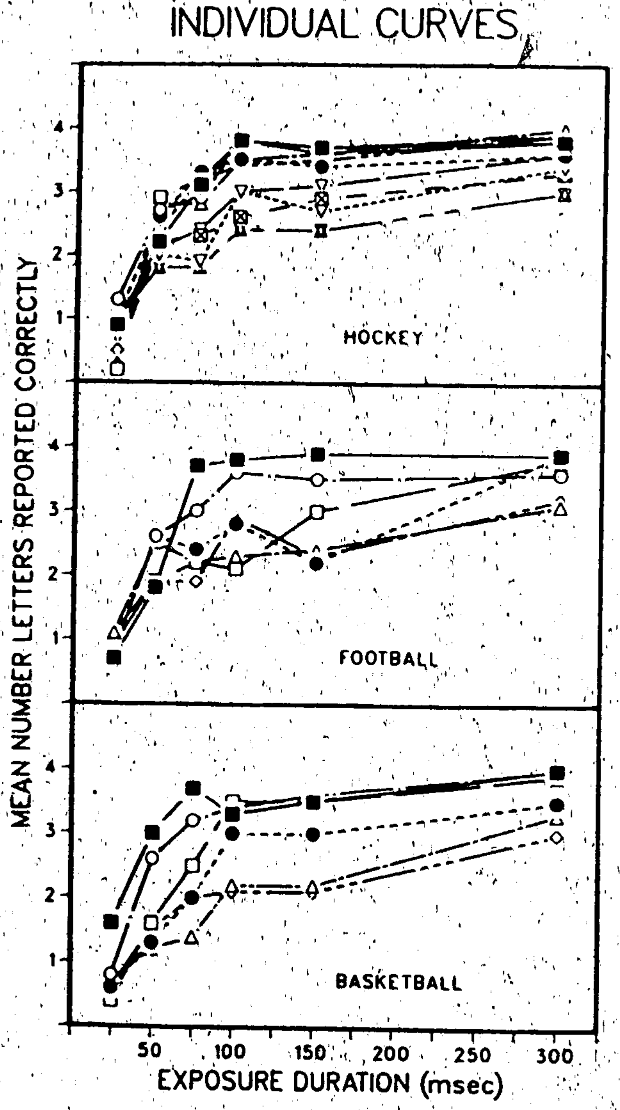

Figure 3. Mean number of letters reported correctly (identity plus location correct) as a function of exposure duration for each individual in the sports of hockey, football, and basketball.

presented in Figure 4. From Figure 4 it is evident that athletes in the three different sports can be classified differentially as "slow" visual information processors or as "fast" visual information processors.

Figure 5 is a summary of Figure 4, and shows the mean performance curve of the "fast" visual information processors (mean age 20.5, range 18 to 23; mean number of years of intercollegiate playing experience 2.3, range 1 to 4); and the "slow" visual information processors (mean age 21.8, range 19 to 25; mean number of years intercollegiate playing experience 2.8, range 1 to 4) averaged over type of sport.

The data underlying the performance curves of Figure 5 were entered in a 2 (group) x 6 (exposure duration) mixed analysis of variance (ANOVA), with repeated measures on the factor exposure duration. This analysis yielded the following significant effects: group, $F(1,20)=74.6$, $p<.001$; exposure duration, $F(5,100)=232.3$, $p<.001$, and the group by exposure duration interaction, $F(5,100)=11.1$, $p<.01$.

The significant interaction between exposure duration and group is of obvious concern. Tests on the simple main effects of the factor group were significant ($p<.01$) at all but the shortest exposure duration (Winer, 1971, pp. 518-532). In other words, at the shortest exposure duration "fast" and "slow" processors performed equally well.

This is an important finding for several reasons. First, it refutes alternative accounts which explain the observed differences at longer exposure durations in terms of other factors like "motivation", "anxiety", and "arousal level".

Second, it suggests that "response bias" factors were not present in this experiment. That is, it could be argued that "fast" visual information processors "guessed" more or had a more lenient "response criterion", and therefore showed

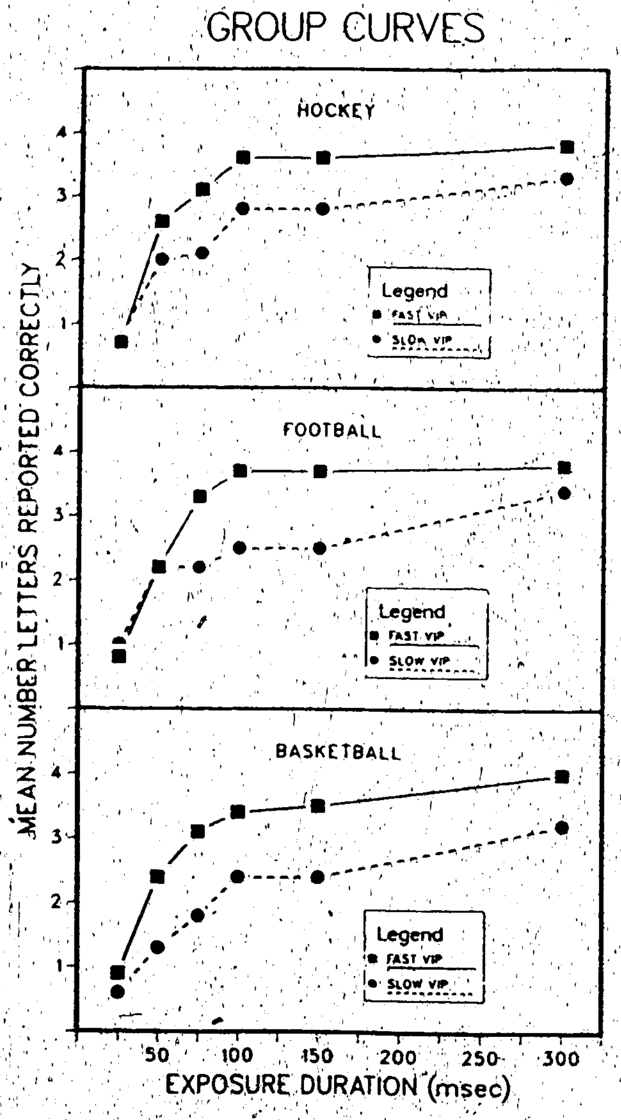

Figure 4. Mean number of letters reported correctly as a function of exposure duration for groups of "fast" visual information processors (VIP) and "slow" visual information processors (VIP), differentiated according to type of sport.

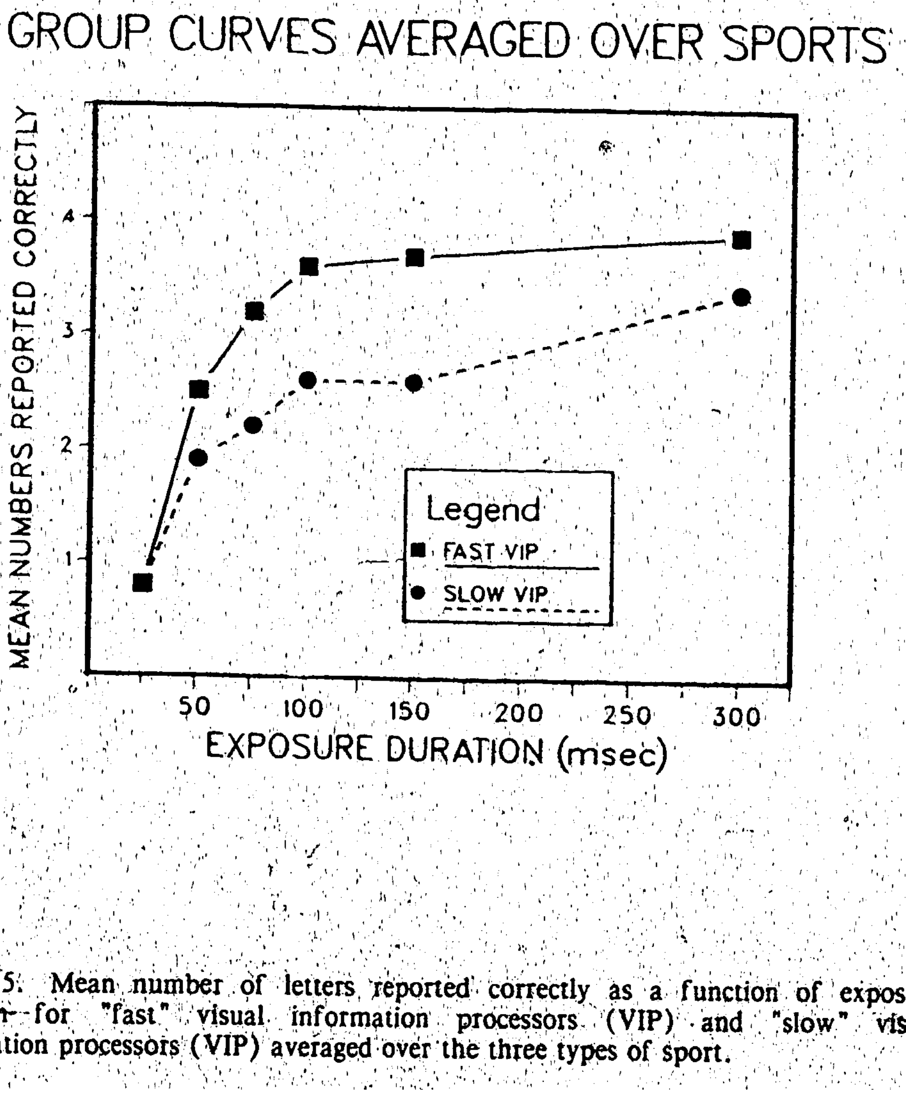

Figure 5: Mean number of letters reported correctly as a function of exposure duration for "fast" visual information processors (VIP) and "slow" visual information processors (VIP) averaged over the three types of sport.

superior performance. However, if such response bias factors had operated in this experiment, they should have been evident at all stimulus durations.

The errors made by "fast" and "slow" processors were analyzed in order to bolster the above argument. Two types of errors were distinguished; errors of identification and errors of localization. Identity or intrusion errors were defined as letters reported that did not appear in the original stimulus array. Location or transposition errors, on the other hand, resulted when subjects correctly reported the identity of a letter, but wrote it down in the wrong location.

In order to calculate these two different error scores, the raw data were analyzed in the following way. Apart from the criterion of identity plus location correct, two new criteria were devised. The first was based on the more lenient criterion of identity correct, that is, independent of location, and the second criterion was simply concerned with report per se, that is, irrespective of the correctness in terms of either identity or identity plus location.

In short, for each subject three different scores were calculated:

1. mean number of letters reported per se.
2. mean number of letters reported correctly under the condition of identity correct.
3. mean number of letters reported correctly under the condition of identity plus location correct.

Subtraction of score number 2 (identity correct) from score number 1 (number of letters reported) was taken as an index of identity errors or intrusion errors. Subtraction of score number 3 (identity plus location correct) from score number 2 (identity correct) was taken as an index of location or transposition errors.

The above three scores and both types of errors are presented in Figure 6 for both the "fast" and "slow" visual information processors, averaged over exposure duration. From Figure 6 it is evident that "fast" and "slow" processors do not differ in amount of errors made (mean number of identity errors .37 and .39 for "fast" and "slow" processors, respectively; mean number of location errors .18 and .22 for "fast" and "slow" processors, respectively). Overall, however, both "fast" and "slow" processors make more identity or intrusion errors than location or transposition errors. This pattern of results was confirmed by a 2 (group) x 3 (score) mixed analysis of variance (ANOVA), with repeated measures on the factor score, which showed significant main effects of both group, $F(1,20)=31.30$, $p<.001$, and score, $F(2,40)=69.48$, $p<.001$, but no interaction between group and score, $F(2,40)<1$. Note that the main effect for group reflects performance differences and not differences in errors made, which is reflected by the interaction between group and score.

Third, the interaction between speed of processing (i.e., "fast" versus "slow") and exposure duration, or more correctly stimulus onset asynchrony (SOA) between the target and the masking stimulus, suggests that different mechanisms constrain performance on the backward masking task dependent on the SOA. That is, the similarity between the "fast" and "slow" processors at the shortest exposure duration (25 ms), suggests no difference in initial iconic memory capacity. At longer exposure durations, or more correctly, at longer stimulus onset asynchrony (SOA) interval values between target and masking stimulus, the observed group differences can be interpreted as reflecting the operation of attentional factors. This interpretation is based on Michaels and Turvey's (1979) three-process model of masking. Michaels and Turvey (1979) conjecture that at relatively short SOAs two of the three masking

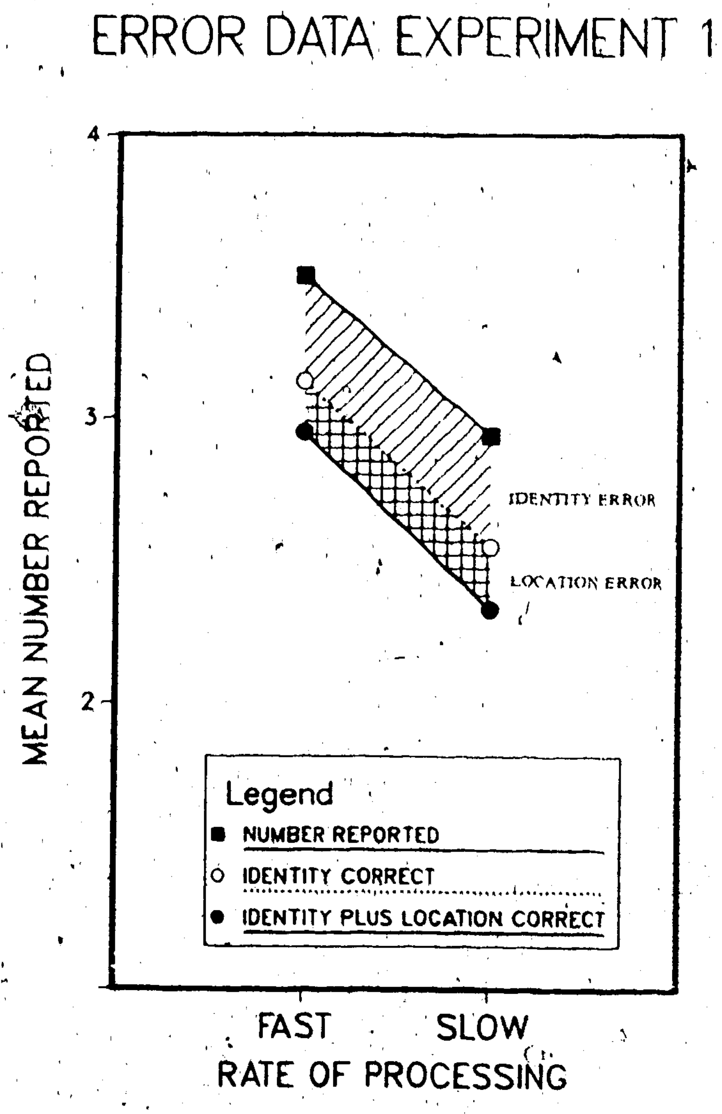

Figure 6. Performance and error scores for "fast" and "slow" visual information processors.

processes exert their influence via integration and interaction at peripheral sensory levels. The third masking process affects the iconic read-out mechanism, which requires allocation of central, selective attention. That is, the mask is thought to divert attention from, or interrupt, the read-out of information from iconic memory, particularly at longer SOAs (see also Turvey, 1973; Breitmeyer, 1984).

At this point, Norman and Bobrow's (1975) distinction between "data-limitations" and "resource-limitations" becomes relevant. That is, performance on the backward masking task at short SOAs (25 ms) can be considered "data-limited" because it is constrained by processes of inhibition and integration at sensory levels which limit the quantity or quality of information available for processing at higher levels. Performance at longer SOAs, on the other hand, can be considered "resource-limited", because it is determined by the rate of read-out or rate of visual information processing.

Michaels and Turvey's (1979) masking theory allows for specific predictions concerning performance at relatively long SOAs. That is, according to Michaels and Turvey (1979), at sufficiently long SOAs, all four letters in iconic memory will have been read-out before the attention attracting and disrupting effect of the mask has set in. Although the data from the present experiment do not allow a clear cut interpretation, they do suggest that at longer SOAs (i.e., 300 ms) "attentional masking" has lost some of its effect (see Figure 5). That is, it is possible that at SOAs of 400 or 500 ms, the performance curves of the "fast" and "slow" processors would have merged, thereby reflecting a change from performance being "resource-limited" to being "data-limited". If this is indeed the case, the deficit of "slow" visual information processors, can be interpreted in terms of a slow attentional transfer mechanism and not in terms of a limited iconic memory or short term memory capacity.

This interpretation is important, especially in light of studies by Gopher and Kahneman (1971) and Kahneman, Ben-Ishai, and Lotan (1973). These researchers devised a dichotic listening task which required subjects to monitor a relevant message on one ear and to ignore an irrelevant message presented simultaneously to the other ear. The key experimental manipulation was the presentation of a tone which *recued* the ear the subject had to monitor and report from. Their basic finding was that errors following the tone had promising validity for predicting proficiency in flying high-performance aircraft and for predicting the number of accidents among Israeli bus drivers. Kahneman, Ben-Ishai, and Lotan (1973) argued that the dichotic listening task could be interpreted as indexing "the *speed* and effectiveness with which *attention* is redirected to a relevant channel after an orientation cue" (p. 113; italics added).

Following these impressive demonstrations, Keele and Hawkins (1982) reported evidence for a trait of "attentional flexibility". Here, attentional flexibility was referred to as the rapid switching of attention from one source to another. Keele and Hawkins (1982) suggested that attentional flexibility "could potentially be of use in predicting success for skills that require *rapid shifts of attention* because of rapidly changing task demands" (p. 3; italics added). In some sense, the processing of short duration multi-letter visual displays can be interpreted as involving the rapid switching of attention from one letter to another letter. Thus, what has been termed "rate of visual information processing" or "read-out from iconic memory" in this study, may well be the same ability that Keele and Hawkins (1982) described as "speed of attention".

Keele and Hawkins' (1982) conceptualization of the process of iconic read-out as being mediated by the mechanism of selective attention is supported by studies which show that selective attention can move to designated locations in space independent of eye movements and improve the processing of a stimulus occupying that location (Bashinski & Bacharach, 1980; Jonides, 1983; Posner, 1980; Remington, 1980; Tsal, 1983). Furthermore, it has been shown that recognition of short duration alphabetic material involves consistent left to right processing (Bryden, 1960; Mewhort, Merikle, & Bryden, 1969; Chow & Murdock, 1976). In other words, transfer of linguistic material from iconic memory to short term memory seems to involve *attentional scanning* in a left to right order. These results, then, are consistent with Michaels and Turvey's (1979) claim that iconic read-out requires allocation of central, selective attention, thus supporting the contention that the construct rate of visual information processing is related to attentional factors.

Having discussed the processes underlying performance on the backward masking task, the critical question of this study can now be addressed. Is speed of visual information processing an important factor influencing performance success in fast action sports? To answer this question, functions relating mean number reported correctly (identity plus location) to exposure duration for the "top-ranked" group and "bottom-ranked" group in each type of sport, are shown in Figure 7. The data for each sport were separately subjected to a 2 (group) x 6 (exposure duration) mixed analysis of variance (ANOVA) with repeated measures on the factor exposure duration.

