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SPATIAL AND TEMPORAL FACTORS IN THE DISCRIMINATION OF LIFTED WEIGHTS

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ABSTRACT

In a series of experiments investigating spatial and temporal factors in the discrimination of lifted weights, differential thresholds (DLs) were measured. The temporal factor, known as the time-order error, was found to be negative in one-handed and two-handed consecutive discrimination paradigms, and at low and high stimulus intensities. The spatial factor, known as the space-error, was found to produce a strong bias in a two-handed simultaneous discrimination paradigm. The direction of the bias did not correlate with hand preference or attentional factors but with sex; with weights appearing lighter in the preferred hand of males and heavier in the preferred hand of females. Other spatial factors, such as hand, hemispace and method of lifting were found to affect DLs. Surprisingly DLs for the preferred hand were not necessarily lower than DLs for the non-preferred hand. The preferred ear provided a more reliable indication of hand advantage by specifying to which cerebral hemisphere language was probably lateralised. The hand contralateral to the non-language (spatial) hemisphere revealed an advantage in weight discrimination.

Left-handed subjects were found to perform better than right handed subjects with their preferred hand. This was explained by the fact that a higher proportion of left-handed subjects have their preferred hand contralateral to the spatial hemisphere. DLs were found to be lower in the

hemispace contralateral to the spatial processing hemisphere for both right and left hands.

It was concluded that weight discrimination should be considered as a manipulospatial activity subserved by higher order functioning of the cerebral hemisphere contralateral to the hand used in lifting the weight and contralateral to the spatial field within which the weight was lifted.

CHAPTER 1: INTRODUCTION

1.1 Psychophysics and weight discrimination

The term "psychophysics" was coined by Fechner (1860) to describe a scientific approach which embraced precise methods of enquiry. The purpose of these methods was to provide the scientist with objective and quantifiable measures of human perceptual abilities. Fechner's aim was to prove the existence of a mathematical relationship between the physical world and the mental world using methods that introduced some of the scientific rigour of the "hard sciences". Many of the 19th century psychologists, such as Weber, Wundt and Helmholtz, had backgrounds in the physical sciences and favoured the "psychophysical" methods. This ensured their acceptance as investigatory tools in the expanding world of perceptual psychology. Even though Fechner's original aim is no longer the object of psychological enquiry and has been shown to be theoretically untenable (Weiss, 1981; McKenna, 1985) his methods have continued to be used by psychologists, albeit in modified form, to provide precise data about perceptual abilities.

The methods devised by Fechner may be divided into those that measure absolute thresholds, or the least amount of energy that may be perceived, and differential thresholds (DLs), or the smallest difference that can be perceived between two stimuli. In this thesis the latter method has been adopted as a means of measuring the human ability to discriminate between objects on the basis of their weight or heaviness.

1.2 The role of weight discrimination in the development of psychophysical methodology

The development and refinement of psychophysical methods and procedures owes much to the discrimination of countless thousands of pairs of weights. However in the 19th and early part of the 20th century many studies purporting to investigate weight discrimination were concerned only with the investigation of the experimental method.

For example, Fechner (1860) was concerned with the development and refinement of his psychophysical methods rather than with the investigation of the underlying psychological or physiological mechanisms of weight discrimination. He measured the ability of human subjects to discriminate between weights lifted with both right and left hands, using a one-handed consecutive weight discrimination paradigm, and the sensitivity of both hands using a two-handed simultaneous discrimination paradigm. However only passing comment was made upon his finding that the right hand was only slightly more sensitive than the left, and that one-handed discrimination was considerably more sensitive than two-handed discrimination (1966, p. 79). No explanations of the effect were advanced or discussed. Fechner also discovered the time-order error, a systematic error introduced when stimuli are separated by temporal position, and the space-order error, a systematic error introduced when stimuli are separated in spatial position. His main preoccupation was in finding ways of compensating for, or eliminating their effect upon the measurement of DLs, not in explaining these "constant errors" in psychological or physiological terms (Hellstrom, 1985).

Similarly Brown (1910) used weights merely as convenient sources of stimuli in the investigation of spatial, temporal and practise effects in the measurement of DLs. He confirmed Fechner's finding of both the time-order error and the space-order error for lifted weights but failed to confirm Fechner's finding that Weber's Law holds for most stimulus intensities. Brown only discussed these results in terms of psychophysical methodology, not in psychological or physiological terms.

Fernberger (1931) investigated psychophysical procedures using weights as convenient stimuli, in order to compare different methods of calculating DLs. He claimed that the drawback with the method of constant stimuli was that it was inefficient and time consuming. He concluded that the method of single stimuli was more efficient and produced just as reliable results as the method of constant stimuli.

1.3 The investigation of weight discrimination

Weber (1834) investigated the role of the touch and muscle senses in the discrimination of weight. He found that the tactile discrimination of weight became more than twice as precise with the addition of muscular kinesthesis. His aim was to discover the physiological processes of sensation that allowed the interaction between mind and body. Although he devised experimental techniques that have stood the test of time, such as the two-point threshold, many of his methodological procedures do not stand up to scrutiny.

The development of more rigorous psychophysical procedures during the late 19th century allowed the investigation of current theoretical concerns. One such concern was whether "sensations of innervation" or a "sense of effort" subserved weight discrimination. That is, whether the subjective experience of the volition or act of will required to lift a weight underlies this discriminatory ability. Waller (1891) when investigating the "sense of effort" found very poor discrimination (1/1 or worse) if reflex (involuntary) lifting was used. He interpreted his result in terms of the importance of the "act of will". His theorising was surprising as it would be expected that discrimination under such circumstances would be at least as good as that provided by tactile discrimination; Weber (1834) had shown discrimination of 1/3 to be possible. The method of producing the involuntary lifting movement most probably interfered in some way with tactile sensitivity (Brodie & Ross, 1984).

Wundt (1894) carried out investigations into weight discrimination in order to investigate "sensations of innervation". He compared active lifting with passive pressure and found that active lifting was better. He attempted to interpret such findings in terms of the then current physiological and psychological theory. Unfortunately these theories were heavily oriented towards introspection and bodily sensations (Boring, 1942). It is thus surprising that the findings of early research have not been scrutinised more thoroughly. For example Brodie & Ross (1984) have shown that discrimination for both pressure sensing and reflex lifting of weights was much better than the 19th century literature suggested.

1.4 Philosophical considerations in weight discrimination

> "For in psychology there are experimental methods and conceptual confusion. The existence of the experimental method makes us think we have the means of solving the problems which trouble us; though problem and method pass one another by." Wittgenstein (1953, p. 232)

Psychophysics grew out of philosophy and physics. For example, both Weber (1834;1846) and Fechner (1860) engaged in philosophical analysis and in empirical investigation. Surprisingly an adequate conceptual framework, within which to place the empirical findings of weight discrimination experiments, is still lacking. The Sensation/Perception Distinction, the Mind/Body Problem and Introspectionism are still evident in current literature. An attempt will be made to highlight, and resolve, some of these conceptual problems. The situation is made worse by the fact that physicists cannot agree upon a definition of weight. They discuss either the gravitational attraction of the earth upon a body *or* the downward force with which a body acts upon its support. It is not surprising that psychologists and physiologists have not been able to agree upon an adequate conceptualisation of weight discrimination.

However from a common sense point of view, it is indisputable that human observers can perceive the weight, or heaviness, of an object when lifting and manipulating that object at the Earth's surface. Furthermore it has been shown that we can discriminate between objects in orbital flight, where objects have no "weight", by imparting accelerations upon the object (Ross, Brodie & Benson, 1984). It would seem likely that a measure of both the forces acting upon the object, due to the attraction of the earth, and the forces imparted by moving the object, combine in some way to subserve the everyday experience of the weight of lifted objects. However care must be taken to differentiate between the levels of physical and psychological discourse. Weight may be defined objectively in physical terms as a force. This does not mean that it can be subjectively defined in psychological terms as a force percept.

1.4.1 The sensation/perception distinction

When an object is lifted, is the weight of the object perceived directly or is the weight of the object perceived indirectly by reference to bodily sensations of force or effort accompanying the lifting of the object? The distinction between perception and sensation was first drawn by Thomas Reid in 1785. His aim was to provide the necessary and sufficient conditions for perception in terms of physical, physiological and psychological mechanisms. For example, he discussed the object making an impression upon the sense organ; this impression in turn affecting both the nerves and ultimately the brain. He argued that for a person to be described as perceiving some quality of an object there must be an object of perception, and the person must be in a sentient and cognicient state. This complex state would allow for the direct awareness of an external object, or some quality of that object. Reid clearly would have wished to consider sensations a causally necessary component of perception, able to be felt, but not the object of "direct perception".

Weber (1834) addressed the sensation/perception distinction by dividing perception into two classes: objective and subjective. Examples of objective perception are those of vision and audition. Examples of subjective perception are those of pain and kinesthesis where Weber argued that there is no object of perception just bodily sensations (1978, p. 55). The former category in Weber's perceptual dichotomy is thus consistent with Reid's view of perception in that direct awareness of the object of perception by means of the sensations transmitted by the sense organs is possible. However a problem arises for Weber's dichotomy when considering the perception of weight of an object: its weight can be directly perceived through the pressure sensing system and indirectly perceived through the kinesthetic system. Weber's simplistic view of the role of these two systems in the discrimination of lifted weights confounds two separate and distinct physiological processes. How cutaneous and kinesthetic information interact, if at all, is still a source of controversy (McCloskey, 1978). The confusion of indirect perception of weight, by means of bodily sensations, and direct perception, by means of unconscious perceptual mechanisms, pervades most of the subsequent research into weight perception.