With respect to the hockey players, this analysis yielded significant main effects for group, $F(1,4)=53.9$, $p<.01$; and exposure duration, $F(5,20)=75.3$, $p<.001$; as well as a significant interaction between group and exposure duration,

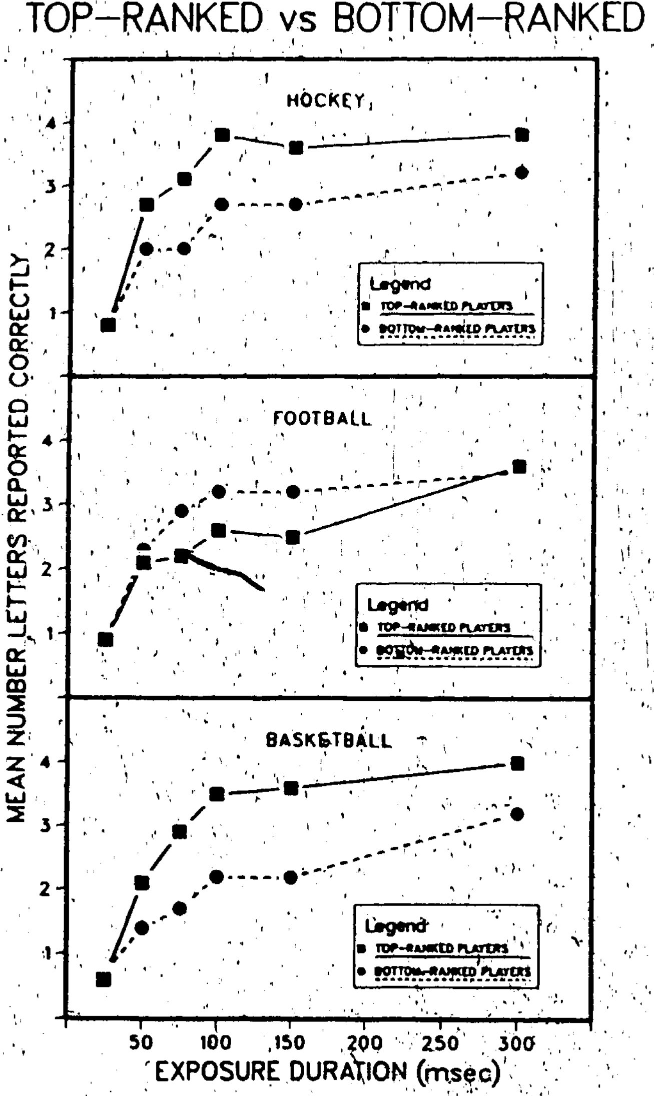

Figure 7. Mean number of letters reported correctly (identity and location correct) as a function of exposure duration for "top-ranked" athletes and "bottom-ranked" athletes in the sports of hockey, football, and basketball.

$F(5,20)=3.42$, $p<.025$. Tests on simple main effects demonstrated that the "top-ranked" players were superior to the "bottom-ranked" players at all but the shortest exposure duration ($p<.025$). A quite similar pattern of results was found for the basketball players. That is, significant effects for group, $F(1,2)=23.02$, $p<.05$; exposure duration, $F(5,10)=56.44$, $p<.001$; and for the group x exposure duration interaction, $F(5,10)=3.77$, $p<.05$. These findings support the notion that the ability "speed of visual information processing" is a correlate of success in the sports of hockey and basketball.

However, in the sport of football only the main effect of exposure duration was significant: exposure duration, $F(5,20)=23.94$, $p<.001$; group, $F(1,4)=2.61$, $p>.2$; group x exposure duration, $F(5,20)=1.25$, $p>.25$. In other words, the "top-ranked" players performed no differently from the "bottom-ranked" players on the backward masking task at any exposure duration.

In short, rate of visual information processing seems to differentiate successfully between "top-ranked" and "bottom-ranked" players in the sports of basketball and hockey, but not in football. Some speculations concerning this anomalous finding for the sport of football follow. Unlike hockey and basketball where the perceptual requirements are similar regardless of playing position, Canadian football makes different perceptual demands contingent upon the position played. Consequently, performers who play on the interior of the offensive and defensive line are selected more on their physical strength, weight, and size than on their perceptual skills. On the other hand, offensive and defensive backfielders have high visual perceptual demands and are selected in part on their ability to gain visual information quickly from a rapidly changing environment and make accurate, fast decisions upon that information. Unfortunately, the subjects from the football team came almost equally from both types of populations. Moreover, since the backfielders scored higher than the linesmen but were ranked lower by their coaches, it is difficult to make unequivocal interpretations of the experimental data with respect to this sample of football players. In retrospect, selection on the basis of players who perform the same function maybe more reasonable in sports that select performers on their ability to play in very diverse but narrowly defined offensive and defensive positions.

Finally, it is important to point out that while the results of this first experiment seem to suggest that rate of visual information-processing is an important determinant of performance level in homogeneous samples of varsity hockey and basketball players, it is certainly not the only determinant, nor necessarily the most important one. Indeed, it is likely that in non-homogeneous groups other factors such as amount of experience, technical expertise, fitness, strength, motivation, personality, body size and body composition probably account for more of the variance in performance level than rate of visual information processing. The results of this first study, however, do suggest that, *other things being equal,* rate of visual information processing is an important factor responsible for differences in athletic performance in fast action, open-skill type sports.

EXPERIMENT TWO

Introduction

The results of the previous experiment seemed to suggest that in the sports of basketball and ice-hockey, "top-ranked" athletes process visual information at a faster rate than "bottom-ranked" athletes. The goal of the present experiment was to extend these findings to varsity downhill skiing and professional ice-hockey. The conjecture was that both these sports provide the athlete with "speeded situations" such that fast perceptual analyses and rapid shifts of attention are required in order to be successful. It was hypothesized, therefore, that "top-ranked" athletes in both the professional ice-hockey group and the varsity downhill skiing group would be faster processors, as indexed by performance on the backward masking task, than the "bottom-ranked" athletes.

METHOD

Subjects

Two groups of subjects participated in this experiment. The first group consisted of 21 professional ice-hockey players (mean age 25.9 years; range 22 to 31), and the second group consisted of 15 male members of the University of Alberta downhill ski team (mean age 22.5 years; range 19 to 25).

Subject selection proceeded on grounds of "accessibility" and "availability". Specifically, the downhill skiers were unpaid volunteers, while the professional hockey players participated in the experiment as part of a regular fitness testing program ordered by the head coach.

All subjects had normal or corrected to normal vision.

Apparatus

Test and masking stimulus were presented on the face of a PDP-11/10 computer-controlled high resolution TV monitor (model VT-55). The display screen was covered by dark green Bristol board in which centrally a rectangular "window" had been made to allow the visible presentation of 7 sequential stimulus positions. This window was 23 mm wide and 5 mm high.

Displays were viewed binocularly in a normally lit room. Viewing distance was fixed at 58 cm by requiring the subjects to rest their chins upon a supporting frame.

Stimuli

The target stimuli consisted of linear arrays containing four different letters. The letters for each array were randomly chosen from all consonants (except the letter "y"), to minimize the possibility of subjects interpreting the arrays as words. A total of 78 target arrays were constructed.

Software generated uppercase characters were employed. Each letter was approximately 3 mm square, with one dark blank space of 3 mm separating each letter in the row.

The masking stimulus consisted of a row of seven stars ("*"), covering completely the four letter array.

Target stimuli were presented for six different stimulus durations: 50, 75, 100, 125, 175, and 300 milliseconds. Following target offset, the masking stimulus was employed for 200 milliseconds.

Procedure

Subjects were tested individually in a session lasting about 15 minutes. After entering the room, the subjects were informed about the nature of the experimental task. Each subject then received 18 practice trials, three at each stimulus duration, to orient them to the task.

Following these practice trials, the subjects received blocks of 10 trials for each stimulus duration. Order of presentation of stimulus duration was from long (300 ms) to short (50 ms).

For each trial, subjects were instructed to fixate on the center of the screen. Subjects then started a trial by pressing a button which initiated a warning tone of 50 ms. After a delay of one second, the target stimulus appeared, which, after a certain stimulus onset asynchrony (SOA), was replaced by the masking stimulus. The masking stimulus stayed on for 200 ms, after which the screen went blank. The subjects were instructed to write down as many letters as possible from the briefly presented stimulus array on a specially prepared response grid. It was emphasized that the letters had to be reported in the correct location and that guessing was allowed if one was uncertain. As soon as the subject had finished the written response, he could initiate the next trial by pressing the button again.

After testing was completed, the head coaches of the respective teams were approached with the request to rank order the athletes who had participated in the experiment according to the criterion of "general excellence", with players of equal ability being given tied or equal ranks. Based on these assessments, "top-ranked" and "bottom-ranked" groups were formed in each sport. That is, athletes in the top 30 percentile of the rankings were classified as "top-ranked" athletes, and athletes in the bottom 30 percentile of the rankings were categorized as "bottom-ranked" athletes.

RESULTS AND DISCUSSION

Based on the criterion of total number of letters reported in the correct position, that is, identity plus location correct, the athletes in both subjects pools were differentiated into two groups: a "fast processor" group, consisting of the athletes with the higher total number of letters reported correctly, and a "slow processors" group, consisting of the athletes with the lower total number of letters reported correctly. In the sport of professional ice-hockey, mean age of the "fast" processors was 26.8 years (range 23 to 31) and of the "slow" processors 25.2 years (range 22 to 31). In the sport of varsity downhill skiing, the mean age of the "fast" processors was 23.2 years (range 20 to 26) and of the "slow" processors 21.8 years (range 19 to 24).

Figure 8 portrays the mean number of letters correctly reported per trial as a function of stimulus duration, for "fast" and "slow" processors in the sports of professional ice-hockey and varsity downhill skiing. For each sport, the data underlying the performance curves of Figure 8 were separately subjected to a 2 (group) x 6 (exposure duration) ~~mixed~~ analysis of variance (ANOVA), with repeated measures on the factor exposure duration. For both sports, the main effects and interaction were significant. That is, for the sport of professional ice-hockey the

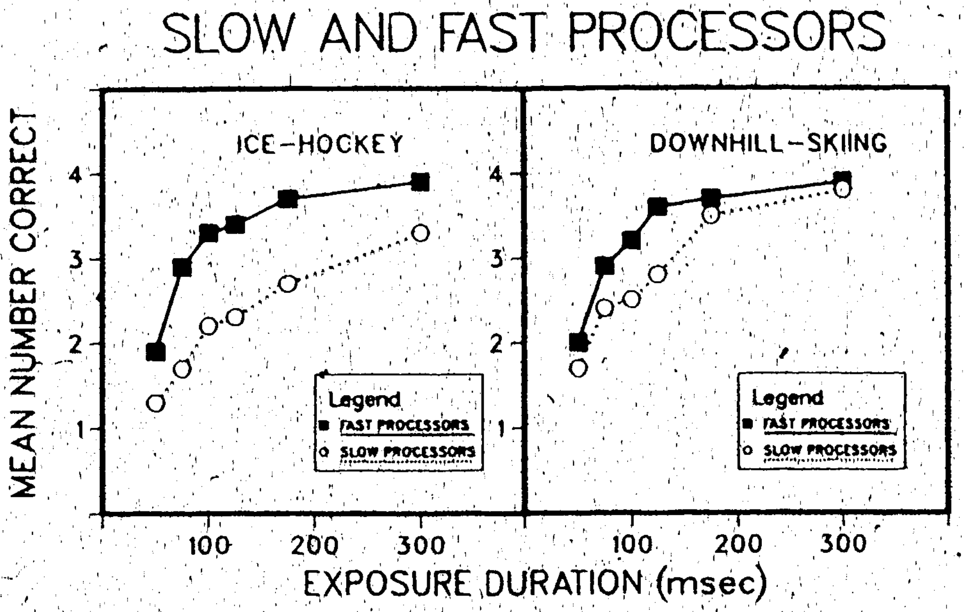

Figure 8. Mean number of letters reported correctly (identity and location correct) for "fast" visual information processors and "slow" visual information processors, in the sports of professional ice-hockey and varsity downhill skiing.

F-values were: group, $F(1,18)=55.55$, $p<.001$; exposure duration, $F(5,90)=88.41$, $p<.001$; exposure duration x group, $F(5,90)=2.95$, $p<.05$; and for the sport of varsity downhill skiing the *F*-values were: group, $F(1,12)=17.14$, $p<.001$; exposure duration, $F(5,60)=75.12$, $p<.001$; exposure duration x group, $F(5,60)=2.89$, $p<.05$.

The most interesting finding is the significant interaction between exposure duration and group. Tests on the simple main effects of the factor group were significant at all exposure durations ($p<.05$). This was the case for both the professional ice-hockey group and the varsity downhill ski group. In other words, "fast" processors reported more letters correctly than the "slow" processors at all exposure durations.

On first sight, this finding does not seem compatible with the results of Experiment 1, where it was found that at the shortest exposure duration "fast" and "slow" processors performed equally well. However, this potential discrepancy is easily reconciled by the fact that in Experiment 1 the shortest exposure duration was 25 milliseconds while in Experiment 2 it was 50 milliseconds.

Another interesting finding is that the range of performance differences between "fast" and "slow" processors in the professional ice-hockey group is twice as large as that in the varsity downhill ski group (mean overall difference .93 and .43 letters, respectively). Almost exclusively, this difference seems to be due to the poor performance of the "slow" processors in the professional ice-hockey group. This effect is demonstrated in Figure 9, where mean number of letters reported correctly is shown collapsed over exposure duration for "fast" and "slow" processors in both sports. What could be the reason for the extremely poor performance of the "slow" processors in the professional ice-hockey group on the backward masking task?

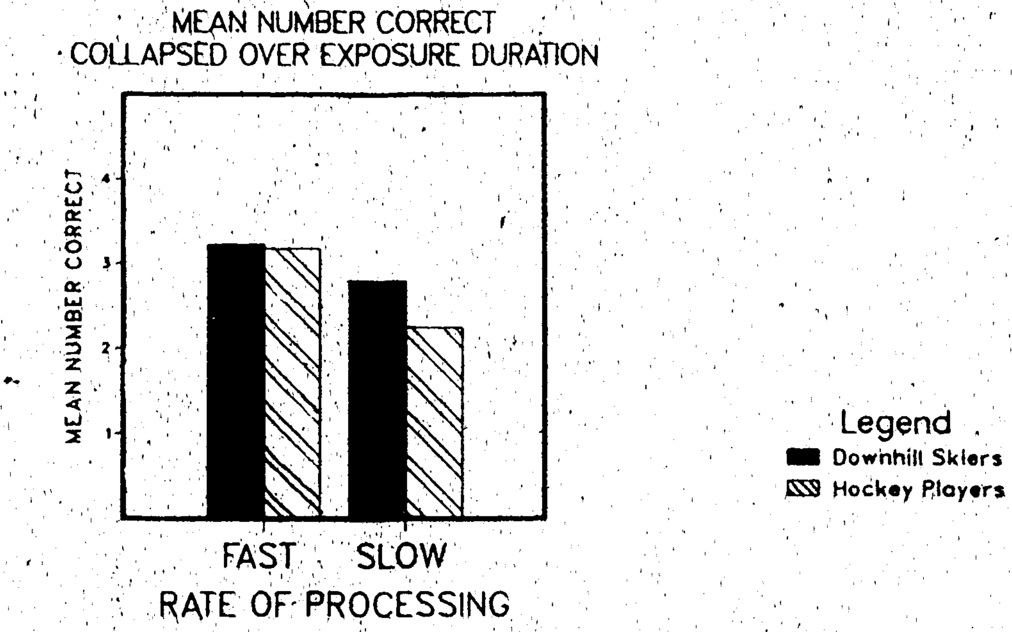

Figure 9. Mean number of letters reported correctly (identity plus location correct) averaged over exposure duration for "fast" and "slow" processors in the sports of professional ice-hockey and varsity downhill skiing.

A plausible explanation focusses on the role of "reading experience" as a confounding factor.[1] It is well established that performance on the backward masking task is influenced by the "familiarity" of the perceiver with the stimulus material (Mewhort, Merikle, & Bryden, 1969; Taylor & Chabot, 1978; Michaels & Turvey, 1979; Campbell & Mewhort, 1980). It seemed possible, therefore, that the professional hockey players differed widely in this respect.

In an attempt to quantify "reading experience", the athletes in the professional ice-hockey team were asked how many years of high school and how many years of college or university they had "enjoyed". Based on this information, a "reading experience" score was calculated for each athlete, defined as the total sum of number of years of high school plus number of years of college or university. The results of this analysis supported the suggestion that the "slow" processors in the professional ice-hockey group were extraordinarily slow, because of lack of reading experience or familiarity with written material. That is, the "fast" processors were also the more educated athletes with a mean "reading experience" score of 5.7 years (range 4 to 10), while the "slow" processors were clearly the athletes who had enjoyed significantly less education, with a mean "reading experience" score of 4.2 years (range 3 to 5) ($t(18) = 4.29$, $p < .01$).

As in Experiment 1, error scores for Experiment 2 were calculated by scoring the data according to three criteria:

1. letters reported per se
2. identity correct
3. identity plus location correct

---

[1] An alternative interpretation related to IQ level or reading ability could not be evaluated, since management of the professional hockey club did not allow their players to be subjected to an IQ test or reading ability test.

This resulted in three performance scores on basis of which mean number of identity errors and mean number of location errors were calculated for each subject (see Experiment 1).

Figure 10 and Figure 11 display the three performance scores and resulting error scores for "fast" and "slow" processors in the sport of professional hockey and varsity downhill skiing, respectively. A 2 (group) X 3 (score) mixed analysis of variance (ANOVA) with repeated measures on the factor score revealed significant main and interaction effects for both sports. For the varsity downhill skiing group the F-values were as follows: group, $F(1,12)=11.64$, $p<.01$; score, $F(2,24)=136.36$, $p<.001$; group X score, $F(2,24)=6.94$, $p<.01$. For the professional ice-hockey group the ANOVA revealed the following F-values: group, $F(1,18)=34.55$, $p<.001$; score, $F(2,36)=92.36$, $p<.001$; group X score, $F(2,36)=7.56$, $p<.01$.

The significant interactions indicated that in both the varsity downhill skiing group and the professional ice-hockey group, "slow" processors made more identity errors than "fast" processors. However, the difference in total mean number of errors made (identity plus location errors) between "fast" and "slow" processors was twice as large in the professional hockey group than in the varsity downhill skiing group (.56 and .27 respectively). This finding, therefore, is not inconsistent with the previously made contention that the "slow" processors in the hockey group might have been "inexperienced readers".

Given the preceding analysis, it is not surprising to find that the backward masking task did not successfully discriminate "top-ranked" ahtletes from "bottom-ranked" athletes" in the professional hockey group. Figure 12 presents mean number of letters reported correctly (both identity and location correct) for "top-ranked" and "bottom-ranked" athletes in both sports as a function of exposure

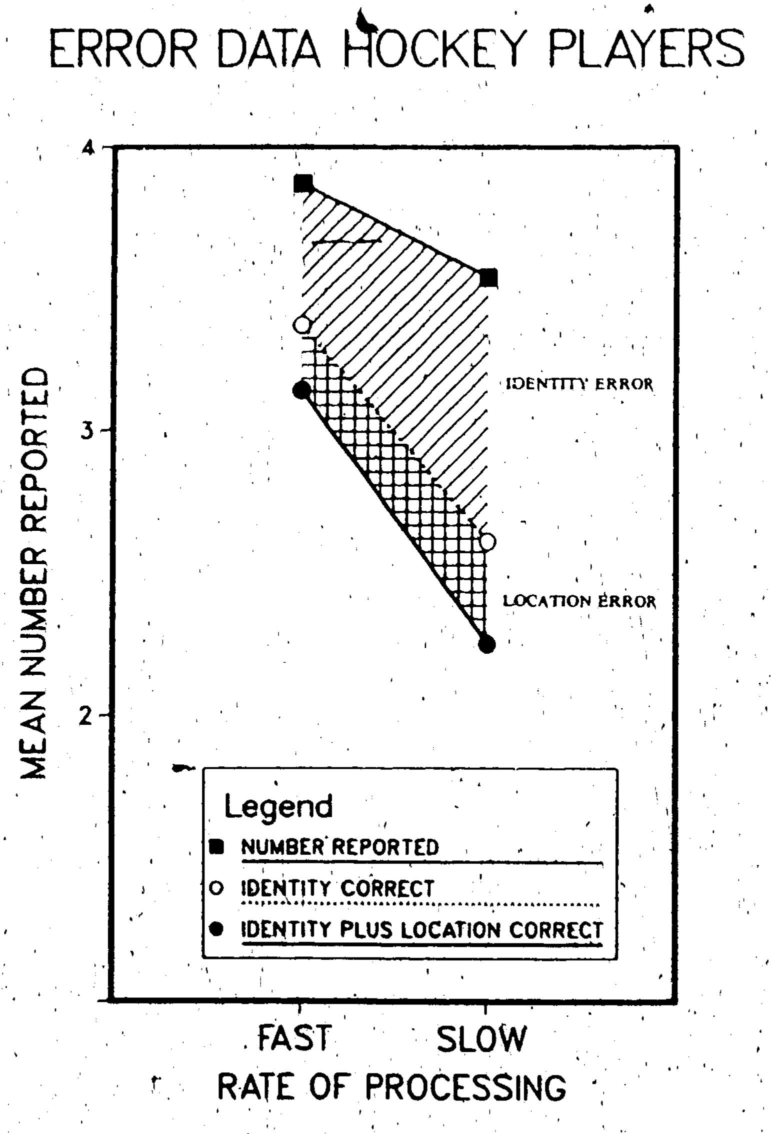

Figure 10. Performance and error scores for "fast" and "slow" visual information processors in the sport of professional hockey.

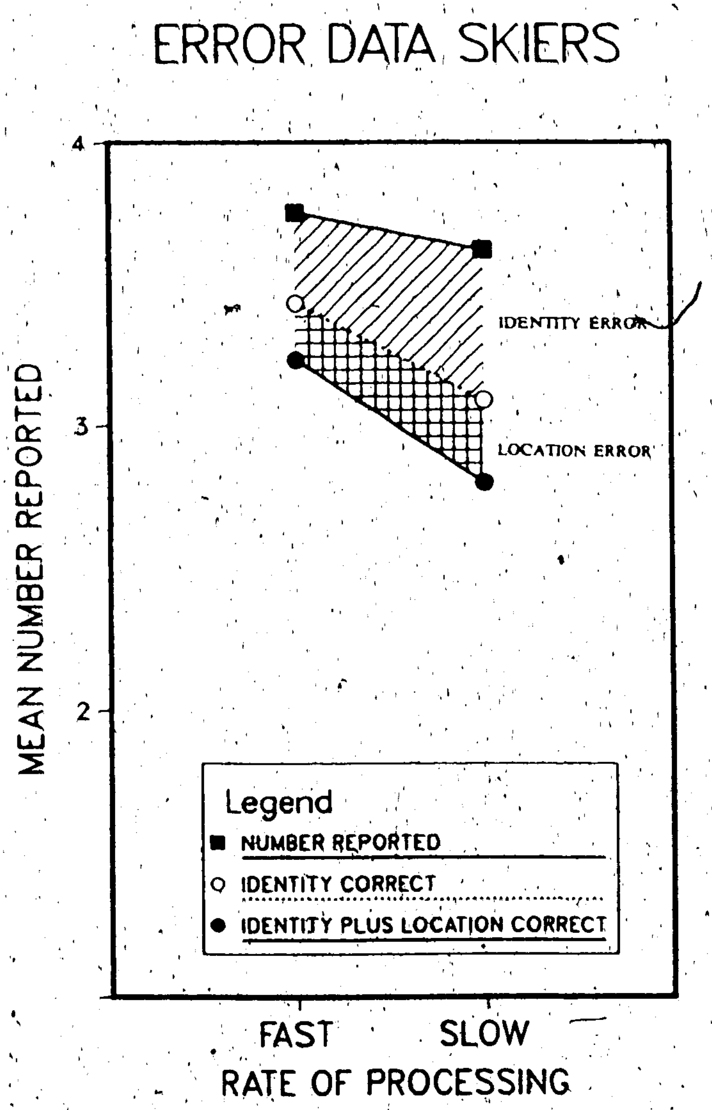

Figure 11. Performance and error scores for "fast" and "slow" visual information processors in the sport of varsity downhill skiing.

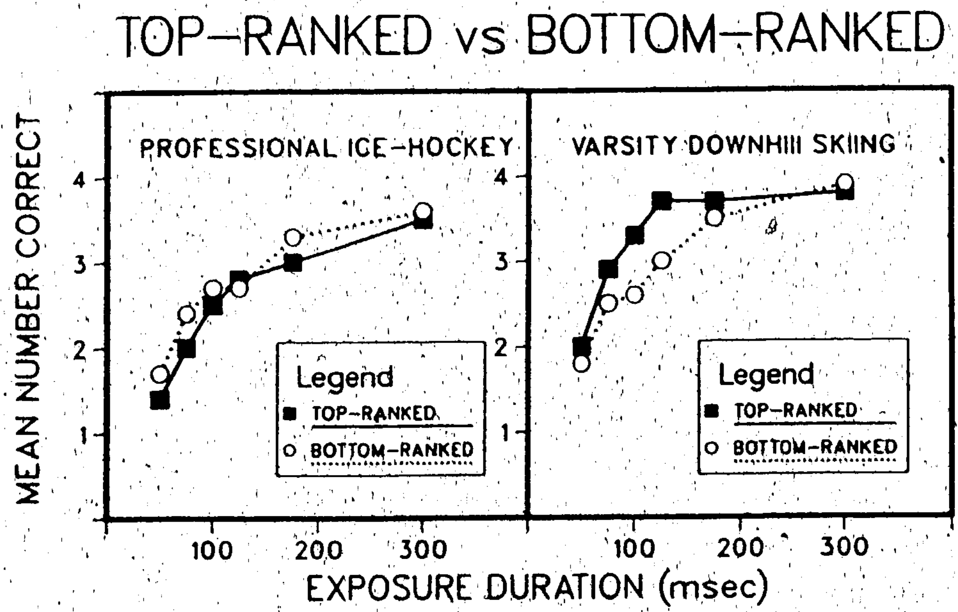

Figure 12. Mean number of letters reported correctly (identity plus location correct) as a function of exposure duration for "top-ranked" and "bottom-ranked" athletes in the sports of professional hockey and varsity downhill skiing.

duration. As is clear in Figure 12, "top-ranked" athletes in the professional hockey group *did not* perform better on the backward masking task than "bottom-ranked" athletes. This finding was statistically confirmed by ANOVA, which yielded only a significant effect for exposure duration (group, $F(1,10)<1$; exposure duration, $F(5,50)=71.38$, $p<.001$; group x exposure duration, $F(5,50)=1.11$, $p>.2$).

In view of the previous discussion of the possible confounding role of "reading experience" in the professional hockey group, this finding is hardly surprising. Clearly, the backward masking task in its present form, namely the identification of a string of consonants, is not a valid instrument to differentiate "top-ranked" from "bottom-ranked" athletes in subject pools who are not homogeneous in terms of "reading experience". It is suggested that for such subject groups high-speed perception tasks have to be developed which require the identification or classification of stimulus material of equal familiarity to all subjects.

An alternative interpretation of the backward masking technique's failure to differentiate "top-ranked" from "bottom-ranked" professional athletes, holds that the process of "natural selection" may have resulted in all professional hockey players having very similar, and fast rates of processing. Given the potential confounding of the present instrument of measuring rate of visual information processing, it is impossible to evaluate this interpretation, which therefore remains a viable possibility. Evaluating professional athletes among themselves on a un-contaminated high-speed perception task, and comparing them as a group to proficient, but lower level athletes in the same sport might test this possibility. In order for the above interpretation to be supported, it should be found that the professional athletes show similar rates of processing within their own group, but superior rates of processing compared to lower level athletes.

With respect to the varsity downhill skiing group, it is evident from Figure 12 that "top-ranked" athletes are faster processors than "bottom-ranked" athletes. An ANOVA carried out on the data underlying the performance curves of the downhill skiers, supported this observation: group, $F(1,8)=3.22$, $p > .1$; exposure duration, $F(5,40)=48.01$, $p<.001$; group x exposure duration, $F(5,40)=3.01$, $p<.025$. Tests on the simple main effects of the factor group (Winer, 1971, pp. 518-532) indicated that the "top-ranked" athletes reported more letters than the "bottom-ranked" athletes at exposure durations of 75, 100, and 125 ms ($p<.025$).

This finding, then, combined with the fact the "fast" and "slow" processors performed equally well at the shortest (50 ms) and longer exposure durations (175 and 300 ms), that is, the "data-limited" regions, indicates that "fast" and "slow" processors, or "top-ranked" and "bottom-ranked" athletes, differ in terms of temporal resources or rate of processing. In other words, the deficit of "slow" processors probably reflects a processing speed limitation, that is, a slow rate of attentional transfer or read-out from iconic memory to short term memory, rather than a structural capacity limitation of either iconic memory or short term memory.

In summary, the results of this experiment demonstrated that rate of visual information processing as indexed by the backward masking task could separate successfully "top-ranked" from "bottom-ranked" athletes in varsity downhill skiing. This result corroborates the findings of Experiment 1, where it was found that rate of visual information processing was a correlate of performance success in varsity basketball and varsity ice-hockey. However, this relationship between rate of visual information processing and athletic performance success was absent in professional hockey players. This latter result was discussed in terms of the possible confounding role of "reading experience", and in terms of the notion of "natural selection" which may equate professional athletes with respect to speed of processing.

EXPERIMENT THREE

Purpose

In the previous two experiments attempts were made to predict performance success in fast action skills from individual differences in rate of visual information processing. The results showed that speed of visual information processing, as measured by the backward masking technique, was relatively successful in differentiating "top-ranked" university athletes from "bottom-ranked" university athletes. These promising results provided the impetus for the present study, which was mainly concerned with *construct validation* of the rate of visual information processing concept. According to the American Psychological Association:

> "Construct validity is ordinarily studied when the tester has no definite criterion measure of the quality with which he is concerned, and must use indirect measures. Here the trait or quality underlying the test is of central importance, rather than either the test behavior or the scores on the criteria." (APA, 1954, p. 14; cited in Neale & Liebert, 1980, p. 40)

In Experiments 1 and 2, rate of visual information processing was operationally defined as a score on the backward masking task. This specific operational definition limits the generality of the rate of visual information processing construct. That is, the theoretical concept of rate of visual information processing was equated with only one set of operations: Rate of visual information processing was considered to be whatever the backward masking task measures. In order to delimit more accurately the construct "rate of visual information processing" an attempt was made to establish its construct validity. Assessing construct validity depends on "testing for a convergence across different measures or manipulations of the same thing" (Cook & Campbell, 1979, p. 61). In other words, if there is indeed a construct rate of visual information processing, defined as a general, task independent, basic ability, then *different measures* of this hypothetical construct should correlate highly. That is, a difference in a general ability (e.g., rate of visual information processing) would likely be manifested in a great variety of tasks, and not be restricted to one specific situation.

Besides increasing the generality of the speed of processing construct, successful construct validation has the additional advantage that other tasks besides the backward masking task will be reflective of speed of visual information processing. That is, a second goal of construct validation is to obtain multiple and overlapping measures or manipulations of the same construct. The attempt to represent the construct rate of visual information processing in "multiple delivery modes" is of significant importance, since the predictive power of the backward masking task is restricted to subject populations which are equated in terms of "reading experience".

The approach taken in this study to investigate the construct validity of rate of visual information processing is from an information processing perspective. Hunt, Frost, and Lunneborg (1973), and more recently Keele and Hawkins (1982) are among the few researchers who have applied this approach to the study of individual differences in performance. One central characteristic of this information processing approach is the attempt to isolate *basic* processes underlying task performance. This goal (to isolate constituent processes) is prompted by the consideration that task performance is generally the combined result of a variety of processes, and therefore, performance on one task might not correlate highly with performance on another task. In order to alleviate this problem, the information processing approach attempts to derive scores which reflect only the basic process in question. The technique of process isolation has been described by Keele and Hawkins (1982) as follows:

> "Typically, the isolation of a process score involves a variant of subtracting two conditions that differ only in a process or duration of a process. Sometimes that subtraction is disguised as a parameter obtained from curve fitting (e.g., slope of a function), but nevertheless the logic is basically subtractive." (Keele & Hawkins, 1982, p. 5)

In combination with process isolation, the general strategy of administering a variety of alternative tasks to the same individuals is employed, so that correlations among derived process scores can be examined.

Following directly from the above, another characteristic of the information processing approach emphasizes theoretical rationale in selecting tasks and processes to be studied (Keele & Hawkins, 1982). This feature of the information processing approach is also necessitated by the large number of potential determinants of individual differences in task performance. A viable strategy to cope with this problem is "to adopt a particular theoretical perspective concerning the etiology of the individual differences" in order to narrow "the range of possible mechanisms that are implicated in the individual differences" (Salthouse, 1985, p. 78). For reasons outlined earlier, in the present series of experiments attention has been focussed on the concept of speed of visual information processing, or speed of attention, as a potentially important mediator in skilled behavior.

In this (third) experiment, an attempt was made to establish the construct validity of the rate of visual information processing concept by investigating performance of the same individuals on five different tasks which supposedly rely heavily on the ability to process visual information quickly and accurately. Besides the backward masking task, which was used in the previous two studies to define rate of visual information processing, two rapid aiming tasks (i.e., single aiming and reciprocal tapping) were employed, a choice reaction time task and a simple reaction time task. In the following, these tasks will be described more specifically, their inclusion justified, and the "subtractive logic" that was applied in order to isolate the speed of processing factor, outlined.

In summary, the goal of the third experiment differed from that of Experiments 1 and 2 (to establish the *criterion validity* of the concept rate of visual information processing, indexed by the backward masking task, in predicting athletic success), for it was aimed at determining the *construct validity* of the rate of visual information processing concept.

Rapid Aiming Tasks

The choice of rapid aiming tasks in the present attempt to validate the construct of speed of visual information processing, presupposes that perceptual processes play an important role in the control of aimed movements. The following brief review of body of literature concerned with the significance of visual information in motor control may both justify and qualify this assumption.

A main issue in the motor behavior area, at least since the beginning of this century, has been the role of visual information in the control of aimed movements. This issue is theoretically important, since it is directly related to the relative contribution of peripheral and central mechanisms in the control of movements. The basic centralist proposition is that movements can be adequately executed in the absence of feedback, since "motor programs" containing the appropriate commands have been specified in advance. Once a motor program for a particular movement has been set up, execution of that movement will be controlled in open-loop fashion, that is, it will "run off" without reliance on peripheral feedback. Peripheral models, on the other hand, emphasize the role of feedback information (visual and kinesthetic) in the control of ongoing movements. In other words, peripheral models argue that movement execution proceeds in closed-loop fashion.

Of course, both positions are not mutually exclusive. More than 80 years ago, Woodworth (1899) realized this, for he contended that aimed movements have two segments: an initial impulse phase, which is preprogrammed and ballistic in nature, and a current-control phase which relies on visual feedback. Recent experimentation and theorizing have supported this integrated view of movement control. Welford, Norris, and Schlock (1969), and more recently Glencross and Barrett (1983), for instance, proposed a distinction between not so accurate ballistic, distance covering processes and feedback-guided corrective processes for homing on to the target.

However, this two-process view of motor control probably does not hold for very fast, short movements. That is, very short duration movements are predominantly executed in open-loop fashion, since the processing of visual information might take longer than the duration of the movement itself (Klapp, 1975).

This particular line of reasoning has been used by Keele and Posner (1968) to experimentally determine visual feedback processing time, that is, the time required to identify, decide, and initiate within movement corrections (Zelaznik, Hawkins, & Kisselburgh, 1983). Keele and Posner (1968) manipulated visual feedback by turning off the lights at the start of the movement on half of the trials. They found that 190 millisecond single aiming movements were made with the same spatial accuracy in the vision trials as in the no-vision trials. However, spatial accuracy for 260 to 450 millisecond movements was superior in the vision condition than in the no-vision condition. On the basis of these findings, Keele and Posner (1968) suggested that visual feedback processing time is in the order of 190-260 milliseconds.

Several authors have pointed out that Keele and Posner (1968) might have overestimated the duration of visual feedback processing time. Carlton (1981), for instance, drew attention to the fact that the basic assumption behind vision manipulation studies might be faulty. That is, in comparing movement accuracy under blind and vision conditions, it is assumed that increased accuracy in the vision condition is due to response adjustments based on visual feedback information regarding the discrepancy between the position of the hand and the target. Carlton (1981), however, suggested and was able to show that subjects actually do not watch their hand but instead focus attention on the target. The implication is that accurate visual error information is not available until the hand approaches the target location. To test this suggestion Carlton (1981) precluded certain portions of the movement via a metal shield. The results demonstrated that increases in movement time and error rate occurred only when 75% or more of the movement amplitude was unsighted. These findings indicate that visual feedback processing times of 190-260 milliseconds are overestimated by the amount of time it takes the hand to reach a position where visual monitoring comes into play. Using high-speed cinematography techniques, Carlton (1981) estimated visual feedback processing time to be 135 milliseconds.

Zelaznik, Hawkins, and Kisselburgh (1983) also critized Keele and Posner's (1968) vision manipulation. They argued that the random presentation of vision and no-vision trials may have led the subjects to adopt the strategy of preparing to control the movement in the absence of feedback. That is, the subjects may have opted for a strategy of preprogramming all fast movements and executing them without consideration of feedback. When Zelaznik, Hawkins, and Kisselburgh (1983) used experimental procedures in which they either block[illegible]r randomized the vision and no-vision trials, they found that subjects could benefit from visual information at movement times as low as 100 milliseconds. They also pointed out that the accuracy score employed by Keele and Posner (1968) (hit or miss) might not have been sensitive enough to detect differences between conditions.

Another serious criticism of Keele and Posner's (1968) study, concerns their technique of turning out the lights as an experimental manipulation of visual feedback. This procedure does not take into account that visual information continues to be available for some time after the physical offset of the stimulus in a buffer-store called iconic memory (e.g., Coltheart, 1980). Therefore, the technique of turning out the lights might not be a valid manipulation to show the role of vision in the control of rapid aiming movements. A similar observation has been made by Elliott and Allard (1985).

In short, most researchers agree upon the existence of two phases in the control of aimed movements: an initial distance covering phase which is under programmed control, and a homing phase, which is under visual control. Recent estimates of the time required to process visual feedback information and to use this information to "home in" on the target are in the order of 100 milliseconds.

Two major mathematical laws have been proposed to define the relationship between speed, amplitude, and accuracy of aimed movements. Using both the reciprocal tapping and the single aiming paradigm, Fitts (Fitts, 1954; Fitts and Peterson, 1964) argued that movement time (MT) is a logarithmic function of amplitude (A) and the target width (W): $MT=C1+C2(Log(2A/W))$. In other words, MT is linearly related to $\log(2A/W)$, which is known as the index of movement difficulty (ID). This linear relationship between MT and ID is called Fitts' Law and is a very robust phenomenon.

An important characteristic of the experimental conditions under which Fitts' Law holds, is that subjects are constrained in terms of movement accuracy. That is, the targets are of a specific width and the subjects are instructed to make no more than 5% errors in their movements. Given this constraint in terms of movement errors, it seems likely that Fitts' Law is especially applicable to movements which are predominantly under visual control.

In fact, Fitts (1954) acknowledged explicitly the importance of perceptual processes in the control of aimed movements. According to Fitts, the function relating movement time to index of difficulty represents the *rate of information processing* of the human motor system. However, Fitts defined the motor system as "including the visual and proprioceptive feedback loops that permit S to monitor his own activity" (p. 381). In other words, Fitts clearly accepted the functional significance of visual feedback in motor control. To emphasize this point, Fitts (1954) stated ".... that the fixed information-handling capacity of the motor system probably reflects a fixed capacity of central mechanisms for monitoring the results of the ongoing motor activity ...." (p. 391).

Fitts' Law, however, has not gone unchallenged. Schmidt, Zelaznik, Hawkins, Frank, and Quinn (1979) discovered a linear speed-accuracy trade off relationship rather than a logarithmic relationship. Schmidt et al. (1979) employed a single aiming task but, unlike Fitts did not constrain the subjects in terms of movement accuracy, but in terms of movement time. That is, subjects were required to make movements of a specific duration and toward a single target point rather than a target region. The movement times ranged from 140 to 200 milliseconds, and thus were considerably less than the ones typically observed in Fitts' experiments, where no upper limit on the duration of the movements was imposed. Under these conditions, Schmidt et al. (1979) found the following linear relation: $W(e)=C1+C2(A/MT)$. $W(e)$ is the effective target width, operationalized as the standard deviation of the movements actually produced.