1.4.2 Bodily sensations and weight discrimination

> "What is left over if I subtract the fact that my arm goes up from the fact that I raise my arm? Are the kinesthetic sensations my willing?" Wittgenstein (1953, p.161)

Controversy has raged over the origins of sensations subserving weight perception despite the direct realism of Reid. Peripheralists have argued that the sense of effort originated in the receptors of the muscles, tendons and joints of the limb raising the weight. Centralists have argued that volitions, "acts of will" or "sensations of innervation" form the basis of weight perception. In the latter half of the 19th century neither philosophical debate nor introspection could resolve these problems. For example, Wundt (1894) oscillated between the two positions (Ross & Bischof, 1981). Hope for an adequate solution was provided by Sherrington (1906) since his physiological research seemed to offer a conceptual framework avoiding introspection and sensations (Boring, 1942). However this optimism has proven misguided as introspection still pervades the physiological literature on weight and heaviness. Centralists (McCloskey, Ebeling & Goodwin, 1974; Gandevia & McCloskey, 1977) still argue with peripheralists (Roland & Ladegaard-Pedersen, 1977) over the origins of a "sense of effort".

The interpretation of the findings of empirical investigation into weight discrimination has been complicated by the continued adherence of many researchers to psychophysical assumptions and thus to sensationism. Weber and Fechner, as the fathers of traditional psychophysics, must admit to the measurement of sensations in their attempt to relate the physical properties of the stimuli to the psychological properties of the mind (Fechner thought that this could only be done indirectly). McKenna (1985) attacked both the "old" (Fechner, 1860) and the "new" (Stevens, 1958) psychophysics on the grounds that they both are concerned with the relationship between stimuli and sensations. Although he concentrated upon magnitude estimation, rather than discrimination, the relationship between sensations and perception, if any, has still to be shown to be causal both in discrimination and estimation.

Traditional psychophysicists have been criticised on the grounds that they assume a dualism of mind and body (Savage, 1970). This assumption is of course untenable since it results in an infinite regress; the mind is forced higher and higher into the brain as the understanding of the physiological mechanisms of "sensations" increases. They are also accused of having a desire to discover a single numerical relationship between the physical and psychological dimensions (Weiss, 1981). The desire is unreasonable as the measurement of a monotonic response function merely reflects the relationship existing between elements in the physical dimension.

An argument propounded in defence of psychophysics is that it describes the law like relationship that exists between the output of the receptor and the magnitude of the stimulus (Stevens, 1970). However even this relationship has been shown to be an arbitary one. In a review of the empirical evidence to support this claim no simple relationship between electrophysiology and psychophysics was found (McKenna, 1985).

To avoid the theoretical problems oulined in the preceding paragraph a discrimination paradigm can be conceived of as a measure of a perceptual ability (Savage, 1970). The questionable assumptions made by traditional psychophysicists of law like relations between sensations and stimuli are avoided. This conceptual approach would seem to provide an adequate framework for the empirical investigation of factors affecting weight discrimination. That is, the measurement of the ability to discriminate between two weights can be used to investigate the spatial and temporal conditions affecting discrimination, without taking onboard the assumptions of traditional psychophysics.

1.4.3 Active and passive theories of perception

Some philosophers (Brown, 1974) have been conceptually narrow in their approach to perceptual matters. They have often treated perception as a largely passive means of acquiring information about the physical world, while ignoring the extent to which the perceiver may be active in his or her transaction with the physical world. That is, when discussing perception, "armchair philosophers" have tended to concentrate upon the perception of objects which may be discerned through vision or audition, and have ignored those perceptions requiring a more obvious interaction with the world. A failure to recognise the importance of such an interaction is detrimental to the consideration of a perception where objects are actively lifted, as is often the case in weight perception. Gibson (1962) argued that there is a qualitative difference between being touched by an object (passive touch) and actively touching an object (active touch). His conceptual approach has been validated to some extent by physiological investigations (Wall, 1975) which have found that separate functional channels operate in active and passive touch. It has been known since Weber (1834) that the discrimination between the weight of objects can be performed both actively and passively, with discrimination found to be more precise when active lifting is involved. However what is new in the Gibsonian approach is the suggestion that there is a qualitative difference between active and passive touch. It cannot be explained in quantitative terms by the simple addition of the touch and kinesthesic senses advocated by Weber. It is probably due to a complex interaction between the two.

1.4.4 Ecologically valid approaches in weight discrimination

Different levels of discourse are often confounded when talking about weight perception. The direct awareness of the efferent or afferent signals that subserve the subjective perceptual experience is not possible (Dennett, 1981). However, the awareness of the effort or force required to lift an object, by reference to bodily sensations, is possible (McCloskey *et al*, 1974). The physical workings of the nervous system and the sensations arising from bodily movement are often confused as being one and the same, especially when perceiving the weight of an object. In studies referring to "weight perception", subjects should lift real objects in as normal a manner as possible. This is because it has been argued that the weight of an object cannot merely be reduced to certain force vectors (Ross, Brodie & Benson, 1985). Also without an object of perception (to refer the weight to) the object of perception will be reduced to a bodily sensation (McCloskey *et al*, 1974). Finally, the mechanisms by which we engage in direct perception and ascribe qualities to external objects through touch is not understood and existing assumptions still need to be questioned. As Wittgenstein (1953, p. 161) succinctly put it:

> "When I touch this object with a stick I have the sensation of touching in the tip of the stick, not in the hand that holds it."

1.5 Physiological mechanisms in weight discrimination

The sensory mechanisms subserving the perception of weight of objects have been divided into two, the skin sense and the muscle sense. This distinction probably follows the general distinction first made by Weber (1834). That is, cutaneous mechanoreceptors in the skin are responsible for signalling the weight of objects through pressure, and the receptors in muscles, tendons and joints, are responsible for signalling the weight of objects through active movement. The former class of receptors can mediate weight in a passive condition, when the object is placed upon a supported limb, the latter when the object is lifted or held against gravity. However, the latter class of receptors normally act in conjunction with the former since it is normally impossible to lift an object without touching it. Thus the ability to perceive the weight of lifted objects would seem to be linked with the ability to move and sense the position of limbs.

The type of movement of the upper limb determines the contribution made by efferent and afferent systems. For example, continuously controlled movements rely upon afferent feedback whereas ballistic movements do not (Fromm & Evarts, 1978). Research has shown that efferent and afferent signals are necessary for kinesthetic sense though their relative contribution is still very much open to debate (Roland, 1978) as is the contribution of the cutaneous sense to kinesthesis (McCloskey, 1978).

1.5.1 Neural transmission from peripheral receptors

A variety of receptors in the skin, muscles and joints send messages to the higher centres of the central nervous system via two neural pathways; the lemniscal and the spinothalamic systems. The nerve fibres that originate from the muscles, tendons and joints project onto the same region in the cortex as the cutaneous receptors (McIntyre, 1974). Thus the information about stimuli touching the skin and that about the position and movement of the arm, is projected onto the precentral and parietal area of cortex. However evidence suggests that the cutaneous and the kinesthetic systems activate separate cortical units which are not shared between systems (McCloskey, 1978). That is, the cutaneous or skin sense information is kept separate from the kinesthetic or position and movement information even at a cortical level.

The projection of sensory information onto the cortex from touch receptors in each hand occurs both contralaterally and ipsilaterally. The contralateral and ipsilateral projections are organised into discrete systems that may serve different purposes. Proprioception or "active touch" (Gibson, 1962) is thought to be mediated by contralateral pathways and "passive touch" by both ipsilateral and contralateral pathways (Wall, 1975). Information from cutaneous receptors invariably reaches awareness whereas in many cases the kinesthetic signals do not reach conscious awareness. They are involved in the unconscious control of actions such as in maintaining an upright posture. The kinesthetic sense is clearly unilaterally represented while the cutaneous sense is bilaterally represented (Sinclair, 1981).

Although the kinesthetic system responds to movement, information is also available when no movement is taking place. This information comes from our continuous battle against the force of gravity. Both movement and postural responses result from the effects of tension, compression and torsion on the muscles, tendons or joints of limbs. These physical forces must be considered as the stimuli for kinesthesis. The fact that accurate discrimination can be made between the weight of hand held objects when no lifting movement takes place (Brodie & Ross, 1984) is evidence for the use of a feedback system in weight discrimination. Muscle, joint and tendon receptors are ideally suited to subserve the perception of weight (Cotman & McGaugh, 1980).

The optimism displayed by Boring (1942) when he argued that the increase in knowledge of sensory physiology provided by Sherrington had made "sensations of innervation" an untenable concept was premature. Physiological research in the 1960s almost totally rejected the view that the "muscle sense" depended upon afferent input from muscle and tendon receptors (Matthews, 1982). Although the role of muscle, tendon and joint receptors is now more fully understood it is still commonly assumed that "sensations of innervation" provide the main basis for the estimation of the heaviness of lifted objects (McCloskey, Ebeling, & Goodwin, 1974; Gandevia & McCloskey, 1977; Matthews, 1982). However, it is not even clear if sensations of innervation are centrally or peripherally generated (Roland, 1978), or if the weight of an object is indirectly sensed by reference to them. This conceptual approach ignores the considerable philosophical debate against introspectionism and sensationism. Furthermore it ignores extensive psychological evidence.