Three major hypotheses have been proposed to characterize the conditions which result in a linear rather than a logarithmic trade-off for aimed movements (Wright & Meyer, 1983). The 'movement-brevity' hypothesis, and the feedback-deprivation hypothesis are closely related and were first discussed by Schmidt et al. (1979). The essence of both hypotheses is that brief movement times make it impossible to process and use visual feedback information to control the movement. In other words, it is suggested that the linear trade-off is a result of programmed control during the initial impulse phase. Schmidt et al. (1979) proposed an impulse-variability model for ballistic, programmed movements, arguing that there is a linear relationship between movement velocity and end-point variability. However, recent estimates of visual feedback processing time are in the order of 100 milliseconds, thus rendering the above hypotheses rather implausible.

Meyer, Smith, and Wright (1982) proposed the temporal-precision hypothesis. This hypothesis implies that a linear trade-off results from the requirement to produce precise movement times. In other words, the temporal-precision hypothesis predicates that the linear trade-off occurs when subjects are required to produce precisely specified movement times. On the other hand, a logarithmic trade-off occurs when spatial precision rather than temporal precision is stressed (Wright & Meyer, 1983).

Wright and Meyer (1983) conducted an experiment to evaluate the above hypotheses. They found a linear trade-off for precisely timed movements even when their durations exceeded an amount of time (200 milliseconds) certainly sufficient to process visual feedback. This result suggests that the linearity does not depend on movement brevity and/or feedback deprivation per se. Instead it supports a temporal precision hypothesis which suggests that linear trade-off occurs when aimed movements must have precisely specified durations (Wright & Meyer, 1983). Therefore, Schmidt's et al. (1979) linear trade-off between speed and accuracy seems to be applicable to movements constrained in terms of designated movement times, while Fitts' Law seems to hold for movements constrained in terms of movement accuracy.

Several models have been developed in attempts to explain Fitts' Law. A common characteristic of these models is that they have emphasized both the distinction between distance covering processes and homing processes, and the crucial role of visual feedback in the latter processes.

According to the iterative correction model (Crossman & Goodeve, 1963; Keele, 1968), following an initial preprogrammed movement which puts the hand controlled stylus close to the target, several discrete corrective movements are made.

These corrective movements are assumed to be made on basis of visual error information. The discrete, iterative correction feedback model predicts that a disproportionate amount of time is spent near the target since presumably several visual error corrections are needed, each requiring a specific amount of time.

Beggs and Howarth (1972) and Howarth, Beggs, and Bowden (1971) suggested a single correction model in which the initial "distance covering" movement would be followed by a single corrective movement.

The general applicability of these two correction models as theoretical accounts of Fitts' Law is open to question since both found only mixed support. For instance, some of the difficulties in deciding the presence of visually guided error corrections in aimed movements on the basis of a marked reduction of velocity during a movement, have been identified by Langolf, Chaffin, and Foulke (1976): (1) initial damping of the arm may smooth and perhaps mask any changes in velocity, and (2) the correction process may by continuous rather than discrete (Wallace & Newell, 1983).

In summary, there appear to be at least two control processes in aimed movements: (a) a rapid, distance covering, not so accurate impulse phase, and (b) a more accurate homing phase which is under visual control. Accepting the idea that Fitts' Law is applicable to visual feedback controlled movements, it can be expected that Fitts' Law is mediated by the rate at which visual feedback information is processed, since the duration of corrective processes carried out in the homing phase will be influenced by rate of visual information processing. Put differently, if the result of the initial impulse phase, that is, the distance covering movement, needs to be corrected, and if these corrections are based on visual error information, then the rate at which this visual information becomes available (rate of visual information processing) will be reflected in the duration of such corrections. That is, the duration of the homing phase may depend on rate of visual information processing. Consequently, movement time in Fitts' Law would not only be a function of amplitude and target width, but also of rate of visual information processing.

There is some evidence from the developmental literature which would suggest that rate of visual information processing is an important variable in Fitts' Law. Hay (1979), for instance, reported that the visually guided component of aiming movements in a pointing task decreases from 7-11 years of age. This might point to a rate of visual information processing related improvement, since it has been demonstrated that rate of visual information processing increases within that age range (Di Lollo, Arnett, & Kruk, 1982).

In a reciprocal tapping task, Schellekens, Kalverboer, and Scholten (1984) studied duration, velocity, acceleration, and accuracy of movements in children of 5, 6, 7, 8, and 9 years of age. They found that age differences appeared mainly in the homing time, not in the duration of the distance covering movement phase. With increasing age, homing time decreased. Schellekens et al. (1984) contended that age differences in homing time may be related to both rate of information processing of the subject, and the accuracy of the distance covering impulse phase.

Following Fitts (1954), in the present study the reciprocal of the *slope* of the function relating movement time to index of difficulty is taken as an estimate of speed of information processing. The argument here is that the slope represents time per unit of information, and consequently its reciprocal can be used as an index of information processed per unit of time. Therefore, it was hypothesized that individuals who are designated as "slow" processors by their performance on the backward masking task, will show relatively steep slopes, while "fast" processors are expected to show relatively shallow slopes.

Choice Reaction Time Task

In a choice reaction time task (Donders B-type) there are several stimuli and each stimulus has its own unique response. In such a situation the subject has to identify the stimulus and chose the correct response. It has been established that reaction time increases linearly as a function of the logarithm of the number of stimulus-response alternatives (Hick, 1952; Hyman, 1953). As with the rapid aiming tasks, the reciprocal of the slope of the function relating reaction time to number of stimulus-response alternatives or amount of information, can be taken as a measure of dynamic capacity or rate of processing.

The particular choice reaction time task employed in the following experiment is an adaptation of the experimental paradigm first developed by Rosenbaum (1980), and later extensively used by Miller (1982, 1985) and Reeve and Proctor (1984, 1985). The imperative stimulus in this paradigm is a plus sign (+) in one of four possible locations. The four possible target stimuli are assigned to four horizontally and linearly arrayed response keys. That is, the four permissable responses involve pressing an appropriate response key with the middle or index finger of either hand. The assignment of responses to stimuli or target positions is in a left-to-right order, so that, for example the correct response to a target in the far left position of the display is with the middle finger of the left hand.

On some trials, a precue, consisting of plus signs in two of four possible stimulus locations, provides partial advance information, in that it indicates that the subsequent target stimulus will appear in one of the two cued locations. These trials with an informational precue are called "prepared" trials, and always indicate, and therefore prepares a combination of two responses. Stated differently, the "prepared" trials can be considered as constituting a 2-choice reaction time task.

On other trials the precue is neutral, that is, it consists of plus signs in all four possible stimulus locations, and, hence, does not provide any useful information. These trials, which are called "unprepared" trials, effectively constitute a 4-alternative choice reaction time task.

In other words, the cue has the effect of reducing the number of possible stimuli and the number of possible responses. In effect, the cue transforms the experimental task from a 4-alternative choice reaction time task (2 bits of information) to a 2-alternative choice reaction time task (1 bit of information). In general, cueing studies have demonstrated that responses to the target stimulus are faster when a cue provides partial information about the upcoming target stimulus. It has been claimed that the effect of the cue is related to "response preparation" (Miller, 1982), "response selection" (Reeve & Procter, 1985), and "stimulus identification" (Adam, Humphreys, & Wilberg, 1986).

Despite the controversy as to the locus of the facilitative impact of the cue, it has been consistently demonstrated that processing of the cue takes time. That is, the effectiveness of the cue in reducing choice reaction time varies as a function of the interval between the onset of the cue and onset of the target stimulus (stimulus onset asynchrony, SOA), which in essence reflects the duration of the cue. At very short SOAs (1 ms), reaction time on the "prepared" trials equals reaction time on the "unprepared" trials. However, increasing SOA to 500 ms results in a substantial (80 ms) benefit in reaction time for the "prepared" trials (2-choice reaction time task) relative to the "unprepared" trials (4-choice reaction time task).

We hypothesized that "fast" visual information processors are able to decode the cue faster than "slow" visual information processors, and therefore will benefit from the informational cue at shorter SOAs than "slow" visual information processors. The choice of the differential reaction time between "prepared" and "unprepared" trials as the dependent variable, follows the "subtractive logic" intended to isolate basic underlying processes as advocated by Keele and Hawkins (1982). Presumably, a differential reaction time at short SOAs is reflective of the speed with which the cue has been processed, and therefore, is an indirect measure of information processing or speed of attention.

Simple Reaction Time Task

The delay between the occurrence of a stimulus and the initiation of a response is called reaction time. Reaction time includes the interval during which neural impulses are conducted to and from the brain, but depends primarily upon central processes (Fitts & Posner, 1967). Consequently, it has often been hypothesized that individuals with fast reaction times may have more efficient processing information systems than those with slower reaction times (e.g., Siegel, 1985).

In general it has been shown that athletes do react quicker than non-athletes (Slater-Hammell, 1955; Youngen, 1959, Knapp, 1961) but simple reaction time has not proven tremendously accurate as a predictor of athletic success (Nielsen & McGown, 1985).

Simple reaction time was included in the attempt to establish the construct validity of the speed of visual information processing ability, even though it was not possible to devise a measure of simple reaction time based on Keele and Hawkins'

(1982) "subtractive logic". It was added because it was easy to measure, but more importantly, because it has been of widespread interest in past research. It was expected that "fast" visual information processors would show faster simple reaction times than "slow" visual information processors.

METHOD

Subjects

Sixty-nine students, 30 male and 39 female, at the University of Alberta served in a single experimental session lasting approximately one hour and thirty minutes (mean age 21.3 years; range 18 to 31). All subjects were unpaid volunteers, claimed they were right handed, and had normal or corrected to normal vision.

Apparatus

A PDP 10/11 laboratory computer was used to present stimuli on a VT-55 Display monitor and to record responses from a 4-key response box.

A 60x60 cm X-Y digitizing tablet (Supergrid), mounted on a 85 cm high table, was used in conjunction with the PDP 10/11 computer to record movement times and accuracies in the rapid aiming tasks. Sampling rate was 100 Hz and measuring accuracy of the X-Y digitizing tablet was set at 0.1 mm.

General Procedure

All subjects received the experimental tasks in the same order: First, the simple reaction time task; second, the backward masking task; third, the choice reaction time task; fourth, the single aiming task; and fifth, the reciprocal tapping task. The order of the experimental conditions within each task was also the same for each subject. At the beginning of each of the above tasks, the subjects were informed about the specific task requirements, and given practice trials.

In the first three tasks, the subject was seated in front of the display screen (VT-55). Viewing distance was kept constant at 50 cm by employing a chin rest.

In the two rapid aiming tasks, the subject stood facing a table on which the X-Y digitizing tablet was mounted.

Experimental Tasks and Procedures

Backward Masking Task. In this task the subject was asked to report as many letters as possible from briefly presented 4-letter target arrays, followed by a masking stimulus. This task was identical to the backward masking paradigm used in Experiment 2.

Simple Reaction Time Task. In this task the subject was required to press a response key as soon as possible following the detection of a target stimulus. Each trial consisted of the following sequence of events:

1. visual warning signal ("+" sign") accompanied by an auditory warning signal, both lasting 400 ms.

2. variable foreperiod, lasting between 500 and 4000 ms.

3. target stimulus ("*" sign), which remained visible until subjects responded.

An intertrial interval of 1.250 s separated the response in one trial from the start of the next trial. The visual stimuli were presented-in the center of the display screen. The display screen was covered by dark green Bristol board in which centrally a rectangular "window" (4x6mm) had been made to allow the visible presentation of the stimuli. Responses were to be made by pressing a response key held in the preferred hand with the thumb.

Eight variable foreperiod durations were employed: 500, 1000, 15000, 2000, 2500, 3000, 3500, and 4000 ms. Each subject received 16 trials at each foreperiod, making a total of 128 trials. The same random order of foreperiods was used for each subject. Sixteen practice trials preceded the test trials, two at each foreperiod.

Subjects were instructed to react as quickly as possible to the target stimulus by pressing the response key. It was emphasized not to make errors of anticipation. Feedback was not provided.

Choice Reaction Time Task. The choice reaction task involved four possible keypress responses made by the index and middle fingers of each hand. The target stimulus was a plus sign (+) in one of four possible locations in a horizontal array. The stimuli were mapped in a spatially compatible manner to four sequentially arrayed response keys. A precue, consisting of plus signs in two of four possible stimulus locations, enabled the selective preparation of 2 of the 4 possible finger responses.

Two general preparation or cuing conditions were used. In the "prepared" trials, the cue consisted of plus signs in either the two left most stimulus positions, or in the two right most stimulus positions. This indicated that the response had to be made by one of the two fingers on the left hand or on right hand, respectively. In other words, in the "prepared" trials subjects could selectively prepare finger responses on either the left or right hand. In the "unprepared" trials, the "cue" consisted of plus signs in all four stimulus locations. Following, this kind of cue, the imperative stimulus could appear in any of four possible locations, thereby rendering selective preparation strategies inappropriate.

Stimuli were presented on the display screen (model VT-55) of the PDP-11/10 computer. The display screen was covered by dark green Bristol board in which centrally a rectangular "window" had been made to allow the visible presentation of 7 sequential stimulus positions. This window was 23 mm wide and 5 mm high. Responses were made by [illegible]ssing one of four circular response buttons, which were linearly arrayed in the center of a home-made response box (20x14x9 cm), resting on the table in front of the subjects. Each button was 8 mm in diameter, with a 12 mm separation between each button.

On each trial, warning, cue, and target stimlus were presented sequentially in the window on the viewing screen. The warning stimulus was a row of four plus signs generated from the standard character set of the computer. Each sign was approximately 3 mm square, with one dark blank space of 3 mm separating each sign in the row. The four element warning stimulus was replaced after 500 ms by the cue stimulus, which consisted of plus signs in two of the four possible positions. After a variable delay (SOA), the cue stimulus was replaced by the target stimulus, a single plus sign that always occupied one of the previous indicated positions by the cue. Five SOAs between cue and target stimlus were employed: 25, 100, 175 250, and 500 ms. An intertrial interval of 1.5 s separated the response in a trial from the start of the next trial.

Each subject received a block of 60 trials for each SOA. Order of SOA presentation was from the longest (500 ms) to the shortest (25 ms). A rest period of 90 s was provided between blocks. Within a block of 60 trials, there were 20 trials for each of the three cuing conditions ("unprepared" trails, "prepared hand:left", and "prepared hand:right"). The same random order of these cuing conditions within a block of 60 trials was administered to each subject. Fifteen practice trials were given at the start of the experiment.

Subjects were explicitly told to take advantage of the cue stimlus. They were instructed to react as quickly as possible to the target stimulus by pressing the correct response key. It was emphasized not to make more than 3 errors in a block of 60 trials. Feedback in terms of response speed was not provided. Feedback in terms of response accuracy was self-evident.

Single Aiming task. In this task the subject was required to produce a single, discrete aiming movement, by moving a stylus from its home position towards a circular target as quickly and accurately as possible. Four movement amplitudes (40, 80, 160, and 320 mm) in combination with two target widths (diameters of 3 and 24 mm), resulted in 8 possible movement conditions. Movement amplitude was measured as the distance between the home position and the centre of the circular target.

Two different sheets of paper, one containing the small circular target, the other containing the large circular target, were used as stimulus material. On each sheet of paper four different home positions were marked by a small dot at distances from the center of the target circle, equivalent to the four movement amplitudes. The target circle was always positioned to the left of the home positions on the same horizontal plane.

The sheets of paper were placed on top of the X-Y digitizing tablet, and covered by a piece of clear perspex. Correct positioning of the paper sheets was ensured by aligning four guide lines on the paper sheets with four guide lines on the X-Y digitizing tablet.

The order of the movement conditions was determined via the random number generator of the PDP 11/10 computer. The sheet with the large circular target (24 mm) was presented first, with the order of amplitudes being 320, 40, 160, and 80 mm. Then the sheet with the small circular target (3 mm) was mounted on the tablet, and the order of movement amplitude was 160, 80, 320, and 40 mm. In each movement condition the subject was required to perform 3 practice trials, and 20 test trials. The subject was instructed to align the body's midline with the location of the circular target, so that the movements were always from right to left, and always towards the midline of the body. In addition, the subjects were required to hold the stylus in a pen grip fashion. On each trial, the subject placed the stylus on the required home position and, when ready, moved the stylus over the perspex as quickly as possible to the circular target. The subject was instructed to keep the stylus in contact with the perspex surface, and to come to a complete stop anywhere within the boundaries of the circular target. Following completion of a movement, the subject then returned the stylus to the home position to begin the next trial. The intertrial interval, therefore, was determined by the subject.

Whenever the stylus contacted the surface of the perspex the computer recorded the x-coordinate from the X-Y coordinate tabloid at a rate of 100 Hz, that is, every 10 ms. From these data, movement time and endpoint accuracy in the horizontal plane were calculated.

Reciprocal Tapping Task. In the reciprocal tapping task the subject was required to move the stylus repetitively between two circular targets of equal width, separated by a certain amplitude, as quickly and accurately as possible for the duration of 15 seconds. Four target widths (diameters of 3, 6, 12, and 24 mm) were orthogonally combined with four amplitudes (40, 80, 160, and 320 mm), resulting in 16 movement conditions. For each movement condition a separate target sheet was constructed, which consisted of two equally wide circular targets horizontally separated by a certain amplitude, as measured between the centres of the targets. The order of the movement conditions was the same for all subjects and was established by use of the random number generator of the PDP 11/10 computer. The order of movement conditions is presented in Appendix 1.

Subjects were instructed to position themselves such that the body midline was aligned with the location of the left target. In each condition, subjects were given a 5 second practice bout, after which one test trial of 15 seconds was administered. At the beginning of each trial, the subject was asked to place the stylus on the right target. The instructions were to start moving in response to an auditory-start signal. Fifteen seconds thereafter a second tone would signal the end of the trial. As in the single aiming task, the computer would sample the position of the stylus by recording its x-coordinate every 10 ms.

RESULTS AND DISCUSSION

In order to investigate the validity of the construct speed of visual information processing, two separate analyses were carried out. In the "extreme group" analysis, the first step consisted of forming a group of "fast" visual information processors (N=20) and a group of "slow" visual information processors (N=20) based on performance on the backward masking task. The next step consisted of comparing the performances of these two groups on the simple reaction time task, choice reaction time task, single aiming task, and reciprocal tapping task. Analyses of variance (ANOVAs) were carried out in order to determine whether the "fast" visual information processors performed more efficiently than the "slow" visual information processors. The main hypothesis to be tested was, that if speed of VIP is indeed a basic ability underlying performance on a variety of tasks, then "fast" visual information processors should outperform "slow" visual information processors especially on tasks which presumably are very sensitive to differences in speed of visual information processing. The rationale for using "extreme groups" is related to the notion of "statistical power", and implicates a greater sensitivity or chance of detecting any differences that might exist.

The second type of analysis was correlational in nature. That is, correlations were calculated between performance scores on all five experimental tasks. Of course, the performance scores of all 69 subjects tested in this study were entered in this analysis. Again, the underlying logic was that if speed of visual information processing is a meaningful, unitary, and task independent construct, it should be manifested in a pattern of high correlations among speeded scores derived from a variety of different types of tasks (Salthouse, 1985).

EXTREME GROUP ANALYSIS

For clarity of presentation this section is organized in terms of the specific tasks involved. First, however, a group of "fast" visual information processors and a group of "slow" visual information processors based on backward masking performance needs to be established. Thereafter, comparisons can be made between the performances of these two groups on the remaining experimental tasks.

Backward Masking Task

Based on the criterion of total number of letters reported in the correct position (identity plus location correct), the subjects were differentiated into two groups: a "fast" processors group (N=34) consisting of the subjects with the higher total number of letters reported correctly, and a "slow" processors group (N=34) consisting of the subjects with the lower total number of letters reported correctly. Mean age of the "fast" processors was 21.4 years (range 18 to 31), and mean age of the "slow" processors was 21.2 years (range 18 to 28). Fifteen subjects in the "fast" group were male and 19 female. In the "slow" group there were 14 male and 20 female subjects.

Figure 13 displays the mean number of letters correctly reported per trial as a function of exposure duration for "fast" and "slow" processors. An analysis of variance performed on the data underlying the performance curves of Figure 13 produced significant main effects for group, $F(1,66)=138.72$, $p<.001$, exposure duration, $F(5,330)=624.40$, $p<.001$, and an interaction of group with exposure

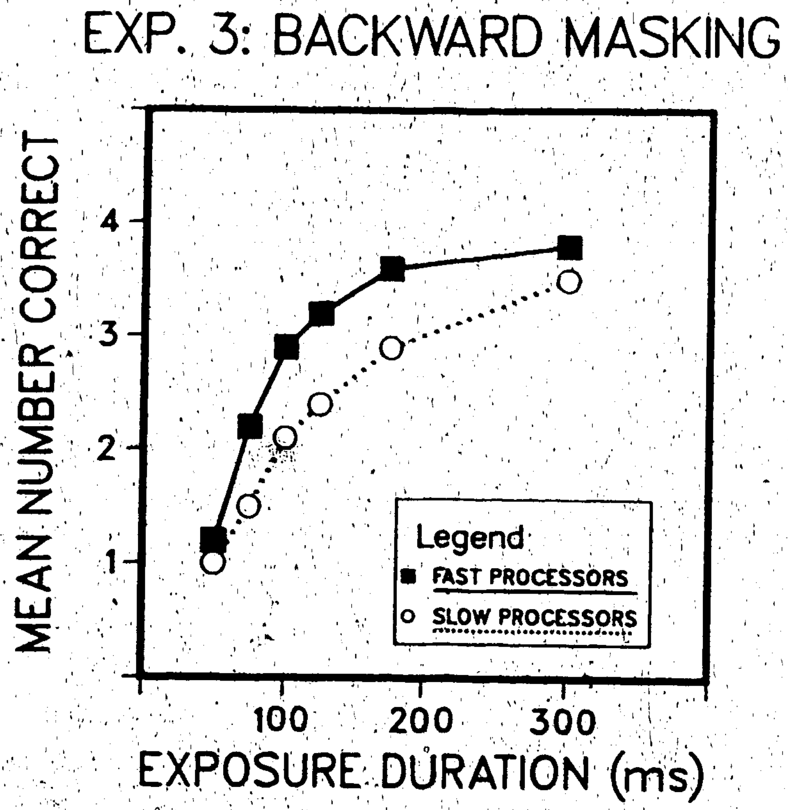

Figure 13. Mean number of letters reported correctly (identity plus location correct) for "fast" visual information processors (VIP) and "slow" visual information processors (SVIP) in Experiment 3.

duration, *F*(5,330)=10.38, p<.001. The main effect for group indicated that "fast" processors (M=3.15) reported more letters correctly than "slow" processors (M=2.60). The overall difference between "fast" and "slow" processors was .55 letter. In Experiment 2 we found an overall difference between "fast" and "slow" processors in the sport of professional ice-hockey of .93 and in the sport of varsity downhill skiing of .43. The present finding of a difference of .55 letter is similar to that of the varsity downhill skiing group, and therefore supports the earlier contention that performance on the backward masking for the professional ice-hockey group was contaminated with "reading experience".

Tests on the simple main effects of the factor group were significant at all exposure durations (p<.01). Nevertheless, the significant interaction indicated that the advantage of the "fast" processors was smaller at the shortest (50 ms) and longest (300 ms) SOAs than at the intermediate SOAs. In other words, the difference between "fast" and "slow" processors was most pronounced in the "resource-limited" regions of the performance functions. This finding, then, corroborates the results of Experiments 1 and 2, and is consistent with the argument that the deficit of "slow" processors is related to speed of attention or speed of iconic read-out.

As in the previous two experiments, error scores were calculated by scoring the data according to three performance criteria:

1. letters reported per se
2. identity correct
3. identity plus location correct

Figure 14 represents the performance scores and resulting error scores for "fast" and "slow" processors. An analysis of variance yielded significant main effects for score, *F*(2,132)=323.55, p<.001, and group, *F*(1,66)=122.33, p<.001. The absence of a

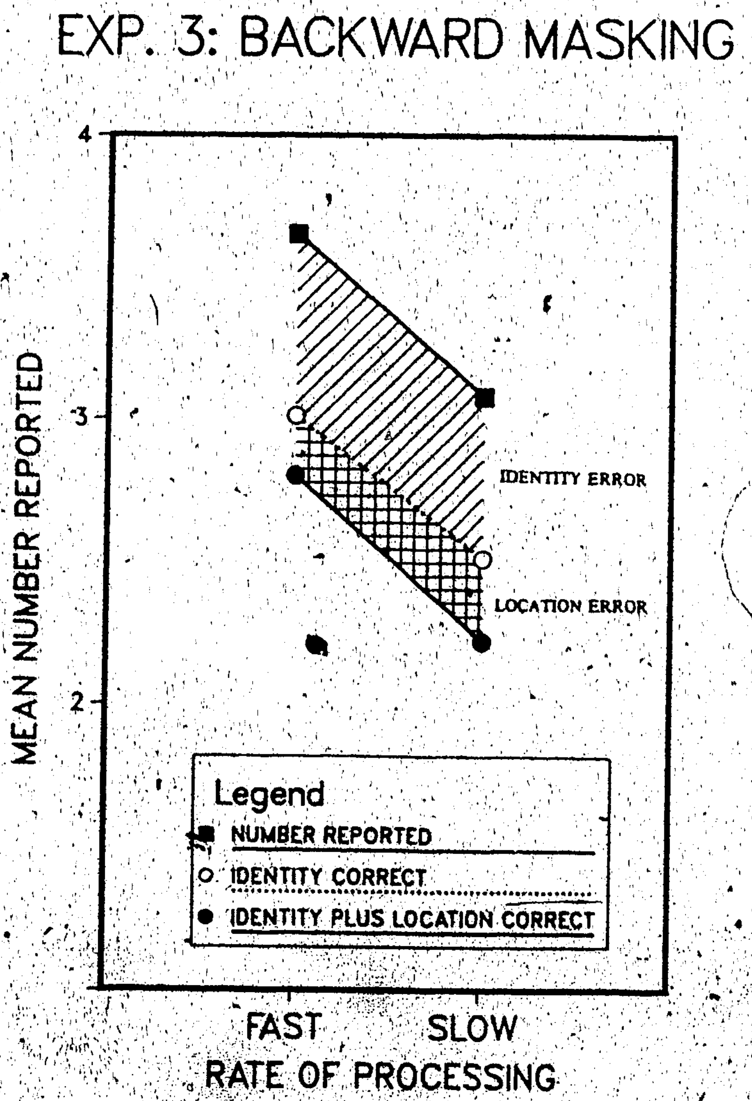

Figure 14. Performance and error scores for "fast" and "slow" visual information processors on the backward masking task in Experiment 3.

significant interaction between group and score ($F(2,132)<1$) indicated that "slow" and "fast" processors did not differ in amount of errors made.

In order to adhere to the idea of "extreme group" research, the subjects with the 20 highest total number of letters reported correctly (identity plus location correct) were selected, and the 20 subjects with the lowest total number of letters reported correctly, and labelled "fast" (visual information) processors and "slow" (visual information) processors, respectively. Mean age of the "fast" processors was 21.2 years (range 19 to 31) and mean age of the "slow" processors was 20.8 years (range 18 to 26). Ten subjects in the "fast" group were male and ten female. In the "slow" group there were 9 male and 11 female. The performance of these two groups of subjects were juxtaposed in the analyses of the following tasks.

Simple Reaction Time Task

Reaction times less than 100 ms or in excess of 500 ms were regarded as errors. Mean correct reaction times were calculated for each subject as a function of variable foreperiod. The means of the reaction times for "fast" and "slow" processors as a function of variable foreperiod are presented in Figure 15.

An analysis of variance (ANOVA) performed on the reaction time data resulted in only one significant effect, namely that of variable foreperiod ($F(7,266)=184.11$, $p<.001$). The main effect for group ($F<1$), and the interaction between group and variable foreperiod ($F(7,266)<1$) were not significant.

Overall error rate was low: 2.32 %. An analysis of variance carried out on the error data failed to detect any significant main or interaction effect, all F-values being less than 1.

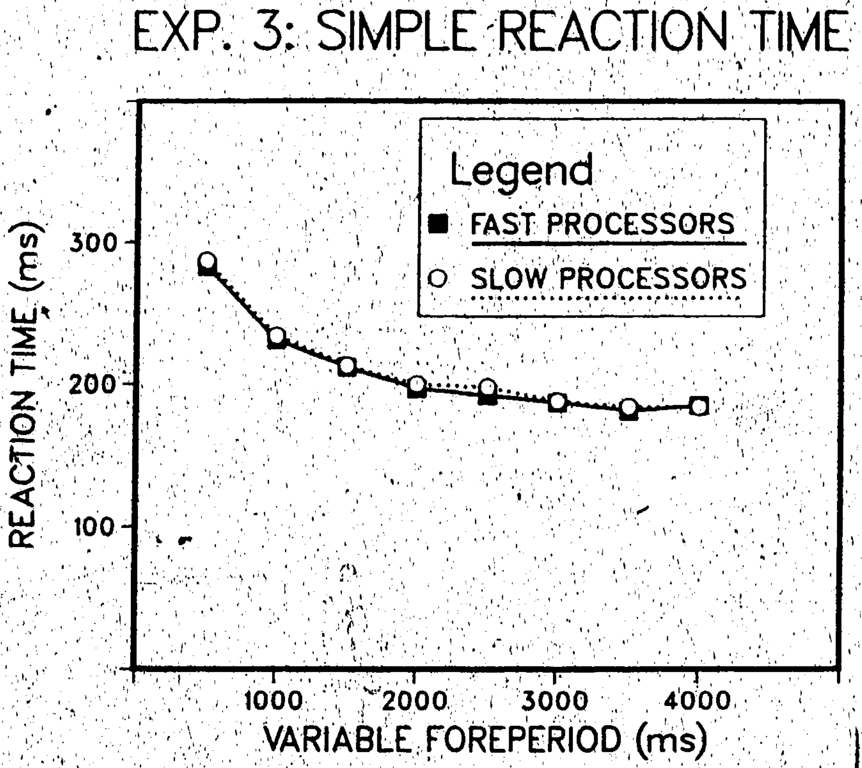

Figure 15. Mean reaction times for "fast" and "slow" visual information processors as a function of variable foreperiod in the simple reaction time task in Experiment 3.

Clearly, "fast" and "slow" processors, as determined by the backward masking task, do not perform differently in a simple reaction time situation. This finding suggests that different processes underly performance in both tasks. In the General Discussion, however, alternative interpretations will be presented.

Choice Reaction Time Task

Reaction times less than 150 ms or in excess of 1250 ms were discarded. Mean correct reaction times and proportions of errors were calculated for each subject as a function of SOA and preparation condition. The differential reaction times between the "prepared" condition (2-choice reaction time task) and the "unprepared" condition (4-choice reaction time task), reflecting in the terminology of Miller (1982) and Reeve and Proctor (1984) the amount of "response preparation", are presented in Figure 16 for the "fast" and "slow" processors as a function of SOA between the cue and the target stimulus.

Two distinct effects are apparent in Figure 16. First, the manipulation of SOA was effective, as shorter SOAs resulted in less response preparation. Second, "fast" and "slow" processors did not differ in their ability to process the cue. Even at short SOAs their performances were equal. This pattern of results was confirmed by analysis of variance performed on the differential reaction time data, which produced only a significant main effect for SOA ($F(4,152)=63.26$, $p<.001$), and not for group ($F(1,38)=1.19$, $p>.2$) or the interaction between group and SOA ($F(4,152)<1$).

Mean error rate was again very low: 2.73%. An analysis of variance with the error data as dependent variable yielded no significant effects, all F-values being less

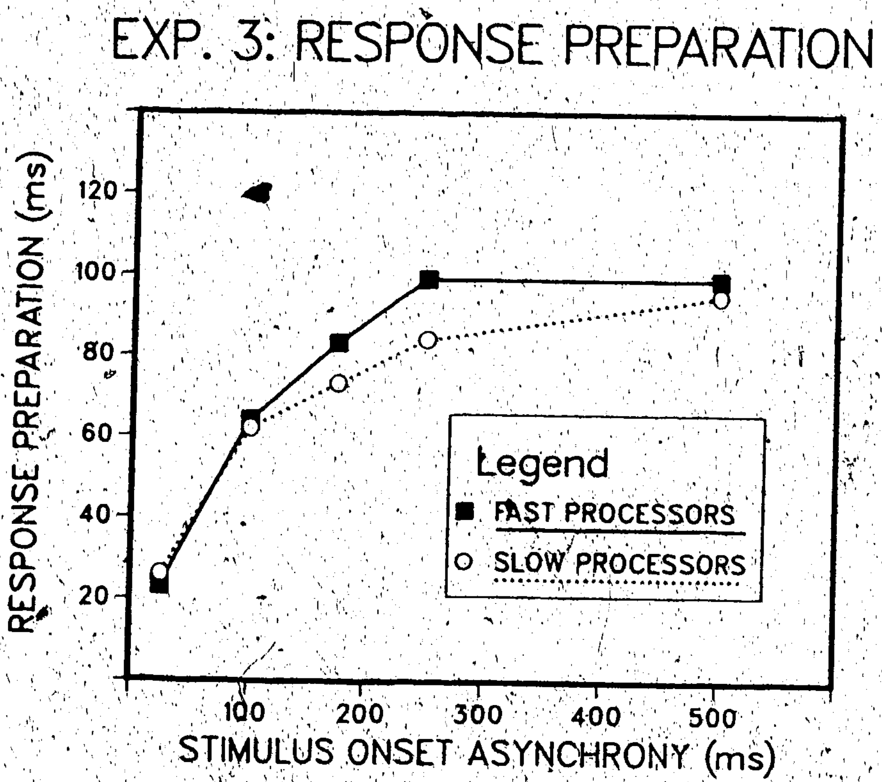

Figure 16. Amount of response preparation, defined as the difference in reaction time on "prepared" trials versus "unprepared" trials for "fast" and "slow" visual information processors as a function of SOA, in the choice reaction time task in Experiment 3.

than 1.

These data, then, do not support the expectation that "fast" processors are able to take advantage of the informational cue at shorter SOAs than "slow" processors. Possibly, different processes underly performance on the backward masking task and on the choice reaction time task.

Single Aiming Task

Mean movement times and mean movement accuracies were calculated for each subject in each condition. Movement accuracy was defined in terms of the effective target width, W(e), which is the standard deviation of the movement endpoints about their own mean also known as variable error (VE). Using effective target widths, the difficulty of the produced movements for each subject in each condition was calculated according to Fitts' formula:

Index of Difficulty=log(2A/W(e)) (A = amplitude or movement distance). By means of linear regression analyses the slope and intercept of the straight line function relating movement time to index of difficulty was established for each individual. T-tests performed separately on the slope values and intercept values indicated no differences between "fast" and "slow" processors ($t(38)=0.82$, $p > .05$, and $t(38)=1.45$, $p > .05$, respectively). That is, "fast" and "slow" processors do not appear to differ in rate of information processing as indexed by the slope of the function relating movement time to index of difficulty.

These results are presented in Figure 17, where mean movement times as a function of index of difficulty are portrayed in combination with the resulting regression lines for "fast" and "slow" processors. The best fitting line for the "fast"

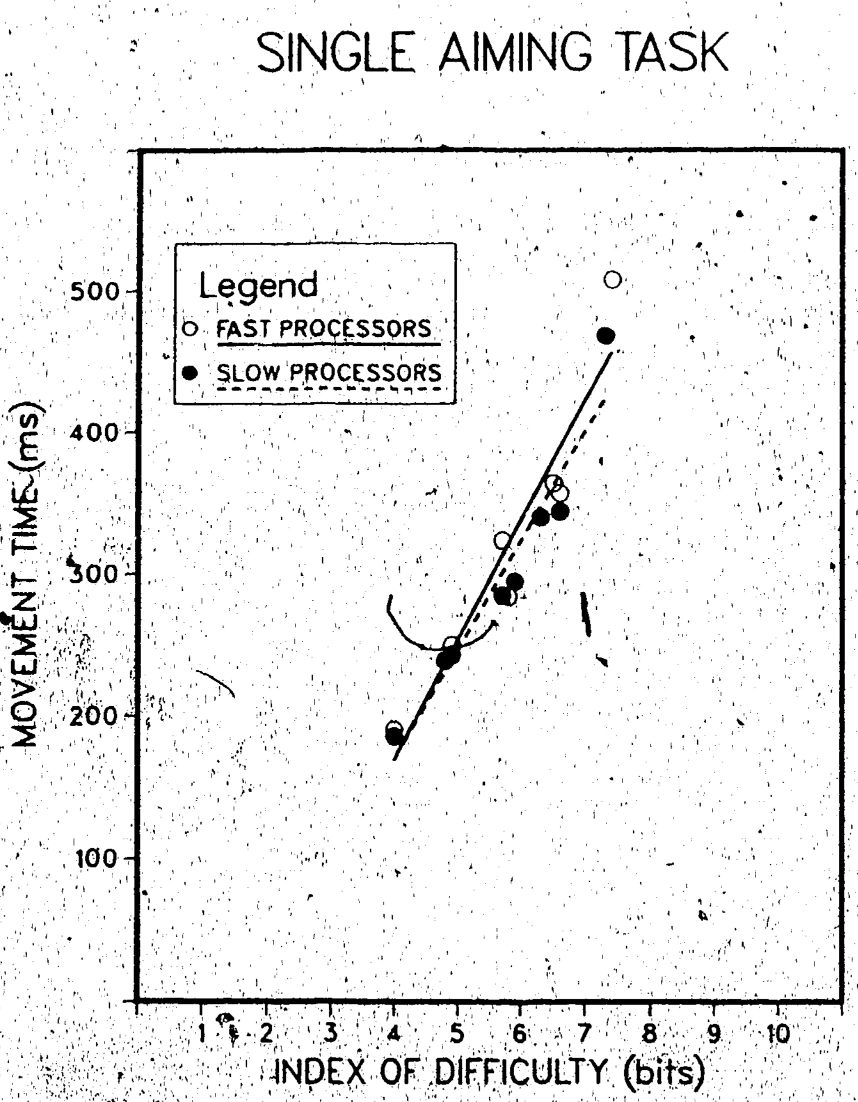

Figure 17. Regression lines relating movement time to index of difficulty for "fast" and "slow" visual information processors in the single aiming task in Experiment 3.

processors was defined by the function MT=-156+82ID, and for the "slow" processors by the function MT=-140 +78ID. The amount of variance that these functions accounted for was 91% for the "fast" processors and 94% for the "slow" processors.

Reciprocal Tapping Task

Mean movement times, effective target widths, and indexes of difficulty were calculated for each subject in each condition. Subsequently, linear regression analyses were carried out in order to establish slope and intercept of the linear function relating movement time to index of difficulty. T-tests performed separately on the slope values and intercept values indicated no differences between "fast" and "slow" processors ($t(38)=0.74$, $p > .05$, and $t(38)=0.81$, $p > .05$, respectively).

A graphical representation of mean movement time as a function of index of difficulty for "fast" and "slow" processors is presented in Figure 18, and demonstrates virtually identical performances by "fast" and "slow" processors. The regression line relating movement time to index of difficulty for the "fast" processors was defined by the function MT=-645+163ID and for the "slow" processors by the function MT=-667+167ID. The amount of variance accounted for by the respective functions was 98% ("fast" processors) and 96% ("slow" processors).