1.6 Psychological aspects of weight discrimination

The philosophical argument presented in Section 1.4 was against the view that bodily sensations and the efferent and afferent signals involved in signalling the position and the movement of the limb when lifting an object, can subserve the weight of the object in a simple manner. The view has also been propounded that an analysis of bio-mechanics of the upper limb can explain the perception of weight in a simple manner. Davis (1973, 1974) and Davis Taylor and Brickett (1977) have investigated factors such as the effective lever length, the rate of lifting and the peak acceleration achieved by the arm in the perception of weight of lifted objects. They have claimed that changes in these factors alter how heavy an object appears when lifted. However, the experimental methods used in their research may have inadvertently forced subjects into attending to the sense of effort or force accompanying the lifting movements, not to the weight of the lifted object. As McCloskey, Ebeling and Goodwin (1974) have shown subjects can attend to bodily sensations accompanying lifting movements, whether to a "sense of effort" or a "sense of tension". Bio-mechanical factors would undoubtably alter in relation to force. However the authors propounding the view that weight perception can be explained simply in such terms fail to take into account the complex psychological mechanisms that are undoubtably involved in the perception of weight. Empirical evidence supporting this view has been provided by psychological experiments on weight constancy and weight illusions.

Constancy is a psychological phenomenon exhibited in many perceptual domains, perhaps the best known being the visual constancies of colour, shape and size. Objects may produce different sensory inputs on different occasions, due to changes in light, angle of regard or distance, but remain relatively constant in appearance to the human observer. The same phenomenon is exhibited in weight perception and can be demonstrated by lifting the same object in a different manner (Fischel, 1926; Ross, 1969). It is exhibited, though to a lesser degree, in mass constancy by moving the same objects in different force environments (Ross, 1981). Although there are factors that may interfere with the operation of weight constancy, in general stimuli of equal weight will be perceived as being equally heavy under different circumstances. That is, different sensory inputs may impinge upon receptors and different "command signals" may be required to lift the object, but the weight of the object is perceived as being stable.

Perceptual illusions occur when the "psychological" perception of an object, or objects, differs from the "objective" perception. For example, in the case of the Mueller-Lyer illusion, the length of the lines contained by the outward and inward pointing fins look different, even though when measured by a ruler they give the same length. Illusions occur in weight perception. For example, objects having the same physical weight, but differing in some other respect (such as size, material, colour, temperature) are perceived as being different in weight (Charpentier, 1891; Wetenkamp, 1933; Ross, 1966; Stevens & Hooper, 1982). Davis and Roberts (1976) and Davis, Taylor and Brickett (1977) argue that the rate of lifting explains both the size-weight illusion and how the weight of lifted objects is ascertained in general. That is, if two objects of the same weight are lifted at different speeds, the object lifted faster will appear lighter. However one criticism of this approach is that it does not fully consider the input and output of a bio-mechanical system. A rate of lifting must be judged in relation to the strength of the command signal. Both the input and the output of the bio-mechanical system must be known. Another criticism is provided by Mounoud, Mayer and Hauert (1979) who point out that the rates of lifting could equally well be interpreted in terms of means of indirectly judging the weight of a lifted object other than those suggested by Davis.

The existence of a central component in weight discrimination is further demonstrated by research into adaptation. For example, in vision and audition, it is well known that sensitivity is better in conditions of adaptation to the stimulus intensity and poorer in conditions of adaptation to higher or lower stimulus intensities. In studies investigating weight discrimination similar findings have been found. For example, Woodrow (1933) found that discrimination was poorer with a varying standard weight than with a fixed standard. Holway, Goldring and Zigler (1938) found that the discrimination of light weights was initially poor after adaptation to a heavy weight and recovered over time. Gregory and Ross (1967) found that discrimination was initially poor both after weighting the lifting arm with a cuff and after removal of the cuff, but recovered in both instances over time. These experiments could be explained in terms of adaptation of peripheral receptors. However, Dinnerstein (1965) found that sensitivity in one hand was reduced when a weight of different intensity was lifted in the opposite hand compared with when a similar weight was lifted in both hands. Ross and Gregory (1970) also found that changes in discrimination due to the size-weight illusion cannot be explained in terms of peripheral adaptation. These findings would suggest that central, psychological mechanisms are involved in weight discrimination.

It has been argued in the preceding paragraphs that there can be no simple correspondance between physical and apparent weight; between untransformed sensory input, or afference, and perceived weight; or between untransformed command signals, or efference, and perceived weight. There must be a complex interaction between efference and afference, between command signals and feedback at both a high and a low level of operation; at both a central and peripheral level.

1.6.1 Weber fractions for lifted weight

Text books often oversimplify the results of weight discrimination experiments by quoting a Weber fraction of 0.02 for lifted weights, probably following Boring Langfeld and Weld (1939) who cited Holway and Pratt (1936). However, this appears to be a best value for one subject in one condition and is not representative of all the factors that can affect the level of discriminatory ability for lifted weights. If a close examination of the literature is carried out a very different picture emerges.

Weber fractions for lifted weights have been obtained at a number of stimulus intensities with great variation being found (Oberlin, 1936; Holway and Hurvich, 1937). Different methods of lifting the stimulus weights have also resulted in a wide variation in Weber fractions (Oberlin, 1936; Holway, Goldring & Zigler, 1938). One and two-handed weight discrimination has been investigated (Fechner, 1860; Holway, Smith & Zigler, 1937) with the finding that the one-handed paradigm gave the finest discrimination. Thus there are a number of factors that have been shown to affect the discrimination of lifted weights.

1.7 Theories of weight discrimination

Although weight perception has been studied for over 150 years very few theories, whether physiological or psychological, have emerged to adequately explain the mechanisms of weight discrimination. This is in part due to the lack of specific sensory channels for weight, and its reliance on the very complex machinery used in voluntary movement. It is also due to the notion that weight discrimination is a very simple process that involves the "muscular sense" or "sensations of innervation". The physiologial theories to have emerged reflect this by explaining weight discrimination either in terms of a simple sensory input channel (pre-efferent) or a simple output channel (pre-afferent). The psychological theories have emerged to explain the size-weight illusion rather than the mechanisms of weight perception itself.

1.7.1 Sensory receptor function

a) Phi-gamma hypothesis: This assumes that in a psychophysical discrimination experiment the relationship of the proportion of responses to stimulus values is described by the integral of the normal probability curve. The assumption is that sensory nerve action is continuous and bears a direct relationship to a sigmoidal psychometric response function.

b) Neural quantum hypothesis: Corso (1956) argued that in a psychophysical discrimination experiment a stimulus increment difference will be noticed whenever it excites one quantum. The assumptions are 1) the apparent continuum of sensory experience is actually discrete i.e. neural processes operate on an all-or-none basis, and can be divided into functionally distinct units; and 2) some psychometric functions are linear in form.

Both these theories assume that the observer's responses bear a direct relationship to receptor output in a pre-efferent system. In an extensive review article of the psychophysical and physiological literature this assumption has been shown to be questionable (McKenna, 1985). The Phi-gamma hypothesis was applied to the results of a psychophysical investigation into weight discrimination by Oberlin (1936) and Holway _et al_ (1937) but has not been applied since. This is probably due to the fact that the afferent input channels signalling weight are not easily specified. Efference is clearly involved in lifting movements of the upper limb. Also, advances in physiological research has shown the all-or-none operation of the nervous system to be applicable only at the basic level of the axon (Sinclair, 1981).

1.7.2 Command Signal Function

a) Sensations of Innervation: This has proved to be the most attractive and long lived theory of weight discrimination. It has been propounded in one form or another since Weber (1834) to McCloskey (1978). It simply states that the weight of a lifted object is judged by reference to the amount of effort, or sense of effort, put into the lift. There have been strong and weak advocates of such a theory. For example, McCloskey *et al* (1974) advocated a theory based solely upon the sense of effort or corollary discharge (Sperry, 1950) and Weber (1834) advocated a hybrid theory that combined pressure and muscular sensing. More recently (McCloskey, 1978) has advocated a modified version of his theory by including feedback as a necessary component.

b) Theory of Motor Set: This theory is a variation of the Sensation of Innervation Theory. Müller and Schumann (1889) propounded the theory that in a consecutive discrimination of two weights, the second weight is judged heavier, or lighter, than an immediately preceding first weight, by reference to the amount of effort used to lift the first weight. The same amount of effort is used to lift the second weight and if it is lifted more easily or quickly then it is judged lighter, if it is lifted with more difficultly or more slowly then it is judged heavier. They did not support the more general theory of sensations of innervation as they held that the motor impulse was unconscious until its effect upon the rate of lifting was noticed.

1.7.3 Interactionist accounts

a) The Muscular Action Theory: This theory stated that the perception of weight of lifted objects was mediated by muscular tension (Payne & Davis, 1940). Electrophysiological evidence recorded during weight discrimination revealed that that the properties normally associated with the central "motor set" were measurable at the periphery. Although not explicitly interactionists Payne & Davis discussed briefly different "command signals" resulting in different levels of tension. This theory has not been widely accepted because of the difficulty in interpreting muscular action potentials unambiguously in terms of efferent or afferent signals.

b) Efference Copy Hypothesis: Von Holst and Mittelstaedt (1950) were concerned with the fact that the perception of the environment is mediated by sense organs that take account of the organism's own actions as well as the incoming environmental stimuli. The afference resulting from external sources was labelled ex-afference and the afference resulting from internal sources reafference. Thus to perceive the weight of a lifted object the ex-afferencee must be distinguished from reafference. That is, the sensory input provided by the weight must be separated from, and take account of, the sensory input provided by the lifting movement of the limb. How this is done is still not resolved. Either the sensory centres distinguish between internally and externally generated afferent signals on the basis of corollary discharges from the motor centres to the sensory centres, or the distinction is made because the afferent messages from the two sources are distinguishable in some other manner. This model has been applied to weight perception by Herschberger & Misceo (1983).

c) Wheatstone Bridge Model: This model purports to explain both the size-weight illusion and the loss of sensitivity due to maladaptation (Gregory, 1968; Gregory and Ross, 1967; Ross and Gregory, 1970). They propose that weight discrimination involves central processing of the sort analogous to the electrical operation of a Wheatsone Bridge. Inputs are set by two mechanisms; the remembered relationship between size and weight of objects and the sensory input from the lifting movement. When these two inputs are different sensitivity decreases and a weight illusion occurs, and when they are the same sensitivity is optimal and there is no illusion. However, this model suffers from the same problems as the Efference Copy Hypothesis.

1.7.4 Theoretical approach to weight discrimination

The theoretical approach adopted in this thesis will not reflect some or all of the theories outlined from 1.7.1 to 1.7.3. It was felt that most of these theories either suffer from a lack of adequate conceptualisation of weight and the discrimination of objects using "active touch" or rely upon physiological theorising reflecting the "state of the art" of the times in which they were conceived. Recently there have been great advances in the physiological knowledge concerning motor and sensorimotor functioning (Roland, 1978; Iverson, 1981; Matthews, 1982). There has also developed both an empirical and theoretical interest in motor skills and mechanisms of motor control (Stelmach, 1976; Adams, 1984). The findings of this thesis will be considered in terms of some of the recent advances in physiology and some of the motor skills models of upper limb control.

CHAPTER 2: METHODS, MEASUREMENT AND MACHINES

2.1 Introduction

The measurement of differential thresholds (DLs) for lifted weights, by manually presenting the stimuli and recording the subject's responses on paper, can be an arduous and time consuming business for both experimenter and subject. For example, Fechner (1860) used over 4,000 stimulus presentations, over a period of weeks, to calculate one DL. The availability of microcomputers in psychological laboratories allows their use in reducing the test time. However the mechanisation of procedures is not without problems, both conceptual and practical.

A major criticism of laboratory based experiments is that in their attempt to control variables they falsify the naturally occurring act that they are trying to investigate. The resultant findings bear little, if any, relationship to the natural act. I have argued that in the investigation of weight perception subjects must be allowed to lift and attribute weight to real objects (Chapter 1.4). I now wish to apply this standard to the previous studies claiming to investigate weight discrimination.

Many experimenters have made recourse to devices that have abandoned the basic requirement of lifting discrete objects or lifting them in a natural way. They have done so in order to fulfil some other experimental requirement. Often this is to simplify stimulus presentation and to control extraneous variables. For example, Sekuler & Bauer (1965) and Sekuler, Hartings and Bauer (1974) had subjects lift one end of a lever whose other end was systematically restrained by an electro-magnetic field to produce different stimulus intensities. Subjects had to discriminate between the "weights" presented by the lever. Such an electro-mechanical device controlled precisely the stimulus intensity, stimulus duration, and interstimulus interval. The time taken to test subjects was considerably shortened. Other experimenters have used weights suspended on pulley systems, with subjects pulling on strings in the horizontal plane, to try and investigate weight perception (McCloskey et al, 1974). This procedure allowed the experimenter to vary stimulus intensities easily and out of sight of the subject. However the investigation of weight perception was not being carried out in either of these studies. The abnormal lifting movements and lack of real objects of perception ensured the measurement of the sense of force or effort, rather than of the weight of an object.

It has been argued in Chapter 1 that if we are to make sense of the world and the objects in it, we must perceive attributes of the same objects as being relatively stable, even though the sensory inputs may differ on different occasions. It is difficult to ascribe weight to an object if it is constantly changing in weight over time. Thus the use of an object whose weight is increased or decreased in intensity continuously is not conducive to the investigation of an attribute of a discrete object. It has been shown that the use of a varying standard weight (Woodrow, 1933) and the use of a constantly varying stimulus weight (Holway *et al*, 1937) results in very poor discrimination.

2.2 Statistical Techniques

Psychophysicists have measured differential sensitivity by a variety of methods. For example, Fechner (1860) introduced the method of just noticeable differences, the method of right and wrong cases and the method of average error. The first two are now better known as the method of adjustment and the method of constant stimuli. The latter is still by far the most widely used. The probability of detecting the difference between two stimuli is calculated over repeated presentations, at a number of stimulus intensities. The desired probability is then read off from the best fitting psychometric function. The major

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Table 2.1 Examples of differential thresholds (DLs) for lifted weights calculated by Methods of Constant Stimuli and Adjustment

METHOD	PRESENTATION PROCEDURE	HAND OF LIFT	DL (g)	TIME PER DL (in min)
Constant stimuli (CS)	self-test	left	5.6[1]	50
CS	self-test	left	5.6[2]	60
CS	self-test	right	4.6-6.3[3]	30
CS	self-test	right	3.5[4]	60
Adjust-ment	Experimenter	right	>20[5]	50

[1] Adapted from the preflight data of Ross, Brodie & Benson (1984); [2] Ross (1981); [3] Ross & Reschke (1982); [4] Oberlin (1936); [5] Holway & Hurvich (1937)

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disadvantage with this method, as with the method of adjustment, is that it is time consuming. As can be seen from Table 2.1, approximately 50 mins are required to produce a threshold using the method of adjustment (Holway & Hurvich, 1937) and approximately 60 mins are required using the method of constant stimuli (Oberlin, 1936). The abnormally high DL produced by the method of adjustment reveals the unsuitability of this method for weight perception.

An adaptation of the method of constant stimuli, the method of single stimuli, was introduced to produce DLs more efficiently (Wever & Zener, 1928). This method required only half the number of trials because it eliminated the need to present the standard stimulus weight. Fernberger (1931) compared the method of single stimuli with the method of constant stimuli, for lifted weights, and found that they produced equally reliable thresholds. However, the method of single stimuli has never been fully accepted for the measurement of perceptual thresholds, possibly due to the complications introduced by series and time errors.

If shorter test sessions are necessary, the method of constant stimuli can still be adapted. Fechner (1860) adopted the strategy of testing his subjects for one hour each day over a number of days. More recently, thresholds have been calculated by repeated sessions (Ross et al, 1984) or by averaging across subjects (Ross, 1981). These procedures estimate average performance over long periods of time and between subjects, ignoring variations due to these factors. However, these procedures are not always successful as is shown by the variations in DLs calculated by Ross & Reschke (1981). This was partly because of the time constraints introduced by the parabolic flight, resulting in insufficient data being collected in the test sessions to enable calculation of reliable thresholds for individual subjects. Even when the average of 9 subjects' data was taken, a good fitting psychometric function was still not obtainable due to the use of a varying standard; a procedure shown to produce unreliable thresholds by Woodrow (1933).

The advantage with the method of constant stimuli is that it is amenable to self-test, paper and pencil techniques. For example, by lettering the stimulus weights, determining the pairings of weights in advance and listing the pairings on a card, subjects can test themselves and record responses independently of an experimenter. Although the experimenter is relieved from testing, he or she is still required to engage in arduous post test calculations of the threshold. However, although this "low-technology" approach is attractive because of its simplicity and reliability (Ross, 1985), and has been used with varying amounts of success (Ross & Reschke, 1981; Ross et al, 1984), it is still not an efficient way of measuring differential thresholds in this "high-technology" age.

Adaptive methods or sequential tracking procedures, such as the staircase procedure (Cornsweet, 1962) or Wetherill tracking (Wetherill & Levitt, 1965), have been derived from the method of limits. At any one time, only one point along the psychometric function is tested by these procedures.

After a number of trials the stimulus intensities are determined by the subject's previous responses and will track the threshold. Thus trials are avoided at stimulus intensities well above and well below the threshold. The disadvantage with this procedure was that it required an experimenter to generate the tracking procedure, record the responses and analyse the data to calculate the threshold. However, with the advent of microcomputers tracking procedures are easily generated, as well as the calculation of the threshold itself. Its great advantage is that (for visual stimuli) a "staircase" procedure requires 1/6th fewer trials than the method of constant stimuli for equally reliable thresholds (Corwin, Kintz & Beaty, 1979).

2.3 Stimulus Presentation Techniques

The manual presentation of stimulus weights is wasteful of the experimenter's time and hinders easy control of stimuli or biases such as the space error. The self test procedures of Ross (1981) required that subjects make different movements to obtain the stimuli, with stimulus weights in different positions relative to the subject. As this has been shown to introduce an error known as the space error (Fechner, 1860) it is advisable to present the stimuli to the same position, relative to subjects. Various attempts have been made to develop apparatus to overcome these problems. For example, Oberlin (1936) used a manually operated turntable to hold and present the stimulus weights to the subject in the same location thus avoiding the "space error". The subject extended his or her arm through an opening in a screen which prevented the subject viewing the stimulus weights. Holway & Hurvich (1937) used beakers suspended out of sight below grasped cylinders. The stimulus intensity was altered by continuously pouring mercury into these beakers. McCloskey et al (1974) suspended weights from a pulley system, out of view of subjects, and had subjects pull horizontally on cords. Both involved an experimenter loading the "weight". Sekuler & Bauer (1965) introduced an automated device for presenting subjects with "weights". It involved subjects in lifting and lowering a lever which was systematically hindered at one end by an electro-magnetic field, to produce differing stimulus intensities. Although these devices shortened test sessions, all but the first hindered the attempt to investigate normal weight perception. For example Holway and Hurvich had subjects experience an object continuously varying in weight, instead of one of constant weight. In the latter two examples subjects estimated force or effort, rather than the weight of an object. These methods forced subjects to discriminate between bodily sensations accompanying the lifting movements, and not between the weight of stimulus objects.