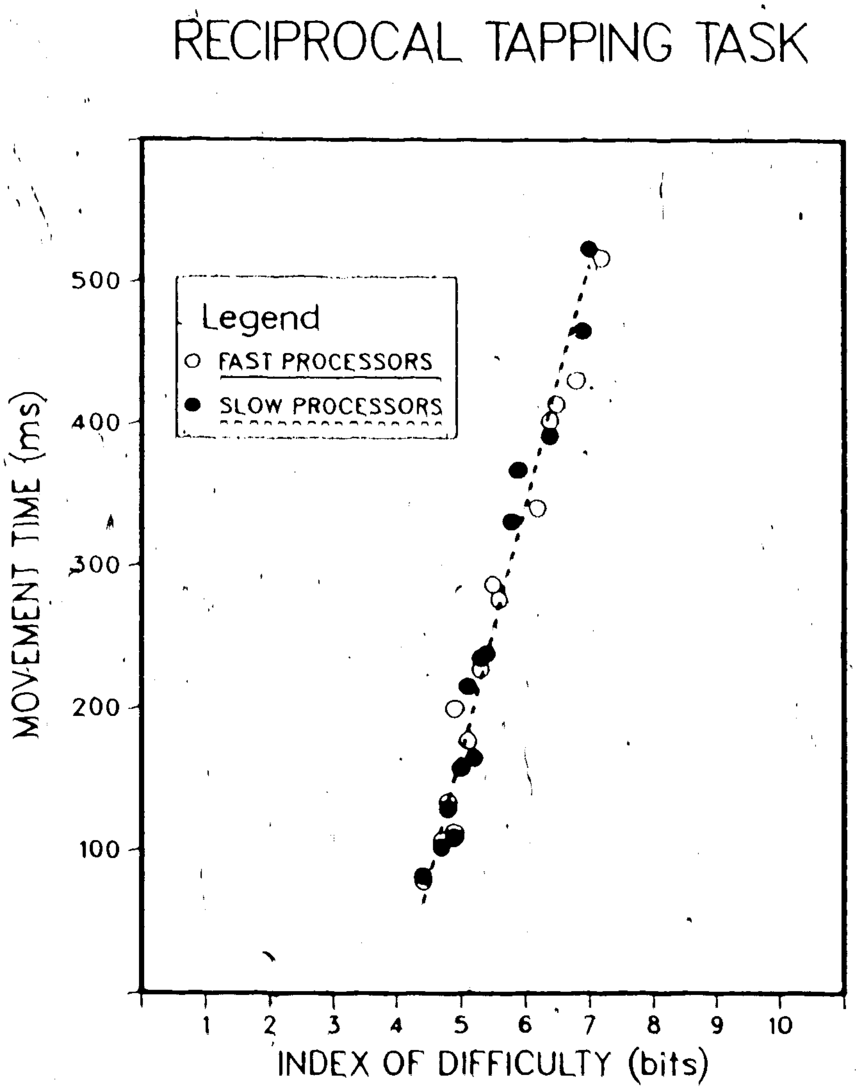

Figure 18. Regression lines relating movement time to index of diffficulty for "fast" and "slow" visual information processors in the reciprocal tapping task in Experiment 3. (Note, the regression line for the "fast" visual information processors is virtually identical to the one shown for the "slow" processors, and is, therefore, not plotted.)

CORRELATIONAL ANALYSES

In this analysis, correlations (Spearman zero-order, product-moment correlations) between the performance scores of all subjects (N=69) on all the tasks were calculated. That is, for each subject the following scores were entered into the correlation analysis:

1. - mean simple reaction time
2. - Total number of letters reported correctly (identity and location correct) in the backward masking task
3. - mean differential reaction time between "prepared" trials and "unprepared" trials in the choice reaction time task
4. - slope of the linear function relating movement time to index of difficulty in the single aiming task
5. - slope of the linear function relating movement time to index of difficulty in the reciprocal tapping task

The results of the correlational analysis are presented in Table 1. The fact that only one correlation was significant (the one between the single aiming task and reciprocal tapping task) is very striking, although not surprising in light of the results of the "extreme group" analysis. Apparently, how one does on one task has very little or nothing to do with how one does on another task.

The extremely low correlations among the different speeded measures which were all thought to reflect a basic speed of processing factor, are of obvious concern. In the following several potential problems will be identified, which may have contaminated the results, and presumably lowered the correlations.

VARIABLE	MEAN	(SD)	1	2	3	4	5
SIMPLE REACTION	210	26		-.06	-.13	.00	.05
BACKWARD MASKING	2.46	0.41			.08	.06	.16
CHOICE REACTION	70	17				.06	.10
SINGLE AIMING	76	19					.48
RECIPROCAL TAPPING	143	28					

Table 1. Correlation matrix from Experiment 3. Note, a correlation with an absolute magnitude of .20 is significant at $p<.05$, and one with an absolute magnitude of .28 is significant at $p<.01$.

One problem concerns the notion of speed-accuracy trade-off. In the two reaction time tasks, the intent was to measure minimum reaction time at the maximum level of accuracy. Since the proportions of errors were very low, it would seem that the goal of maximum accuracy was achieved. However, it can not be concluded with all certainty that each subject performed at his or her optimal speed. That is, according to the speed-accuracy operating characteristic, maximum accuracy can be achieved with different levels of speed (Pew, 1969; Pachella, 1974). It is unclear, therefore, whether the observed reaction times truly reflected the maximum speed capabilities of the subjects. It has been proposed that the best solution for this problem is to establish entire speed-accuracy operating characteristics for all subjects (Keele & Hawkins, 1982; Salthouse, 1985). Unfortunately, this strategy is often impracticable, especially when large numbers of subjects are involved.

The potential confounding between capacity to perform rapidly and bias towards either speed or accuracy is even more serious in the rapid aiming tasks. That is, whereas strict accuracy instructions were given in the reaction time tasks, the instructions in the rapid aiming tasks were potentially very confusing and ambiguous, for they required the subject to move both as quickly and as accurately as possible to the target(s). In some sense, as Salthouse (1985) has observed, these instructions are mutually exclusive, since, at least within certain regions of task difficulty, speed and accuracy are inversely ~~related.~~ In other words, even though the targets were meant to constrain all subjects in the same way, they could not prevent subjects implementing their own accuracy criteria and performing more or less to their own standards. The lack of feedback information may have encouraged subjects to do this.

In order to investigate the extent of possible speed-accuracy trade-offs, an index of "bias towards accuracy" was devised. This "bias towards accuracy" index was operationally defined as the mean absolute error (AE) produced on both left and right targets collapsed over the sixteen movement conditions in the reciprocal tapping task. Based on this criterion of "bias towards accuracy", three groups of 23 subjects each were formed. That is, the 23 subjects with the lowest mean absolute error score were classified as "high accuracy bias" subjects, and the 23 subjects with the highest mean absolute error score were classified as subjects with a "low accuracy bias". The remaining 23 subjects were categorized as subjects with a "medium accuracy bias". In Figure 19 and 20 mean movement time and mean absolute error are presented as a function of "accuracy bias". It is evident from Figure 19 and 20 that subjects in the reciprocal tapping task were differently biased towards either speed and/or accuracy. That is, some subjects emphasized the accuracy requirements of the rapid aiming task at the cost of movement speed ("high accuracy bias" group), while other subjects were more concerned with moving quickly as opposed to moving accurately ("low accuracy bias" group).

What are the implications of differential speed-accuracy trade-off strategies for Fitts' Law? In order to shed some light on this question, mean movement times and associated indexes of difficulty were calculated for the low, medium, and high "bias towards accuracy" groups. Application of linear regression analyses to this data resulted in the best fitting regression lines depicted in Figure 21. The linear regression functions for the low, medium, and high "accuracy bias" groups were, $MT = -661 + 165ID$, $MT = -707 + 174ID$, and $MT = -612 + 156ID$, respectively. The amount of variance accounted for by these regression equations was 89, 97, and 99 percent, respectively. Clearly, Fitts' Law best fits the results produced by subjects biased towards accuracy. This finding could be interpreted as suggesting that movements produced under different speed-accuracy biases might have fundamentally

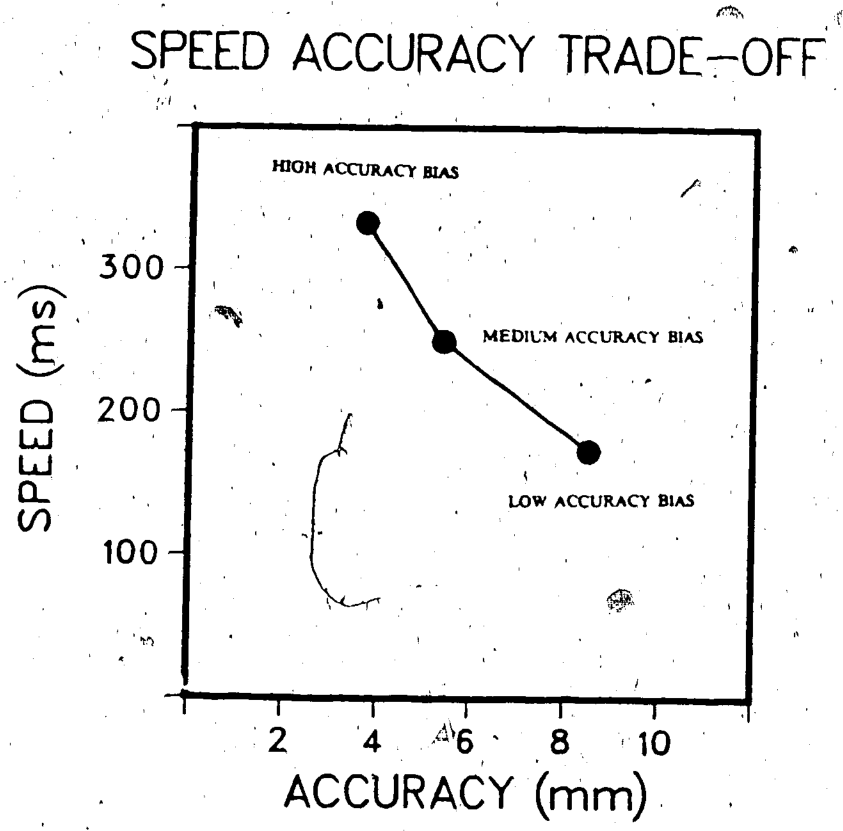

Figure 19. The inverse relationship between speed (movement time) and accuracy (absolute error) in the reciprocal tapping task.

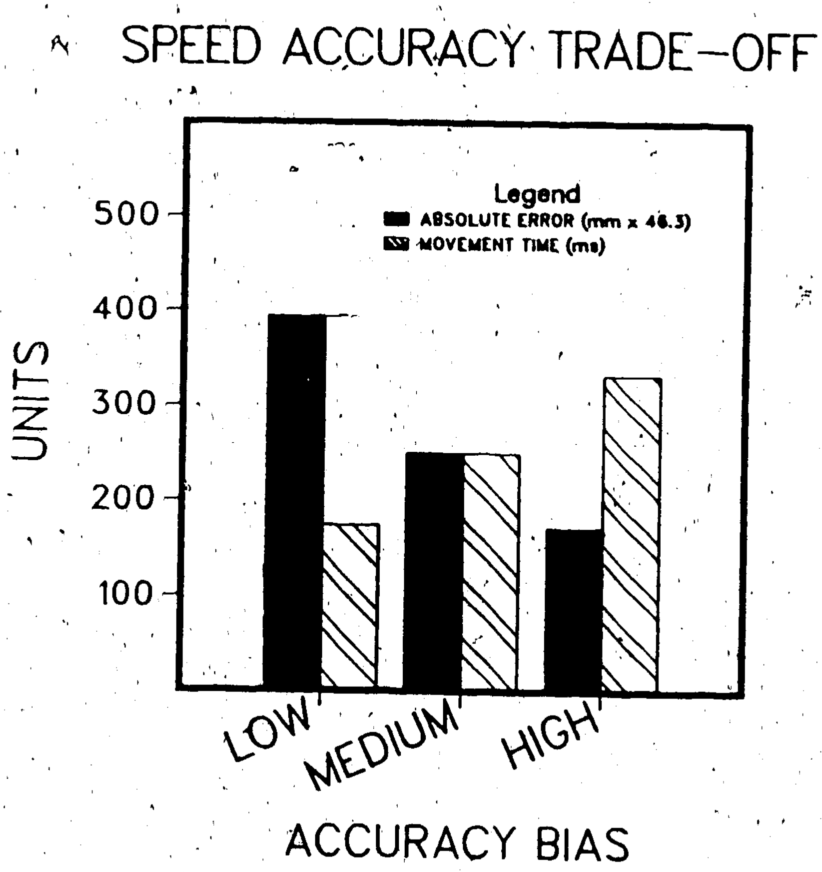

Figure 20. Mean absolute error and mean movement time as a function of "bias towards accuracy".

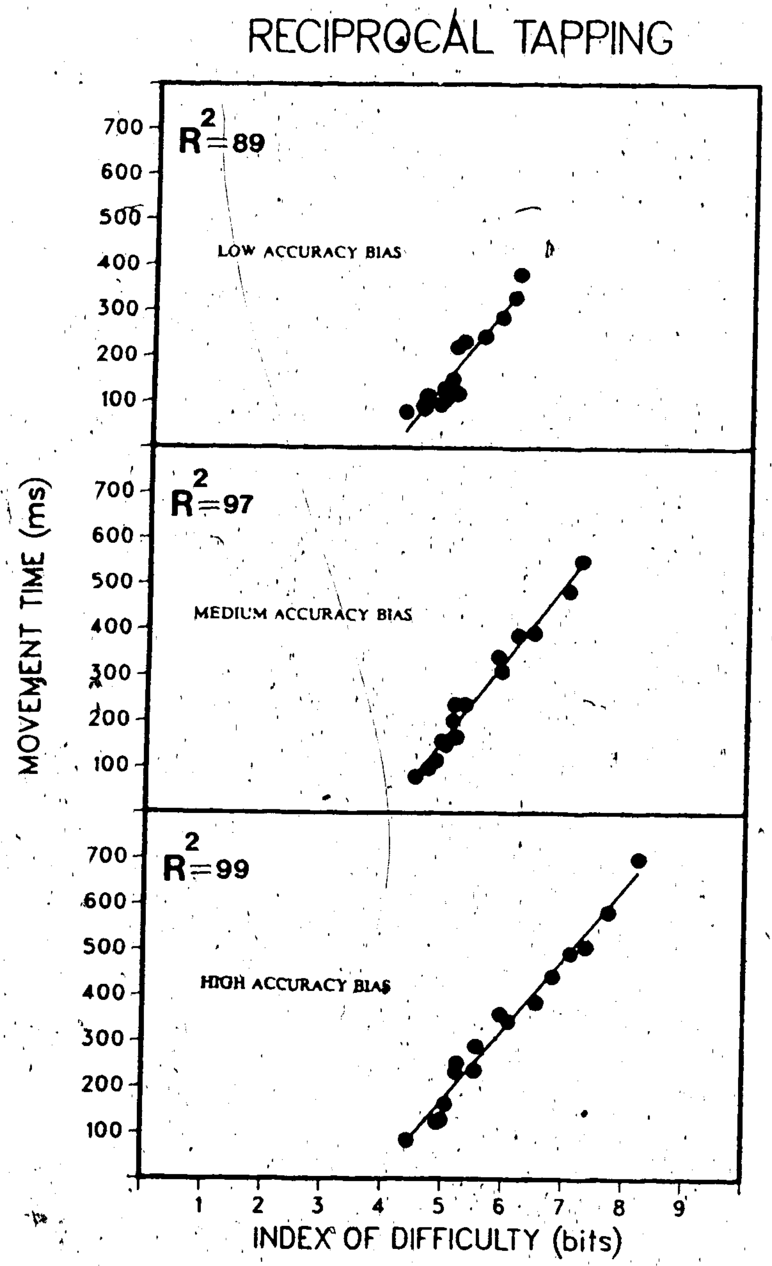

Figure 21. Movement time as a function of index of difficulty for low, medium, and high "bias towards accuracy" subjects.

different underlying processes. In order to examine how different speed-accuracy strategies are manifested in rapid aiming movements, a more detailed but descriptive analyses of the reciprocal tapping task, follows.

Several movement parameters were investigated. The first one was defined as the difference between mean movement time to the left target and mean movement time to the right target. In the preceding analyses these two movement times were averaged, but subsequent analyses had indicated that movements to the left target, that is, towards the body midline, were *faster* than movements away from the body midline, that is, towards the right target. Figure 22 displays the differential movement times to the left and right target as a function of movement condition, that is, as a function of target width and movement amplitude, for the low, medium, and high "accuracy bias" groups. Two effects are of particular interest. First, subjects inclined towards speed and with little or no consideration for accuracy ("low accuracy bias" subjects) produced very symmetric movement times, in that, movements to the right target were as fast as movements to the left target. Second, when subjects were biased towards accuracy, movements to the right target (or away from the body midline) were generally slower than movements to the left target (or towards the body midline). This phenomenon needs to be qualified, however, as it is evident from Figure 22 that this effect varied as a function of both target width and movement amplitude. That is, at short amplitudes (40 and 80 mm) the effect was minimal or non-existent. At longer movement amplitudes, however, the effect varied in a very systematic way as a function of the size of the target. That is, the smaller the target, or the more stringent the accuracy requirements, the slower the movements away from the body midline were relative to movements towards the body midline. In the most difficult condition, that is, the smallest target combined with the longest amplitude,

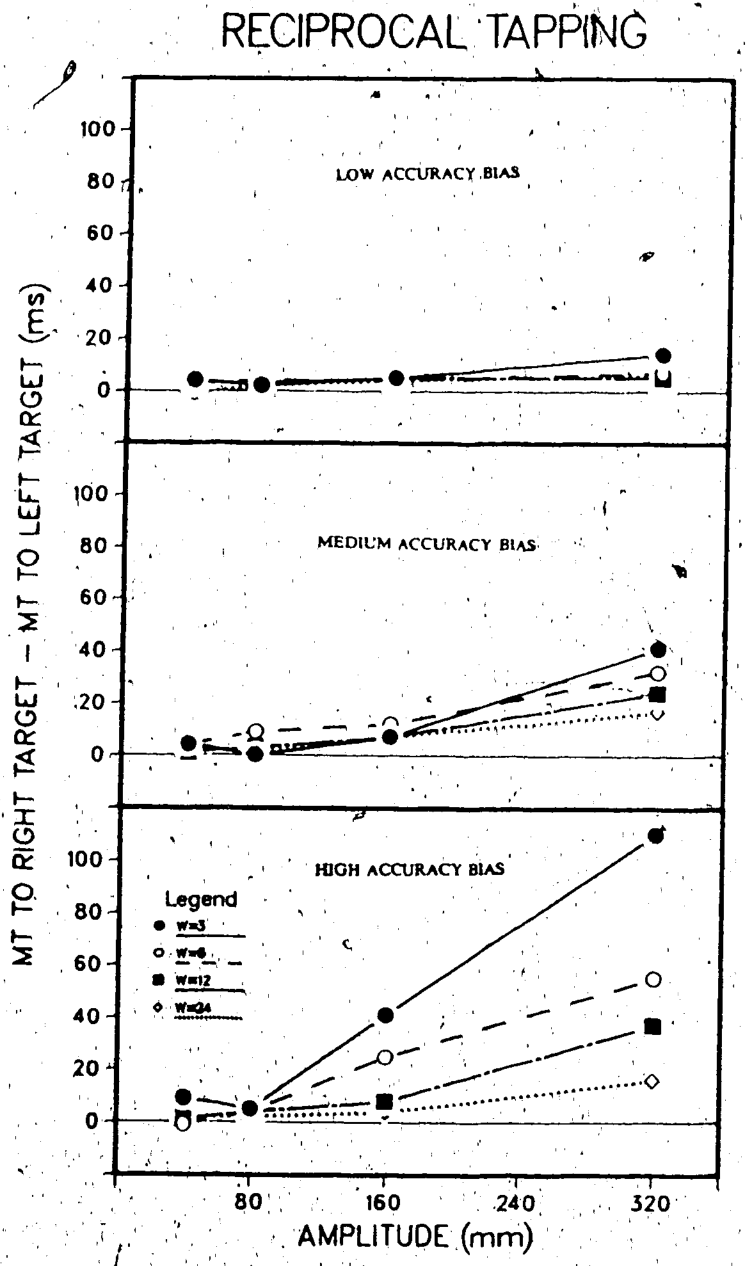

Figure 22. Mean difference between movement time to left target and movement time to right target as a function of target width and movement amplitude, for low, medium, and high "bias towards accuracy" subjects.

this difference was a striking 110 ms. Clearly, these findings strongly suggest that movements produced under different biases (speed or accuracy) might be generated by processes that are qualitatively different.