The requirement is to measure reliable DLs, in as short a time as possible, using a self test procedure, in a variety of controlled lifting conditions, for discrete weights. The combination of computer generated Wetherill Tracking procedures (driven by subjects' push button responses) and an electro-mechanical turntable system (to hold and present the stimulus weights to the same position) offers a solution.

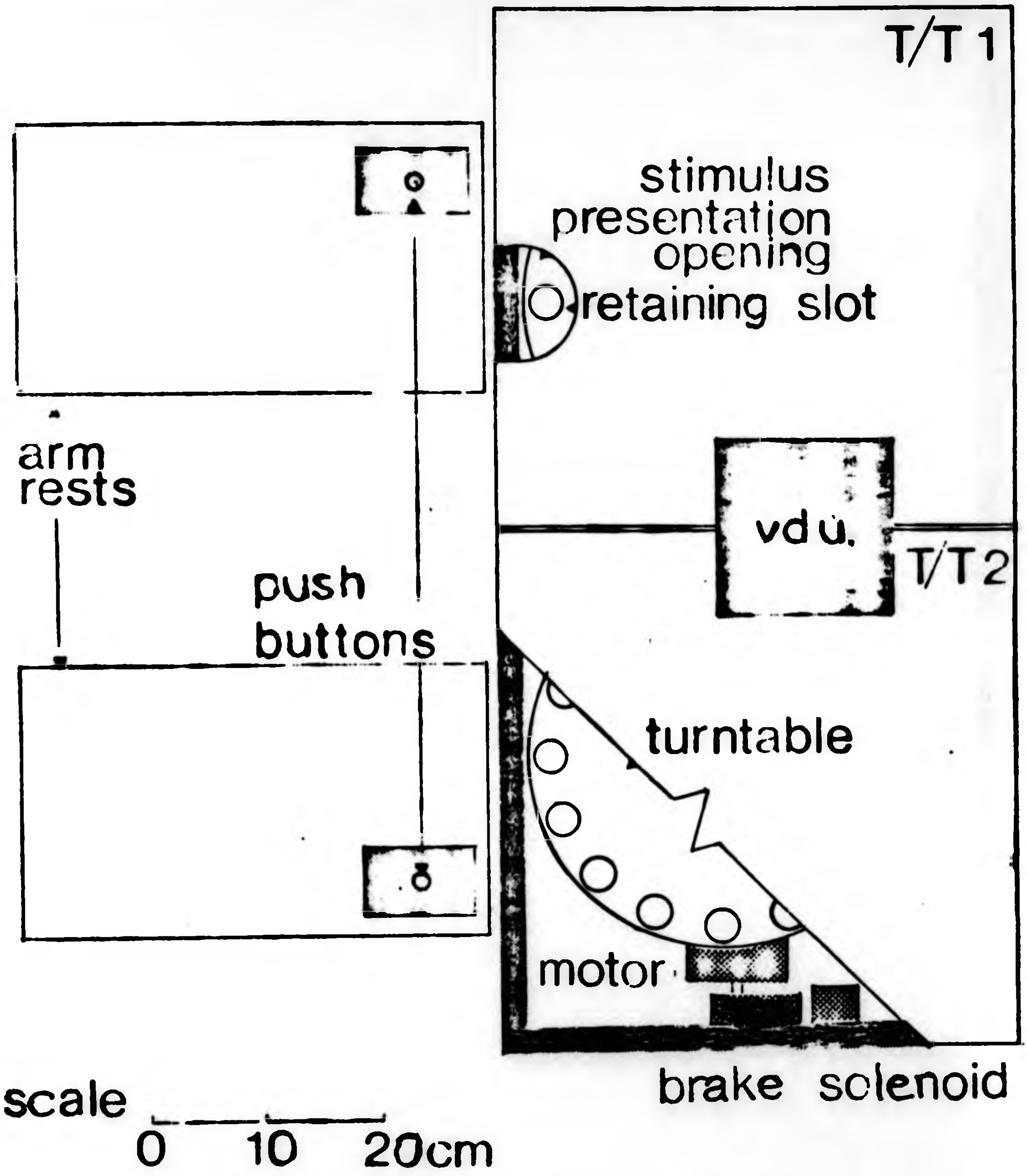
2.4 Apparatus

2.4.1 Hardware: A standard 600 RPM electric motor, with a 20:1 reduction gearbox, was used to drive each of the 16 sector turntables. The turntables were constructed from 12 mm Darvic material (a very strong plastic) with 16 retaining slots on the circumference for holding stimulus weights. Figure 2.1 shows an exploded view of the apparatus from above but excludes the microcomputer and interface circuitry box.

An encoder disk, made from 2 mm Darvic Material was fitted beneath each turntable on the motor spindle. The encoder disk was configured in Binary Grey Code to allow the detection of any one of the 16 sectors on the turntable by a reflective opto-switch. The output signal was fed via a variable resistance, to a preset sensitivity, and used to control a switching transistor, the output of which was buffered by a logic inverting integrated circuit (IC), before being input to an Apple II microcomputer via a John Bell Engineering 6522 parallel input/output (I/O) card. Four reflective opto-switches and circuits were used with each turntable. The output of the sense heads was in binary grey code and was derived from the encoding disk fitted under the turntable. Thus the position of either turntable could be sensed at any time by reading the contents of the appropriate address.

Output signals from the microcomputer were taken to the turntables via an output port on the I/O card. Logic control signals were buffered by an inverting IC, the output of this being wired to dual in line (DIL) reed relays. These relays

Figure 2.1 Computer controlled apparatus for the presentation of discrete stimulus weights



Top view of T/T 1 and T/T 2 with push buttons and arm rests in position. The microcomputer and interface circuitry box are not shown. Cut-away section of T/T 2 reveals the position of the turntable, motor and brake assembly. Subjects sat in front of the apparatus with their fore-arms resting on the arm rests and hands in front of the openings.

were used to activate a solid state relay which switched a turntable motor on or off, or activated a mercury contact relay which controlled a solenoid to switch a motor brake mechanism on or off. The run time of the motor and the duration of the braking pulse were both controlled by changing the address argument. Push button response signals were fed into the microcomputer via the I/O card. The logic state of each was ascertained by reading the content of the appropriate address.

The interface circuitry was housed in an instrument case containing its own DC power supply. Circuits were constructed on printed circuit scripboard. All connections between the microcomputer, interface box and turntables were via plug-in connectors allowing the system to be portable. The turntables themselves were housed in substantial wooden boxes with an opening allowing access to one sector. A standard VDU was placed on top of the boxes.

There were two financial constraints placed upon component selection. Firstly stepper motors, capable of stopping the turntables when fully laden with high intensity stimulus weights, were considered too expensive. The development of an adaquate braking system was therefore necessary. Secondly the input circuitry of the interace did not include any grey scale decoding. This did not have any deterious effect as it was easily accounted for in the software.

2.4.2 Software: Applesoft Basic Programs were written to incorporate Wetherill Tracking procedures at the 70.7%

correct level. Examples of these programs are given in the appendices. The program for the two-handed procedures randomly interspersed two conditions; the lighter (or standard) weight being presented via turntable 1 (T/T 1) with the heavier (or comparison) weight being presented via turntable 2 (T/T 2) and vice versa (Appendix A.1.2 & 3). The program for one-handed procedures, on each turntable, randomly interspersed the presentation of the lighter weight first and lighter weight second (Appendix A.1.2). Thus the turntables presented the standard and comparison weights in a systematic way dictated by the tracking procedure, using PEEK and POKE statements in the programs.

Subjects were instructed when to lift and lower the appropriate weights and when and how to respond via messages flashed upon the VDU. All the experimental procedures were forced choice, with subjects inputing responses of heavier via push-buttons. The termination of testing and the calculation of each DL occurred after 48 trials (the first 6 trials being ignored) or 16 reversals (Wetherill & Levitt, 1965), whichever was achieved first. All responses at each stimulus intensity were recorded onto disk.

2.6 Discussion

The use of microcomputers for implementing sequential tracking procedures is now well established (e.g. Corwin *et al*, 1980). The operational constraints enforced by such procedures are similar to those enforced by the use of discrete weights to measure DLs for lifted weights. That is, the inter stimulus intensity interval and the range of stimulus intensities for the tracking procedure, must be decided beforehand, just as the range and interval of the stimulus weights must be fixed in advance to enable their manufacture. Sequential tracking procedures would therefore seem to be the logical way of measuring DLs for lifted weights. Wetherill Tracking was adopted in order to calculate DLs at the 70.7% correct level, and thus allow comparison with other research. The 75% correct level is normally used for the method of constant stimuli.

Although variations upon the staircase procedures, such as PEST routines, where inter-stimulus intervals are varied (Lieberman & Pentland, 1982), are available and increase precision, they cannot be easily implemented when the stimuli must be individual weights. Subjects must lift discrete objects in order to engage in the perception of weight. The apparatus described avoids making the assumption that sensations of force or effort are the same as the perception of heaviness.

The necessity of labelling stimulus weights for a self-test procedure (with the risk of subjects recognising pairings) or having large numbers of duplicate weights, is avoided. All the weights, other than the current stimulus pair, are hidden from view and in any case are identical. Subjects would find it difficult to follow or recognise weights in the test sequence. The use of more than one sequential tracking procedure (randomly interspersed) eliminates the effects of any response bias.

Problems could exist when presenting the weights in this manner. The weights near the threshold become warm with continual handling. Evidence for possible interference is provided by the temperature-weight illusion where warmer objects appear lighter than colder objects, of the same weight and size (Weber, 1834; Stevens & Hooper, 1982). More than one standard, and comparison weight at any one stimulus intensity, must be used to prevent temperature acting as a cue to particular weights or as an uncontrolled variable. The sixteen sectors on the turntables provide space for a number of duplicate standard and comparison weights within a reasonable range to encompass performance.

Weight perception is a complex and little understood phenomenon. It is advisable that subjects should be presented with discrete weights and be allowed to lift them in as normal a way as possible. These criteria can be incorporated

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Table 2.2 Examples of differential thresholds (DLs) for lifted weights calculated by Wetherill Tracking (70.7%)

TRACKING PROCEDURE	PRESENTATION PROCEDURE	LIFTING HAND	DL (g)	TIME PER DL (in min)
Generated by Computer	Experimenter	right	4.25	15[2]
Generated manually	Experimenter	right	4.93	20[1]

[1] Brodie & Ross (1984); [2] Brodie & Ross (1985)

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along with the efficiency introduced by sequential tracking procedures by experimenter presentation. As can be seen from Table 2.2. sequential tracking procedures, with the experimenter presenting the stimulus weights, recording the responses and generating the tracking preocedures, can measure 3 DLs in 60 mins. With the experimenter presenting the stimulus weights and a microcomputer recording and generating the tracking procedure 4 DLs can be measured in 60 mins. Both these procedures are quicker than the method of constant stimuli which takes at least 50 mins for one threshold.

In the experiment described Chapter 3 the experimenter was required to present the stimulus weights to different positions on the upper limb so the manual presentation of weights and the computer generated tracking procedure were utilised. In the experiments described in Chapters 4, 5 6, and 7 the automatic presentation of stimuli was possible as subjects were required to grasp the weights between thumb and fingers. A further saving in time was made by using the apparatus described thus: instructing the subjects via the VDU, systematically varying the stimulus intensity by means of the sequential tracking procedure, presenting the weights automatically, and recording the responses via pushbuttons.

CHAPTER 3: ONE HANDED WEIGHT LIFTING : STIMULUS INTENSITY, METHOD OF LIFTING AND POSITION OF STIMULI

3.1 Introduction

Weber (1834) measured the tactile sensitivity of various parts of the body surface using two-point discrimination. He found that the finger tips were the most sensitive part of the volar surface of the hand (1978, p. 112). This finding may well reflect the distribution of specific receptors in the skin of the palm and fingers (Vallbo & Johansson, 1978). Weber did not investigate the relationship between stimulus intensity, position of stimulation and sensitivity for weight discrimination on different parts of the upper limb. He assummed that those areas most sensitive to two-point discrimination were also most sensitive to weight discrimination. However, some areas may well provide optimum discrimination at low stimulus intensities while others may provide optimum discrimination at high stimulus intensities. This would reflect cutaneous receptor distribution for pressure and not two-point discrimination (Sinclair, 1981).

Weber fractions for the discrimination of lifted weights have been found to vary with stimulus intensity and method of lifting (Holway & Pratt, 1936; Holway & Hurvich, 1937). That is, Weber fractions increase as stimulus intensity decreases and increase with more distal lifting movements of the upper limb (e.g. shoulder-as-fulcrum lifting movements produced lower Weber fractions than wrist-as-fulcrum lifting movements). Fechner (1966, p.166) suggested that the poorer discrimination he obtained at low stimulus intensities resulted from an effect of arm weight. Holway & Hurvich (1937) suggested that the better discrimination they obtained with proximal lifting movements was due to more sensory receptors signalling the weight of the lifted object. However, the Weber fractions obtained by Holway & Hurvich (1937) are abnormally high by a factor of about 10 compared to other authors. Furthermore, Table 3.1 reveals that if the

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Table 3.1 Weber fractions from Holway & Hurvich (1937) for three stimulus intensities and two methods of lifting calculated using two different formulae

STIMULUS INTENSITY (in grams)	Method of lifting	$\Delta W/W2$	$2\Delta W/W1+W2$
20	wrist as fulcrum	0.68	1.04
20	shoulder as fulcrum	0.64	0.93
50	wrist as fulcrum	0.51	0.68
50	shoulder as fulcrum	0.44	0.57
100	wrist as fulcrum	0.39	0.49
100	shoulder as fulcrum	0.31	0.37
200	wrist as fulcrum	0.26	0.29
200	shoulder as fulcrum	0.21	0.23

Weber fraction is recalculated, using the formula $2\Delta W/W1+W2$, the extremely high Weber fractions at stimulus intensities of 20 and 50 g, were partly masked by the use of the formula $\Delta W/W2$. This suggests that the methodology adopted by Holway & Hurvich (1937) was not condusive to accurate weight discrimination especially at low stimulus intensities. This is probable due to the continuous adaptation during each lift.

Oberlin (1936) found that a shoulder-as-fulcrum lifting movement produced the finest discrimination at a stimulus intensity of 100 g, when compared with wrist and elbow lifting movements. Athough there was great variation between his two subjects, the explanation given was in terms of the number of functional sensory receptors involved in signalling the weight. Two further experiments were reported by Oberlin in which the stimulus intensities were varied and the method of lifting kept constant. It was argued that the number of receptors signalling the weight of a lifted object was proportional to both stimulus intensity and type of movement. That is, the number of receptors operating for a wrist-as-fulcrum lifting movement with a high stimulus intensity was the same as with a shoulder-as-fulcrum lifting movement at a low stimulus intensity. This assumption is open to a number of criticisms: 1) As there is only a finite number of receptors available in any one muscle (Granit, 1966), sensitivity can only increase within limits. 2) It is debatable whether there is a simple relationship between receptor output and sensation (McKenna, 1985). 3) The physiological theorising assumes the operation of a "pre-efferent" or afferent input system. Such a system is highly unlikely due to the interaction between afference from muscle receptors and efference occurring both locally at a spinal reflex level and through the gamma-efferent system.

More recently it has been shown that lifting and jiggling a weight, using the shoulder-as-fulcrum, results in finer discrimination than lifting and holding the weight using the shoulder-as-fulcrum (Brodie & Ross, 1985). Various explanations of this finding are possible but it is likely that the receptors in the arm are operating most sensitively in the jiggling condition through the use of feedback. Thus numbers of receptors per se may not be important.

Given the small subject numbers used by Oberlin (1936) and the unconventional methods and statistical analysis adopted by Holway & Hurvich (1937) the relationship between stimulus intensity and method of lifting needs further investigation and expansion. A very low stimulus intensity (5 g) may produce much higher Weber fractions than low and medium stimulus intensities because the kinesthetic signals generated by lifting movements may inhibit the transmission of cutaneous signals. However, the Weber fractions may well be not as high as those obtained by Holway & Hurvich (1937). At a low stimulus intensity (50 g) a distal lifting movement may aid discrimination due to a specific number of receptors operating optimally. At a medium stimulus intensity (200 g) proximal movements may aid discrimination by allowing a large number of receptors to operate optimally.

When comparing the weight of two sucessively lifted stimuli of equal weight, a systematic error or Time-order Error (TOE) is introduced. If the first stimulus appears less intense than the second then the direction of the error is negative. Fechner (1860) was the first to and try to take account of the TOE in the calculation of differential thresholds when presenting successive stimuli. Although he did not provide a detailed explanation of why it should occur (Hellström, 1985), TOEs were found by him to be negative at high stimulus intensities and positive at low stimulus intensities for the discrimination of lifted weights. This effect was also found by Woodrow (1933) and Bartlett (1939) for lifted weights. As it is surprising that a reversal of direction should occur due to stimulus intensity and not method of lifting it was decided to investigate further the TOE in relation to stimulus intensity and method of lifting.

The aims of this experiment were to investigate further the relationship between stimulus intensity and method of lifting and the direction of the time-order error in one-handed consecutive discriminaton of weight, at three stimulus intensities.

3.2 Method

3.2.1 Subjects

Eighteen undergraduate psychology students acted as subjects as part of a course requirement. They were divided into three groups of of six, with three male and three female in each. All were right handed and between the ages of 18 and 26 with a mean age of 20.5.

3.2.2 Apparatus

Three sets of stimulus weights were used - each comprising 7 standard weights and two sets of 7 comparison weights. The standard weights were 5 g, 50 g, and 200 g. The comparison weights ranged from 5.5 g to 8.5 g, 52 g to 64 g and from 204 g to 228 g. All the weights were cylinders (4.5 cm x 2.5 cm), identical in shape and construction. Additional comparison weights were available for the 5 g set, ranging from 8.5 g to 12.5 g, as very poor discrimination was expected. The weights were constructed out of aluminium by removing a central core along the longer axis. The even distribution of material reduced the possibility of unequal moments of inertia providing an additional cue (Kreifeldt & Chuang, 1979).