A second parameter thought to be reflective of different movement strategies or biases was time to reach peak velocity as a proportion of movement time. It was surmised that subjects concerned with accuracy would reach peak velocity sooner in order to allow for a relatively longer and slower and, therefore, more accurate homing phase. For a first global analysis it was decided that mean movement time and mean time to peak velocity (that is, averaged over movements to the left and right target) would be used as variables to calculate time to peak velocity as a percentage of movement time.

In Figure 23, mean time to peak velocity as a percentage of movement time is presented for the three "accuracy bias groups", as a function of target width and movement amplitude. It is clear from Figure 23, that "low accuracy bias" subjects produced very similar movement profiles in all movement conditions. That is, peak velocity was reached at about 50 to 55 percent of the movement time and was relatively independent of target width and movement amplitude. There seemed to be a tendency, however, to reach peak velocity sooner at longer amplitudes and smaller target widths.

This tendency to reach peak velocity sooner at longer amplitudes and smaller target widths, became a very strong and striking effect for subjects who were biased towards accuracy. The size of the targets seemed to be especially powerful in determining the time it takes to reach peak velocity. That is, "high accuracy bias" subjects seemed to manipulate the moment to reach peak velocity by as much as 15% depending on the size of the targets. Again, this analysis indicated that differences in

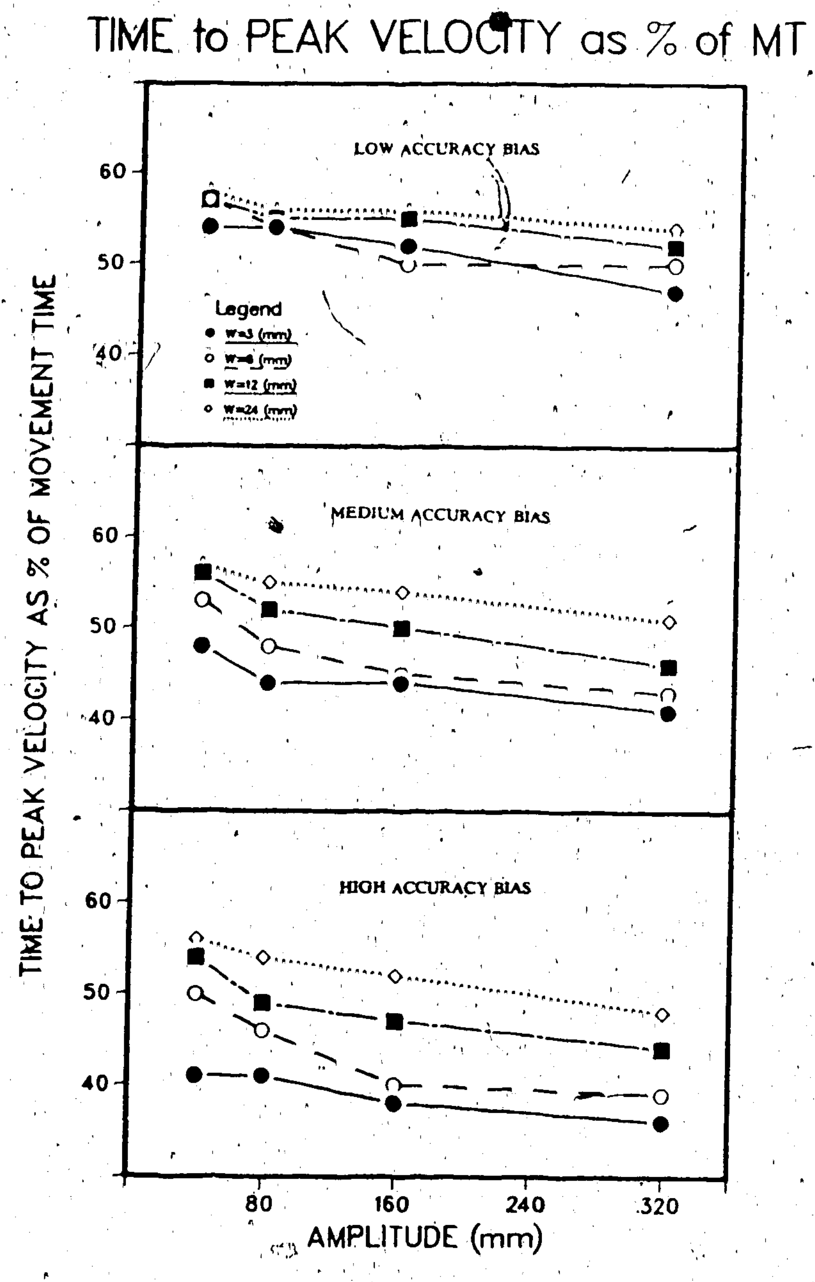

Figure 23. Time to peak velocity as a percentage of movement time as a function of target width and movement amplitude, for low, medium, and high "bias towards accuracy" subjects.

speed-accuracy bias lead to different types of movements.

A third parameter, "dwell time", was also investigated in the attempt to demonstrate the importance of speed-accuracy biases in how movements are produced. Dwell time was defined as the amount of time the subject "stayed" on the target, that is, the time span between stopping on the target and leaving the target by resuming movement speed in the opposite direction. In operational terms, dwell time was defined as the amount of time at which the effective speed of the stylus was zero during reversal of movement direction. Due to the limited sample rate of the X-Y digitizing tablet (i.e., 100 Hz), the minimum dwell time was by definition 10 milliseconds, which therefore reflected a floor effect.

Dwell times on the left targets were not different from dwell times on the right targets. In the following analysis, mean dwell times, that is, dwell time collapsed over left and right targets, are presented. In Figure 24, dwell time as a function of movement amplitude and target width, for low, medium, and high "accuracy bias" groups is displayed. Figure 24 shows that bias towards accuracy or speed is a very influentual determinant of dwell time. Subjects biased towards speed demonstrated similar dwell times in all movement conditions, that is, they hardly dwelled on the target at all. Subjects biased towards accuracy, on the other hand, dwelled on the target according to movement amplitude and target size in an interactive way. That is, the smaller the targets, the longer the dwell times, and, the longer the amplitudes, the longer the dwell times. The interaction between amplitude and target width indicated that when the targets are very big (24 mm) dwell time is minimal and independent of amplitude.

In summary, the preceding analyses strongly suggest that speed-accuracy strategies have a marked influence not only on the *quantitative* aspects of rapid

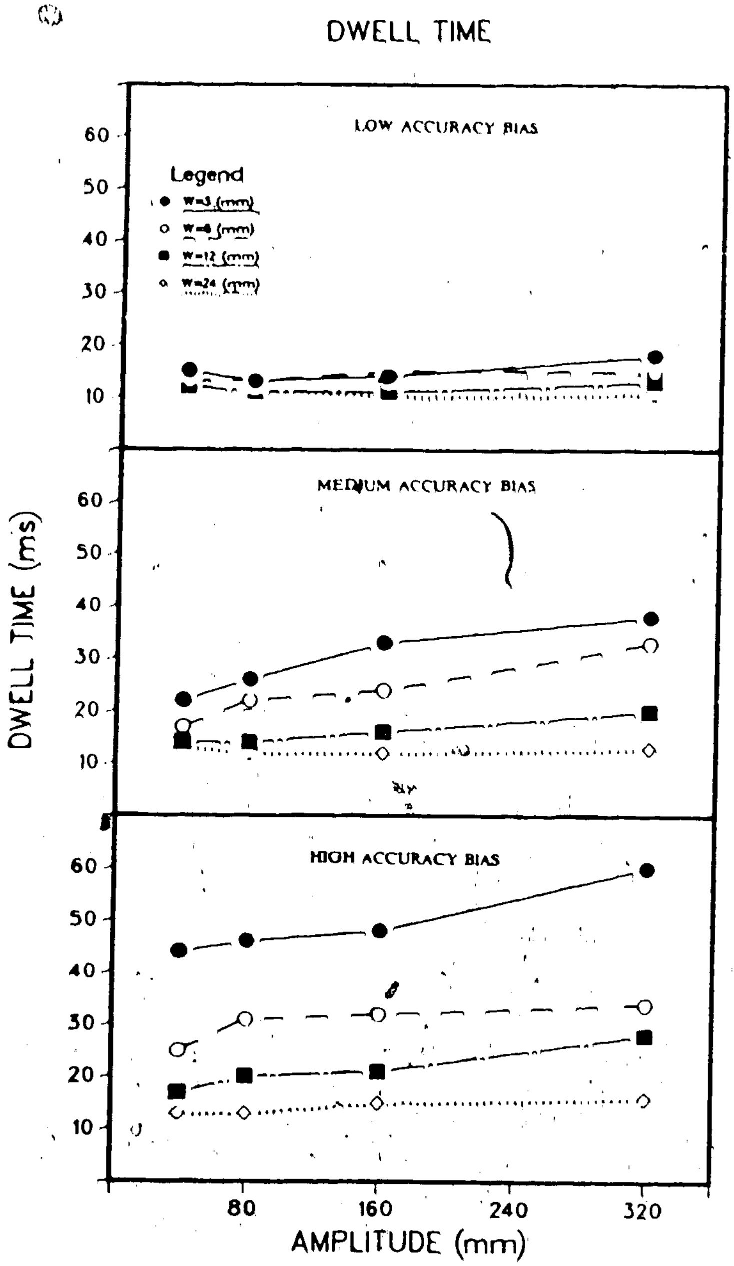

Figure 24. Dwell time as a function of target width and movement amplitude, for low, medium, and high "bias towards accuracy" subjects.

reciprocal aiming movements (movement time and movement accuaracy), but also on *qualitative* aspects (dwell time, time to peak velocity as a percentage of movement time, differential movement time to left and right targets). That is, subjects biased towards accuracy generally dwell on the target, vary the time to reach peak velocity, and vary movement time to the left and right targets. All of this is done in a systematic way depending on the amplitude of the movement and the size of the target. Subjects geared towards speed do very little or none of the above. In other words, the preceding analysis suggests that, depending on the particular strategy employed (i.e., speed versus accuracy), performance on the reciprocal tapping task is produced by qualitatively different processes or mechanisms. Specifically, "low accuracy bias" subjects do not seem to process as much visual feedback information concerning achieved endpoint accuracy as "high accuracy bias" subjects. The analysis of dwell time provides strong support for this claim. "Low accuracy bias" subjects do not dwell or dwell minimally. "High accuracy bias" subjects do dwell and in a very systematic way, namely according to the size of the target. That is, the smaller the target the longer the dwell time. This pattern of results seems to indicate that dwell time is a reflection of time needed to assess the discrepancy between endpoint position of the stylus and the target boundaries. Apparently, then, the smaller the target, the longer it takes to evaluate "where you are with comparison to where you intended to be", or more specifically, whether or not the stylus stopped within the boundaries of the target.

The analysis of the differential movement times to the left and right targets also suggests that perceptual processes concerned with evaluating the terminal position of the stylus play an important role in rapid aiming tasks. That is, the finding that movements away from the body midline are slower for "high accuracy bias" subjects but not for "low accuracy bias" subjects, suggest that processes of *localization* are more time consuming away from the body midline. Presumably, subjects ~~have~~ to make eye movements if not head movements in order to be accurate on both targets. Therefore, the differential movement times to the left and right targets, suggest that eye and/or head movements are easier and more efficiently accomplished when directed towards the body midline than when directed away from the body midline.

In sum, following the finding that subjects used different strategies in the rapid aiming tasks and therefore presumably relied upon *different processes*, the extremely low correlations between performance on the rapid aiming tasks and performance on the other experimental tasks are not surprising. That is, since the goal of "process isolation" was not consistently achieved, it is unreasonable to expect substantial correlations. Evidently, the results of the present rapid aiming tasks can not be taken as valid measures of a basic speed of processing factor.

A second problem concerns the undocumented reliabilities of the measures obtained. Two types of reliabilities can be distinguished: split-half reliability and test-retest reliability. Split-half reliability is measured by correlating scores on two subsets of items or trials of a test. For instance, scores on the first half of all trials on a particular test can be correlated with the scores on the second half of the trials. Similarly, scores on the even numbered trials of a test can be correlated with the scores on the odd numbered trials. Split-half reliabilities asses the internal consistency of a test and reflect the degree of measurement error.

Test-retest reliabilities are measured by correlating scores obtained from the same test administered on two separate occasions. Test-retest reliabilities, therefore, represent the stability of the subjects' performances on the test or task.

It has been argued that the test-retest form of reliability is superior to the split-half form, since the latter is relatively insensitive to behavioral instability (i.e., strategies), and therefore "fails to provide an appropriate basis for evaluating the likelihood of obtaining similar results on a subsequent occasion" (Salthouse, 1985, p. 129).

> "A preferable procedure for assessing reliability in individual differences research is the test-retest technique in which an interval, during which changes in strategy or set could conceivably occur, elapses between successive measurements of the variable. Only if the test-retest correlation coefficient is reasonably large can one claim that the phenomenon is stable, and not merely that its measurement is consistent." (Salthouse, 1985, p. 225)

[illegible]ortunately, for practical and economical reasons test-retest reliabilities were not established. It is therefore impossible to know how stable or reliable the obtained measures were. Clearly, if the tasks used were unable to produce reliable results, it is unreasonable to expect substantial correlations between the several task measures (Salthouse, 1985).

Taken together, the above mentioned problems, differential speed-accuracy biases and undocumented reliabilities, seriously question the success of the present attempt to isolate and assess a basic speed of visual information processing factor in different situations. Admittedly, the task is not without challenge, as observed by Keele and Hawkins (1982):

> "The measurement of isolated processes is an ideal not often met in practice. Imperfect isolation of processes likely accounts for many correlations being smaller than otherwise expected." (Keele & Hawkins, 1982, p. 5)

Therefore, the present finding of very low correlations does not necessarily imply that there is no general speed of processing factor, but rather that the present experiment failed in the attempt to measure it.

GENERAL DISCUSSION

This study was concerned with individual differences in speed of visual information processing and how they influence effective functioning in the context of fast action sports. The major premise was that fast and accurate perception is a *conditio sine qua non* for successful behavior in rapidly changing environments. Therefore, it was hypothesized that "top-ranked" athletes process short duration visual displays faster than "bottom-ranked" athletes.

The results of Experiments 1 and 2 seemed to support above hypothesis, for it was found that "top-ranked" university athletes generally processed visual information faster than "bottom-ranked" university athletes, as indexed by performance on the backward masking task. It was tentatively concluded that the backward masking task has promising validity in predicting performance excellence in fast action sports.

The practical implications of this conclusion are potentially very important to those concerned with selecting, screening, and advising athletes. For instance, in order to capitilize on their superior perceptual ability, fast processors could be directed towards sports of the open skill variety. Individuals with a slow speed of processing, on the other hand, could be directed away from situations in which fast and accurate perceptions are crucial, for they lack the requisite ability of fast processing.

However, two serious limitations restrict the validity of the backward masking task as an accurate index of rate of visual information processing, and, therefore, as a valid predictor of performance excellence. First, in the present study, speed of visual information processing was defined as the ability to perceive rapid visual displays containing *letters of the alphabet* in a backward masking situation. Since it has been demonstrated that the subject's familiarity with the stimulus material influences performance on this kind of task, it is imperative that the to be tested subjects are equal in this respect.

How can it be assured that subjects are of equal familiarity with the to be identified stimulus material? In this study university athletes were used, for it was assumed that they would be of equal familiarity with written stimulus material. When this condition was not met, as was the case for the professional athletes in Experiment 2, the backward masking task had no predictive power. One possible solution to this problem would be to use a high speed perception task in which pre-experimental knowledge would be inconsequential. The "inspection time" index, operationally defined as the minimal exposure duration necessary to make a reliable discrimination between two briefly presented lines, would seem to satisfy this condition (e.g., Hulme & Turnbull, 1983). A possible alternative solution would be to use geometric figures (i.e., circles, squares, and triangles) as stimulus material.

A second limitation of the backward masking task as an accurate instrument for assessing speed of visual information processing is related to the age of the to be tested subjects. Evidence for an "age-limitation" is provided by Arnett and Di Lollo (1979) and Di Lollo, Arnett, and Kruk (1982), who demonstrated that rate of processing increases rapidly in early childhood (age 7 to 13 years), remains stable in young adulthood (age 19 to 31 years), and declines slowly thereafter. The increase in speed of processing in early childhood is quite considerable as 13 years old children show twice as fast processing rates as 7 years old children. Since, developmental or maturational factors can cause a discrepancy between biological age and chronological age, unequivocal interpretation of backward masking performance of young children seems problematic. That is, poor performance on the backward masking task by a child between age 7 and 13 could be the result of a slow basic speed of processing ability; but could also be the result of a delayed "maturational development". Therefore, without taking into account the maturational development stage or biological age of the child, interpretations of backward masking performance in terms of the *ability* to process information quickly, are not valid for children aged 13 and under.

The results of the first two experiments generally supported the hypothesis that speed of visual information processing is an important factor in performance level in open skills. There are several considerations, however, which seriously qualify and restrict the scope or generality of the proposition that fast perception is of paramount importance in fast action skills. Consequently, these considerations also have important ramifications for the power of the backward masking task as a predictor of performance excellence.

First of all, the predictive value of the backward masking task should be interpreted in relative terms, that is, as indicating an individuals' *potential* for being successful in fast action sports. This qualification is prompted by the argument that a fast speed of processing is meaningless unless it is appropriately used. In other words, while the ability to process visual information quickly may be a *necessary* condition for superior performance, it is certainly not a *sufficient* condition. Inappropriate use of this ability, by concentrating on or selecting irrelevant stimulus information, will obviously not contribute to excellent performance.

Also crucial to an evaluation of the predictive power of the speed of processing concept, is the fact that successful performance has many prerequisites. That is, speed of processing is not the only significant component in successful performance. Other factors, such as those related to attitude, physical abilities, and sport specific skills, are of utmost importance in realizing athletic success. For example, a fast visual information processor who lacks the "output facilities" to transform the results of his or her superior perceptual processes into an adequate and efficient response, will probably not rise to "star status".

Another qualification of the proposition that fast processing is a valuable asset in open skills, is indicated by the observation that in many sports "role players" contribute in a very specific and restricted way to *team success*. That is, even in sports classified as belonging to the "open skill" variety, certain players excel in activities which depend relatively less on the ability to process visual information quickly. The so called "enforcers" in hockey belong to this latter category.

A final limitation of the speed of processing concept as a predictor of performance success is suggested by the Hick-Hyman Law (Hick, 1952; Hyman, 1953). The Hick-Hyman Law postulates that the more stimulus-response alternatives the subject has available, the longer it will take to choose and initiate the correct response. Applying this law to the notion of speed of processing, it would follow that fast visual information processors should show longer response times than slow visual information processors, because fast processors perceive more information in a fixed period of time, and hence have more stimulus-response alternatives to choose from than slow processors. Fortunately, it has been shown that the *compatibility* between the stimulus and its appropriate response is an important mediating factor in the Hick-Hyman Law. That is, when stimulus-response compatibilities are very high, the Hick-Hyman Law breaks down, for in such situations response time has been shown to be independent of the number of stimulus-response alternatives (Leonard, 1959; Mowbray, 1960). In other words, a fast speed of processing might not be harmful for experienced athletes since they have very strong and well established stimulus-response compatibilities. For inexperienced athletes, however, who lack firm and direct bonds between the possible stimuli and the associated appropriate responses, the Hick-Hyman Law seems to suggest that a fast speed of processing may have an adverse effect on performance.

The relative success of the backward masking task in accounting for performance differences among university athletes led to the conception of Experiment 3. In Experiment 3, an attempt was made to establish the construct validity of the speed of processing concept. The rationale was that if speed of visual information processing is indeed a general, context independent, basic ability, then performances on tasks all supposed to be indicative of speed of processing, should be related. To test this hypothesis, five laboratory tasks, all thought to be reflective of speed of processing, were administered to a large number of subjects (N=69). However, correlations between derived scores of these tasks were extremely low. This finding indicated that the different measures intended to reflect a basic speed of processing factor, had little or no common variance. The idea of a general processing ability was therefore not supported. However, several problems, which may have contaminated the results and lowered the correlations, were identified. These problems were related to differential speed-accuracy biases and undocumented reliabilities.

The failure to find evidence for a general construct of speed of processing does not, of course, mean that there is no such construct. It does make the point though that performance is determined by a wealth of different factors, and that if a general speed of processing factor is to be demonstrated, rigorous experimental, statistical, and theoretical control is essential.

It is recommended that entire speed-accuracy operating characteristics be established in order to avoid problems of differential speed-accuracy trade-offs, that is, in order to ascertain that the derived scores truly reflect the *maximum speed capabilities* of the subjects rather than subjective, volitional preferences towards either speed or accuracy. It is also recommended that all subjects perform the tasks twice, and on separate days, so that test-retest reliabilities can be established.

The issue of "theoretical control" is more complex. It would seem that in order to make inferences about specific mental processes from total reaction time or movement time, one must have a theory that specifies how the durations of the various processes involved in a task jointly determine reaction time or movement time in that task (Miller, 1982). Basically, two types of information processing theories have been proposed. Discrete information processing models assume that processes operate in a strict sequential and independent manner. According to these models, total reaction time is the sum of the durations of a number of discrete and independent processes or "stages" (e.g., Sternberg, 1969). In continuous information processing models, on the other hand, it is argued that several processes may operate simultaneously (e.g., Eriksen & Schultz, 1979). That is, it is assumed that, before completion, a process can transmit partial or preliminary output to a subsequent process or stage. Obviously, according to continuous models, total reaction time is not simply the sum of the duration of the component processes. Eriksen and Schultz's (1979) "continuous flow conception" is typical of this latter perspective.

> "In this conception, information about stimuli accumulates gradually in the visual system, and as it accumulates, responses are concurrently primed or partially activated. We conceive of several processes

> or levels comprising the events from stimulation to response activation. With the onset of stimulation, input channels begin to feed a continuous output to feature detectors which, in turn, continuously feed to form units. The output from the form units is a priming or activation flow to the response system. The output from each process becomes increasingly more detailed or exact over time as energy is integrated in the visual sense organ. The effect at the response level, with this continuous low, is an initial priming of a wide range of responses. But as the processing at the lower levels proceeds in time, the priming flow becomes increasingly restricted to fewer and fewer responses, namely, those that are still viable alternatives in terms of the increasingly more exact or complete output of the lower processes." (Eriksen & Schultz, 1979, p. 252)

At the present time, the issue of discrete versus continuous models of information processing is hotly debated (Miller, 1982, 1985; Reeve & Proctor, 1984, 1985). It would seem, therefore, that the technique of "process isolation" is, as yet, based on unverified assumptions about additivity and independence of processes (Pachella, 1974). Until sound and sophisticated cognitive theories of human information processing become available, attempts of construct validation remain therefore more or less "shots in the dark".

In view of the failure to detect a common, task independent speed of processing ability in Experiment 3, the success of the backward masking task in Experiments 1 and 2 in differentiating "top-ranked" from "bottom-ranked" athletes, might seem surprising. It should be realized, however, that contrary to many tasks in Experiment 3, the backward masking task seems to be relatively insensitive to subjective strategies and speed-accuracy trade-offs. The backward masking task, therefore, seems to be a very powerful tool to measure a basic speed of processing factor.

Nevertheless, the present series of experiments are not compelling. One problem concerns the small number of subjects in Experiments 1 and 2. Clearly, large scale replication experiments need to be conducted which test the speed of processing idea with different kinds of subject groups. Athletes in the sports of badminton, table-tennis, lawn-tennis, boxing, and archery, for example, would be prime candidates to be examined. However, sports are not the only activities which provide excellent opportunities to test the validity of the speed of processing notion in predicting performance success. Certain occupations or professions, such as pilots, (mail) sorters, bus-drivers, and taxi-drivers would also be very suitable.

Another, more structural, problem concerns the potential danger of "circular reasoning". Specifically, the idea of construct validation of the speed of processing notion seems somewhat circular. That is, the reasoning behind the construct validation attempt is similar to the argument "If A then B; so B therefore A", which is logically wrong. In concrete terms, even when a pattern of high correlations was to be demonstrated between the several "measures of speed", it would be incorrect to postulate that the existence of a general speed of visual information processing factor was proven. It could only be claimed that the results were consistent with, or in support of a general speed of processing ability.

The danger of circular reasoning is also present in experiments concerned with the criterion validity of the speed of processing notion (e.g., Experiments 1 and 2). That is, any failure to find an effect of speed of processing as an important mediator in skilled performance, could be explained by invoking some "confounding variable". Undoubtedly, the overwhelmingly complexity of human behavior allows for such "escapes", and illustrates the danger of oversimplification by assigning "super status" to the rate of processing notion. It also illustrates the difficulty which accompanies the attempt to predict complex behavior from a single variable. In Keele and Hawkins' (1982) words, "the task is rather formidable" (p. 16).

It is hoped that the present study not only provides some insight into the problems associated with this task, but also yields a promising direction towards a partial solution. That is, the results of the present study, in combination with the studies of Gopher and Kahneman (1971), Kahneman, Ben-Ishai, and Lotan (1973), and Keele and Hawkins (1982), seem to suggest that, *other things being equal*, speed of attention or speed of visual information processing is an important determinant of skilled performance.

REFERENCES

Adam, J.J., Humphreys, I., & Wilberg, R.B. (1986). Perceptual factors affect the [illegible]-hand advantage: A reappraisal of Miller's cuing paradigm. Manuscript submitted for publication.

Allard, F., Graham, S., & Paarsalu, M.E. (1980). Perception in sport: Basketball. *Journal of Sport Psychology, 2,* 14-21.

Allard, F. & Starkes, J.L. (1980). Perception in sport: Volleyball. *Journal of Sport Psychology, 2,* 22-23.

American Psychological Association (1954). Technical recommendations for psychological tests and diagnostic techniques. *Psychological Bulletin, 51(2),* 1-38.

Anstis, S.M. (1974). A chart demonstrating variations in acuity with retinal position. *Vision Research, 14,* 589-592.

Arnett, J.L., & Di Lollo, V. (1979). Visual information processing in relation to age and to reading ability. *Journal of Experimental Child Psychology, 27,* 143-152.

Averbach, E., & Coriell, E. (1961). Short-term memory in vision. *Bell System Technical Journal, 40,* 309-329.

Bashinski, H.S., & Bacharach, V.R. (1980). Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations. *Perception and Psychophysics, 28,* 241-248.

Baumeister, A.A., Runcie, D., & Gardepe, J. (1984). Processing of information in iconic memory: Differences between nonretarded and retarded subjects. *Journal of Abnormal Psychology, 93,* 433-447.

Beggs, W.D.A., & Howarth, C.I. (1972). The accuracy of aiming at a target: some further evidence for a theory of intermittent control. *Acta Psychologica, 36,* 171-177.

Breitmeyer, B. (1984). *Visual masking: An integrative approach.* Oxford University Press.

Bryden, M.P. (1960). Tachistoscopic recognition of alphabetic material. *Canadian Journal of Psychology, 14,* 78-86.

Campbell, A.J., & Mewhort, D.J.K. (1980). On familiarity effects in visual information processing. *Canadian Journal of Psychology, 34,* 134-154.

Carlton, L.G. (1981). Processing visual information for movement control. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 1019-1030.

Cerella, J., Poon, L.W., & Fozard, J.L. (1982). Age and iconic read-out. *Journal of Gerontology, 37,* 197-202.

Charness, N. (1979). Components of skill in bridge. *Canadian Journal of Psychology, 33,* 1-16.

Chase, W.G., & Simon, H.A. (1973). The mind's eye in chess. In W.G. Chase (Ed.), *Visual Information Processing.* New York: Academic Press.

Cook, T.D., & Campbell, D.T. (1979). *Quasi-Experimentation: Design and analysis issues for field settings.* Chicago, Ill.: Rand McNally College Publishing Company.

Chow, S.L., & Murdock, B.B. (1976). Concurrent memory load and the rate of readout from iconic memory. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 179-190.

Coltheart, M. (1972). Visual information processing. In P.C. Dodwell (Ed.), *New horizons in psychology* (Vol.2, pp. 62-85). London: Penguin Books.

Coltheart, M. (1980). Iconic memory and visible persistence. *Perception and*

Psychophysics, 27, 183-228.

Coltheart, M. (1983). Iconic Memory. *Phil. Trans. R. Soc. Lond., B302*, 283-294.

Crossman, E.R.F.W., & Goodeve, P.J. (1963). Feedback control of hand-movement and Fitts' Law. Paper presented at the meeting of the Experimental Psychology Society, Oxford, July 1963. Published in *Quarterly Journal of Experimental Psychology*, 1983, *35A*, 251-278.

deGroot, A.D. (1965). *Thought and choice in chess*. The Hague: Mouton.

Di Lollo, V., Arnett, J.L., & Kruk, R.V. (1982). Age-related changes in rate of visual information processing. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 225-237.

Di Lollo, V., Hanson, D., & McIntyre, J.S. (1983). Initial stages of visual information processing in dyslexia. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 923-935.

Elliott, D., & Allard, F. (1985). The utilization of visual feedback information during rapid pointing movements. *Quarterly Journal of Experimental Psychology, 37A*, 407-425.

Eriksen, C.W. , & Schultz, D.W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception and Psychophysics, 25*, 249-263.

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movements. *Journal of Experimental Psychology, 47*, 381-391.

Fitts, P.M., & Peterson, J.R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67*, 103-112.

Fitts, P.M., & Posner, M.I. (1967). *Human Performance*. Belmont, California:

Brooks/Cole.

Fleishman, E.A. (1966). Human abilities and the acquisition of skill. In E.A. Bilodeau (Ed.), *Acquisition of skill* (pp. 147-167). New York: Academic Press.

Fleishman, E.A. (1978). Relating individual differences to the dimensions of human tasks. *Ergonomics, 21,* 1007-1019.

Fleury, M., Bard, C., & Carriere, L. (1982). Effects of reduction of processing time and level of expertise in a multiple choice decision task. *Perceptual and Motor Skills, 55,* 1279-1288.

Galbraith, G.C., & Gliddon, J.B. (1972). Backward visual masking with homogeous and patterned stimuli: Comparison of retarded and nonretarded subjects. *Perceptual and Motor Skills, 34,* 903-908.

Glencross, D., & Barrett, N. (1983). Programming precision in repetitive tapping. *Journal of Motor Behavior, 15,* 191-200.

Gopher, D., & Kahneman, D. (1971). Individual differences in attention and the prediction of flight criteria. *Perceptual and Motor Skills, 33,* 1335-1342.

Haber, R.N. (1983). The impending demise of the icon: The role of iconic processes in information processing theories of perception. *Behavioral and Brain Sciences, 6,* 1-11.

Hay, L. (1981). The effect of amplitude and accuracy requirements on movement time in children. *Journal of Motor Behavior, 13,* 177-186.

Hick, W.E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psycholgy, 4,* 11-26.

Howarth, C.I., Beggs, W.D.A., & Bowden, J.M. (1971). The relationship between speed and accuracy of movement aimed at a target. *Acta Psychologica, 35,* 207-218.

Hulme, C., & Turnbull, J. (1983). Intelligence and inspection time in normal and mentally retarded subjects. *British Journal of Psychology, 74,* 365-370.

Hunt, E., Frost, N., & Lunneborg, C. (1973). Individual differences in cognition: A new approach to intelligence. In G. Bower (Ed.), *Advances in learning and motivation* (Vol. 7). New York: Academic Press.

Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology, 45,* 188-196.

Jensen, A.R. (1980). Chronometric analysis of intelligence. *Journal of Social and Biological Structures, 3,* 103-122.

Jonides, J. (1983). Further toward a model of the mind's eye's movement. *Bulletin of the Psychonomic Society, 21,* 247-250.

Kahneman, D., Ben-Ishai, R., & Lotán, M. (1973). Relation of a test of attention to road accidents. *Journal of Applied Psychology, 58,* 113-115.

Keele, S.W. (1968). Movement control in skilled motor performance. *Psychological Bulletin, 70,* 387-403.

Keele, S.W., & Hawkins, H.L. (1982). Explorations of individual differences relevant to high level skill. *Journal of Motor Behavior, 14,* 3-23.

Keele, S.W., & Posner, M. (1968). Processing of visual feedback in movement. *Journal of Experimental Psychology, 77,* 155-158.

Klapp, S.T. (1975). Feedback versus motor programming in the control of aimed movements. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 147-153.

Kline, D.W., & Szafran, J. (1975). Age differences in backward monoptic visual noise masking. *Journal of Gerontology, 30,* 307-311.

Knapp, B. (1961). Simple reaction times of selected top-class sportsmen and research students. *Britisch Journal of Psychology, 74,* 365-370.

Langolf, G.D., Chaffin, D.B., & Foulke, J.A. (1976). An investigation of Fitts' Law using a wide range of movement amplitudes. *Journal of Motor Behavior, 8*, 113-128.

Leonard, J.A. (1959). Tactual choice reactions. *Quarterly Journal of Experimental Psychology, 11*, 76-83.

Lovegrove, W., & Brown, C. (1978). Development of information processing in normal and disabled readers. *Perceptual and Motor Skills, 46*, 1047-1054.

Magill, R.A. (1985). *Motor Learning*. Dubuque, Iowa: Brown.

Mandler, G. (1985). *Cognitive Psychology: An essay in cognitive science.* Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Marcel, A.J. (1983). Conscious and unconscious perception: An approach to the relations between phenomenal experience and perceptual processes. *Cognitive Psychology, 15*, 238-300.

Marteniuk, R.G. (1974). Individual differences in motor performance and learning. In J.H. Wilmore (Ed.), *Exercise and sport sciences review* (Vol. 2, pp. 103-130). New York: Academic Press.

Marteniuk, R.G. (1976). *Information processing in motor skills.* New York: Holt, Rinehart and Winston.

Mewhort, D.J.K., Merikle, P.M., & Bryden, M.P. (1969). On the transfer from iconic to short-term memory. *Journal of Experimental Psychology, 81*, 89-94.

Meyer, D.E., Smith, J.E.K., & Wright, C.E. (1982). Models for the speed and accuracy of aimed movements. *Psychological Review, 89*, 449-482.

Michaels, C.F., & Turvey, M.T. (1979). Central sources of visual masking: Indexing structures supporting seeing at a single, brief glance. *Psychological Research, 41*, 1-61.

Miller, J. (1982). Discrete versus continuous stage models of human information processing: In search of partial output. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 273-296.

Miller, J. (1985). A hand advantage in preparation of simple keypress responses: Reply to Reeve and Proctor (1984). *Journal of Experimental Psychology: Human Perception and Performance, 11,* 221-233.

Mosley, J.L. (1981). Iconic store readout of mildly mentally retarded and nonretarded individuals. *American Journal of Mental Deficiency, 86,* 60-66.

Mowbray, G.H. (1960). Choice reaction time for skilled responses. *Quarterly Journal of Experimental Psychology, 12,* 193-202.

Neale, J.M., & Liebert, R.M. (1980). *Science and behavior.* Englewood Cliffs, New Jersey: Prentice-Hall.

Neisser, U. (1967). *Cognitive Psychology.* New York: Appleton-Century-Crofts.

Nielsen, D., & McGown, C. (1985). Information processing as a predictor of offensive ability in baseball. *Perceptual and Motor Skills, 60,* 775-781.

Norman, D.A., & Bobrow, D.J. (1975). On data-limited and resource-limited processes. *Cognitive Psychology, 7,* 44-64.

Pachella, R.G. (1974). The interpretation of reaction time in information-processing research. In B.H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition* (pp. 41-82). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Pew, R.W. (1969). The speed-accuracy operating characteristic. *Attention and Performance II. Acta Psychologica, 30,* 16-26.

Posner, M.I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3-25.

Poulton, E.C. (1957). On prediction in skilled movement. *Psychological Bulletin, 54,* 467-478.

Reeve, T.G., & Proctor, R.W. (1984). On the advance preparation of discrete finger responses. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 541-553.

Reeve, T.G., & Proctor, R.W. (1985). Nonmotoric translation processes in the preparation of discrete finger responses: A rebuttal of Miller's (1985) analysis. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 234-241.

Reitman, J. (1976). Skilled perception in Go: Deducing memory structures from inter-response times. *Cognitive Psychology, 8,* 336-356.

Remington, R.W. (1980). Attention and saccadic eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 6,* 726-744.

Rosenbaum, D.A. (1980). Human movement initiation: Specification of arm, direction, and extent. *Journal of Experimental Psychology: General, 109,* 444-474.

Salthouse, T.A. (1982). *Adult cognition: An experimental psychology of human aging.* New York: Springer-Verlag.

Salthouse, T. (1985). *A theory of cognitive aging.* Amsterdam: North-Holland.

Schellekens, J.M.H., Kalverboer, A.F., & Scholten, C.A. (1984). The micro-structure of tapping movements in children. *Journal of Motor Behavior, 16,* 20-39.

Schmidt, R.A. (1982). *Motor control and learning: A behavioral emphasis.* Champaign, Ill.: Human Kinetics.

Schmidt, R.A., Zelaznick, H.N., Hawkins, B., Frank, J.S., & Quinn, J.T. Jr. (1979). Motor Output Variability: A theory for the accuracy of rapid motor actions. *Psychological Review, 86,* 415-451.

Siegel, D. (1985). Information processing abilities and performance on two perceptual-motor tasks. *Perceptual and Motor Skills, 60,* 459-466.

Slater-Hammel, A.T. (1955). Comparisons of reaction-time measures to a visual stimulus and arm movement. *Research Quarterly, 26,* 470-479.

Sloboda, J.A. (1976). Visual perception of musical notation: Registering pitch symbols in memory. *Quarterly Journal of Experimental Psychology, 28,* 1-16.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs, 74,* (11, Whole No. 498).

Sperling, G. (1967). Successive approximations to a model for short-term memory. *Acta Psychologica, 27,* 285-292.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. In W.G. Koster (Ed.). *Attention and Performance II. Acta Psychologica, 30,* 276-315.

Taylor, G.A., & Chabot, R.J. (1978). Differential backward masking of words and letters by masks of varying othographic structure. *Memory and Cognition, 6,* 629-635.

Tsal, Y. (1983). Movements of attention across the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 523-530.

Turvey, M.T. (1973). On peripheral and central processes in vision: Inferences from an information processing analysis of masking with patterned stimuli. *Psychological Review, 80,* 1-52.

Vernon, P.A. (1983). Speed of information processing and general intelligence. *Intelligence, 7,* 53-70.

Wallace, S.A., & Newell, K.M. (1983). Visual control of discrete aiming movements. *Quaterly Journal of Experimental Psychology, 35A,* 311-321.

Walsh, D.A. (1976). Age differences in central perceptual processing: A dichoptic backward masking investigation. *Journal of Gerontology, 31,* 178-185.

Walsh, D.A., Till, R.E., & Williams, M.V. (1978). Age differences in peripheral perceptual processing: A monoptic backward masking investigation. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 232-243.

Welford, A.T., Norris, A.H., & Schlock, N.W. (1969). Speed and accuracy of movement and their changes with age. In W.G. Koster (Ed.), *Attention and Performance II,* Amsterdam: North-Holland Publishing Company.

Winer, B.J. (1971). *Statistical principles in experimental design.* Tokyo: McGraw-Hill Kogakusha.

Woodworth, R.S. (1899). The accuracy of voluntary movement. *Psychological Monographs, 3.*

Wright, C.A., & Meyer, D.E. (1983). Conditions for a linear speed-accuracy trade-off in aimed movements. *Quaterly Journal of Experimental Psychology, 35A,* 279-296.

Youngen, L. (1959). A comparison of reaction and movement time of woman athletes and nonathletes. *Research Quarterly, 30,* 349-355.

Zelaznik, H.N., Hawkins, B., & Kisselburgh, L. (1983). Rapid visual feedback processing in single-aimining movements. *Journal of Motor Behavior, 15,* 217-236.

APPENDIX ONE

Order of movement conditions in reciprocal tapping task.

CONDITION	AMPLITUDE (mm)	TARGET WIDTH (mm)
1	40	24
2	160	6
3	320	24
4	40	3
5	160	12
6	80	12
7	320	3
8	40	12
9	320	12
10	80	24
11	80	3
12	160	24
13	40	6
14	160	3
15	320	6
16	80	6