An Apple Microcomputer was programmed to generate two randomly interspersed Up-down Transformed Response Rules at the 70.7% correct level with responses input via the keyboard. A listing of the program is presented in the appendices (A.1.1). Randomly assigned numbers were attached to the stimulus weights and these numbers were displayed upon the monitor for the experimenter to follow. The subjects' responses were elicited verbally by the experimenter after the second weight had been presented. "F" was typed if the first weight was deemed heavier by the subject and "S" was typed if the second weight was deemed heavier by the subject. The DLs were automatically calculated after 16 reversals or 48 trials, whichever occurred first, and were recorded with the subjects' responses onto disk.

3.2.3 Procedure

Subjects were presented with two weights, a standard and comparison, consecutively with an stimulus presentation time (SPT) of 3 sec and an inter stimulus interval (ISI) of 5 sec. The experimenter placed and removed the weights and gave the command to lift and lower the weights. The subjects responded "first heavier" or "second heavier" in a forced choice manner. The weights were presented to blindfolded subjects by the experimenter who also recorded their responses. Each session lasted for approximately one and a half hours and subjects were required to perform three sessions. Only one of the three stimulus intensities was tested at each session in order to avoid adaptation effects. The subjects' arm was located in the same position for each presentation. The weights were held in position on the upper limb using small male velcro pads of negligible mass. At the wrist and elbow positions straps made of female velco were used as retainers for the weights.

DLs were calculated for both orders of presentation (OOP) of standard first and standard second at three stimulus intensities (SI) 5 g, 50 g and 200 g. Each group of subjects was presented with the stimuli on different parts of the upper limb (POS). The first group was tested with the stimulus weights presented in the palm of their hands (G1), the second group was tested with the stimulus weight presented upon the volar surface of skin on the wrist below the pisiform bone (G2), and the third group was tested with the stimulus weights presented to the volar surface of skin just on the inside surface of the elbow joint (G3). Three methods of obtaining stimulation (MOS) were tested, one passive with the limb supported by the bench and the other two active with the elbow and shoulder as fulcrum. One further condition was tested with the third group, the stimulus weights being presented to the palm of the hand with active lifting using wrist as fulcrum. The order of testing MOS was counterbalanced across subjects and the OOP was randomly interspersed, with testing completed after 16 reversals or 48 trials for each "staircase".

3.3 Results

Six DLs were calculated in each session with many subjects reaching the criteria of 16 reversals before 48 presentations. The time taken is thus comparable to that of Brodie & Ross (1985) in that one threshold was calculated in 15 minutes.

In order to compare results at the three stimulus intensities DLs were converted to Weber fractions using the formula $2\Delta W / W1 + W2$. The mean Weber fractions for the three groups of subjects in the three conditions at three stimulus intensities are presented in Tables 3.2 and 3.3.

Two fixed effects analyses of variance (ANOVAs) were performed upon the Weber fractions, for 1 between subject variable (POS) and for 3 within subject variables SI, MOS and OOP. One grand ANOVA could not be performed since there could only be one elbow as fulcrum condition with the weights placed upon the skin at the elbow.

The first ANOVA was performed with 3 levels of POS: hand, wrist elbow; three levels of SI: 5, 50, 200 g; two levels of MOS: passive and shoulder as fulcrum; and two levels of OOP: standard first, standard second. A significant effect was found for POS ($F(2,15)=16.42$ $p=0.0002$) and a significant interaction was found for SI X POS ($F(4,30)=15.91$ $p=0.0000$). Figure 3.1 shows that the POS effect was caused by

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<u>Table 3.2 Weber fractions for a one-handed consecutive weight discrimination paradigm at three stimulus intensities using three methods of obtaining stimulation for groups 1 & 2 (G1 & G2)</u>

METHOD OF STIMUL-ATION	STIMULUS INTENSITY (g)	WEIGHT ON PALM G1(n=6) Order of Presentation SF	SS	Mean	WEIGHT ON WRIST G2(n=6) Order of Presentation SF	SS	Mean
passive	5	0.240	0.410	0.325	0.694	0.667	0.680
elbow as fulcrum	5	0.251	0.395	0.316	0.506	0.687	0.597
shouder as fulcrum	5	0.280	0.415	0.348	0.484	0.725	0.605
passive	50	0.114	0.111	0.113	0.170	0.183	0.176
elbow as fulcrum	50	0.096	0.079	0.088	0.118	0.175	0.146
shouder as fulcrum	50	0.109	0.134	0.121	0.109	0.178	0.143
passive	200	0.060	0.056	0.059	0.101	0.074	0.088
elbow as fulcrum	200	0.058	0.059	0.058	0.063	0.072	0.068
shouder as fulcrum	200	0.046	0.082	0.064	0.055	0.085	0.070

Table 3.3 Weber fractions for a one-handed consecutive weight discrimination paradigm at three stimulus intensities using three methods of obtaining stimulation for group 3 (G3)

METHOD OF STIMULATION	STIMULUS INTENSITY (g)	WEIGHT ON PALM G3(n=6) Order of Presentation SF	SS	Mean	WEIGHT ON ELBOW G3(n=6) Order of Presentation SF	SS	Mean
passive	5				0.676	0.751	0.714
wrist as fulcrum	5	0.362	0.395	0.379			
shouder as fulcrum	5				0.702	0.821	0.762
passive	50				0.131	0.151	0.141
wrist as fulcrum	50	0.109	0.082	0.379			
shouder as fulcrum	50				0.137	0.128	0.133
passive	200				0.063	0.059	0.061
wrist as fulcrum	200	0.047	0.043	0.045			
shouder as fulcrum	200				0.041	0.058	0.50

discrimination being best with stimulus presentations to the palm, followed by presentation to the skin of the wrist, followed by presentation to the skin of the elbow. The interaction of SI X POS was caused by considerably better discrimination at 5 g when the weights were presented on the subjects' palm as compared with wrist or elbow, but not at higher stimulus intensities where discrimination was finest on the elbow at 200 g. A significant effect was found for SI $(F(2,30)=261.18\ p=0.0000)$ and OOP $(F(1,15)=6.87\ p=0.0193)$. A significant interaction between SI X OOP was found $(F(2,30)=9.15\ p=0.0008)$. The SI effect was caused by discrimination improving as stimulus intensity increased and the OOP effect by Weber fractions being lower when the standard weight was pesented first. The SI X OOP effect was caused by Weber fractions decreasing for both standard first and standard second conditions as stimulus intensity increased. An effect for MOS X POS approached significance $(F(2,15)=2.78\ p=0.0943)$. This was possibly caused by the fact that at 5 g different lifting methods gave no advantage.

The second ANOVA was performed with 2 levels of POS: hand and wrist; three levels of SI: 5, 50, 200 g; three levels of MOS: passive, elbow as fulcrum and shoulder as fulcrum; and two levels of OOP: standard first, standard second. A significant effect was found for POS $(F(1,10)=17.88$ $p=0.0017)$ and a significant interaction was found for SI X POS $(F(2,20)=11.33\ p=0.0005)$. Figure 3.2 shows that the POS effect was caused by discrimination being better with stimulus presentations to the palm than wrist. The interaction of SI X POS was caused by considerably better discrimination at 5 g when the weights were presented on the subjects' palm compaed with wrist but less of an effect as stimulus intensity increased. A significant within subject effect was found for SI (F(2,20=92.40 p=0.0000) and OOP $(F(1,10)=4.59\ p=0.0500)$ with a significant interaction

Figure 3.1 Weber fractions for the discrimination of weight using pressure at three stimulus intensities with three different positions on the upper limb

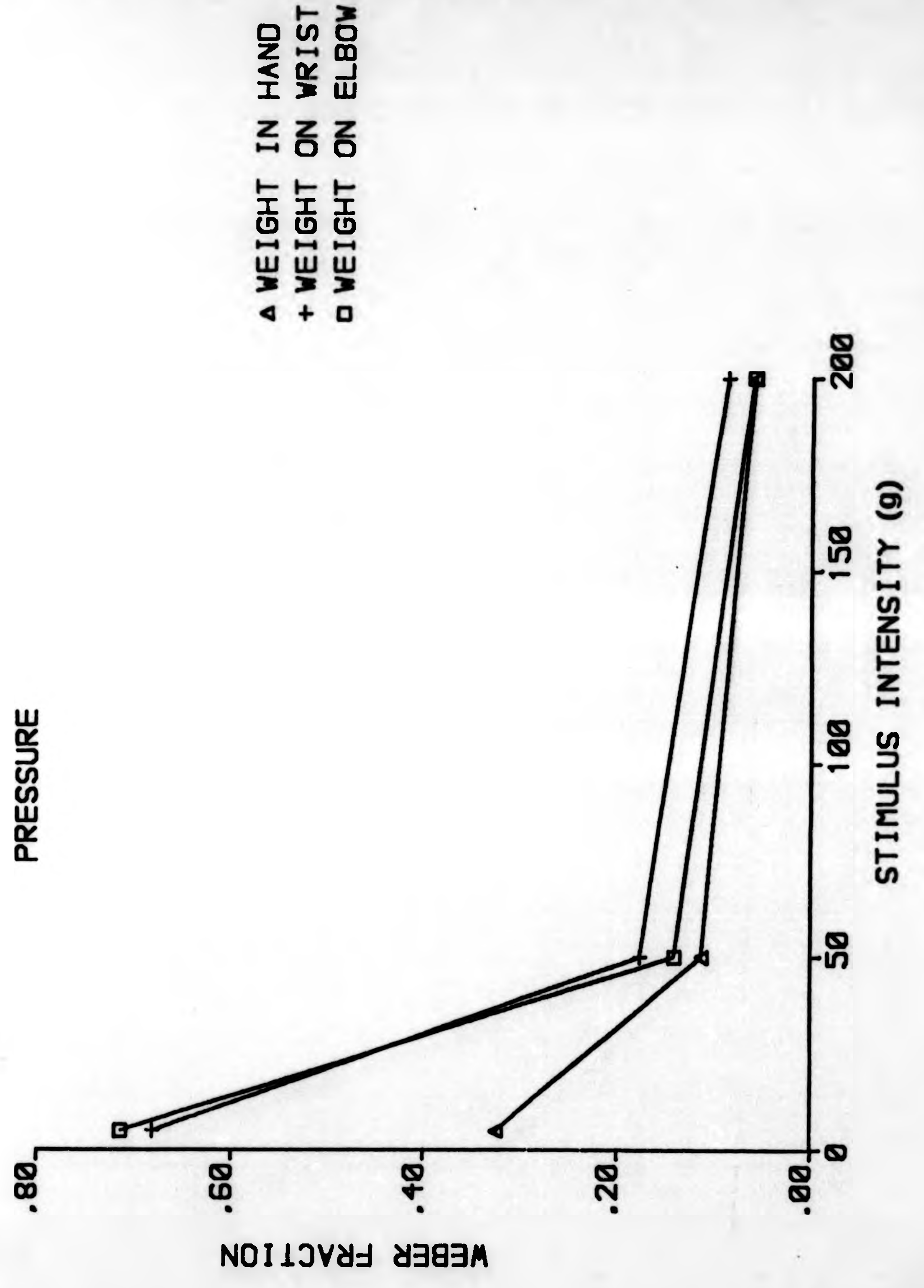


Figure 3.2 Weber fractions for the discrimination of weight using shoulder as fulcrum at three stimulus intensities with three different positions on the upper limb

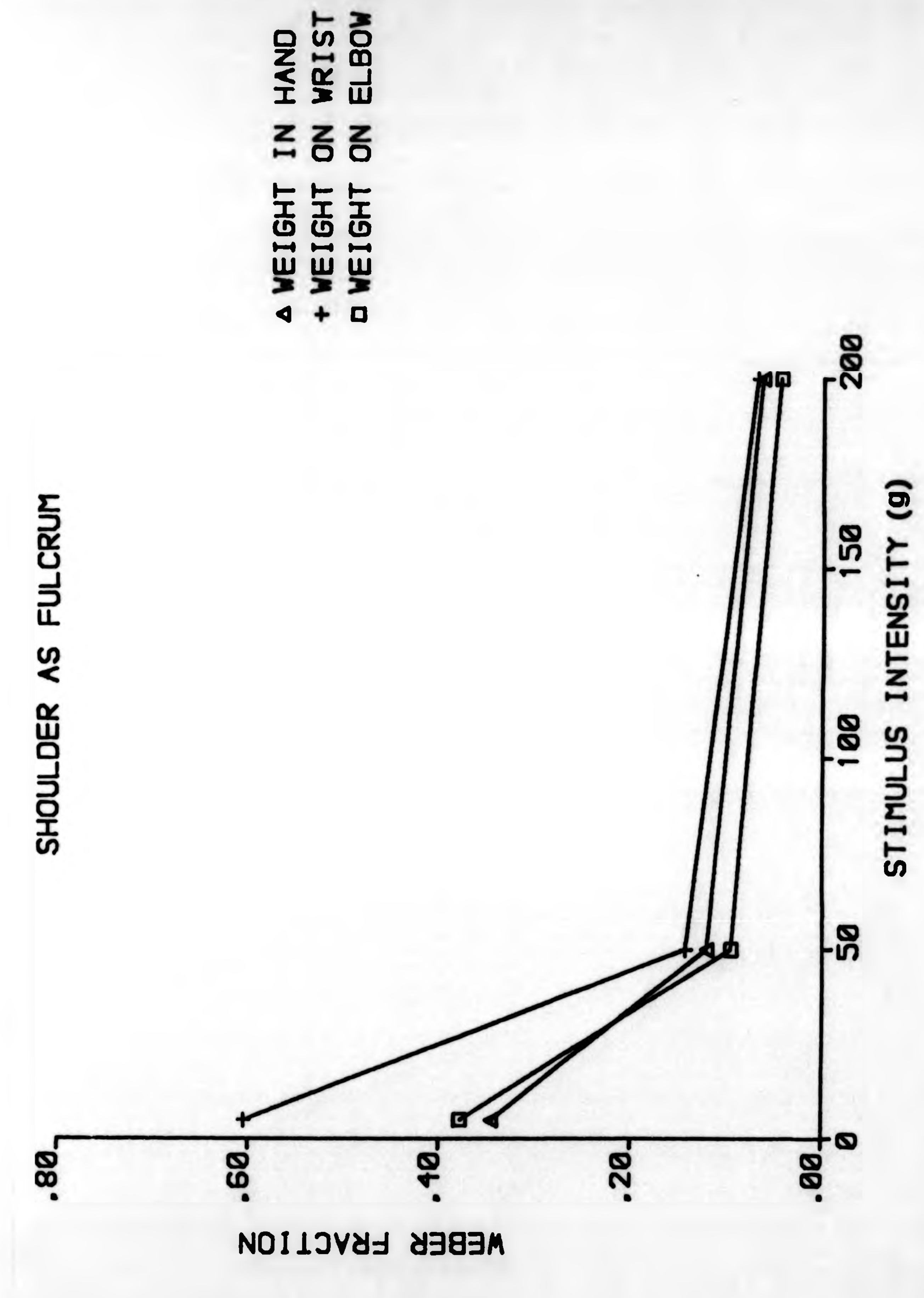


Figure 3.3 Weber fractions for the discrimination of weight on the volar surface of the hand at three stimulus intensities with three different lifting movements

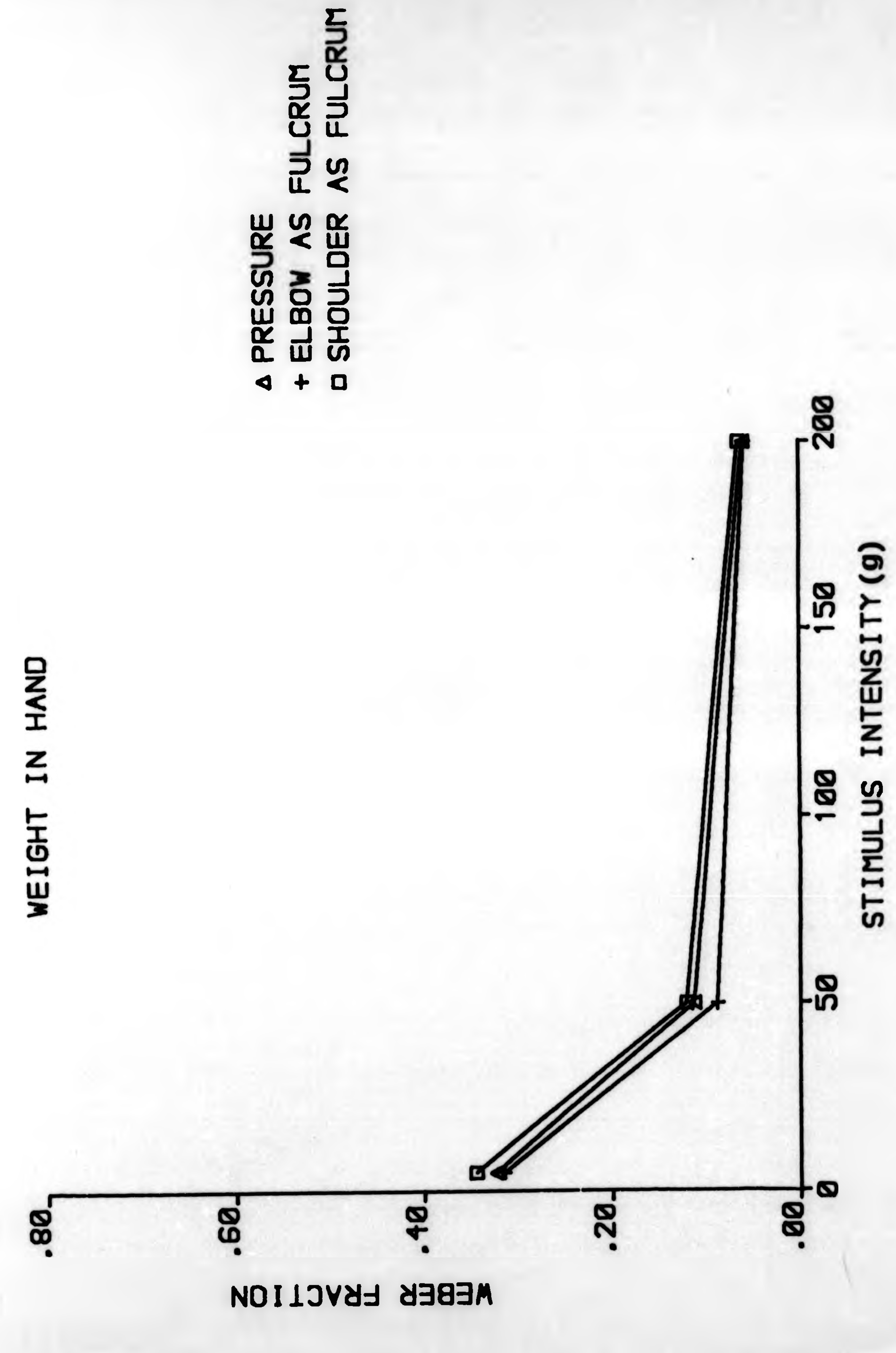
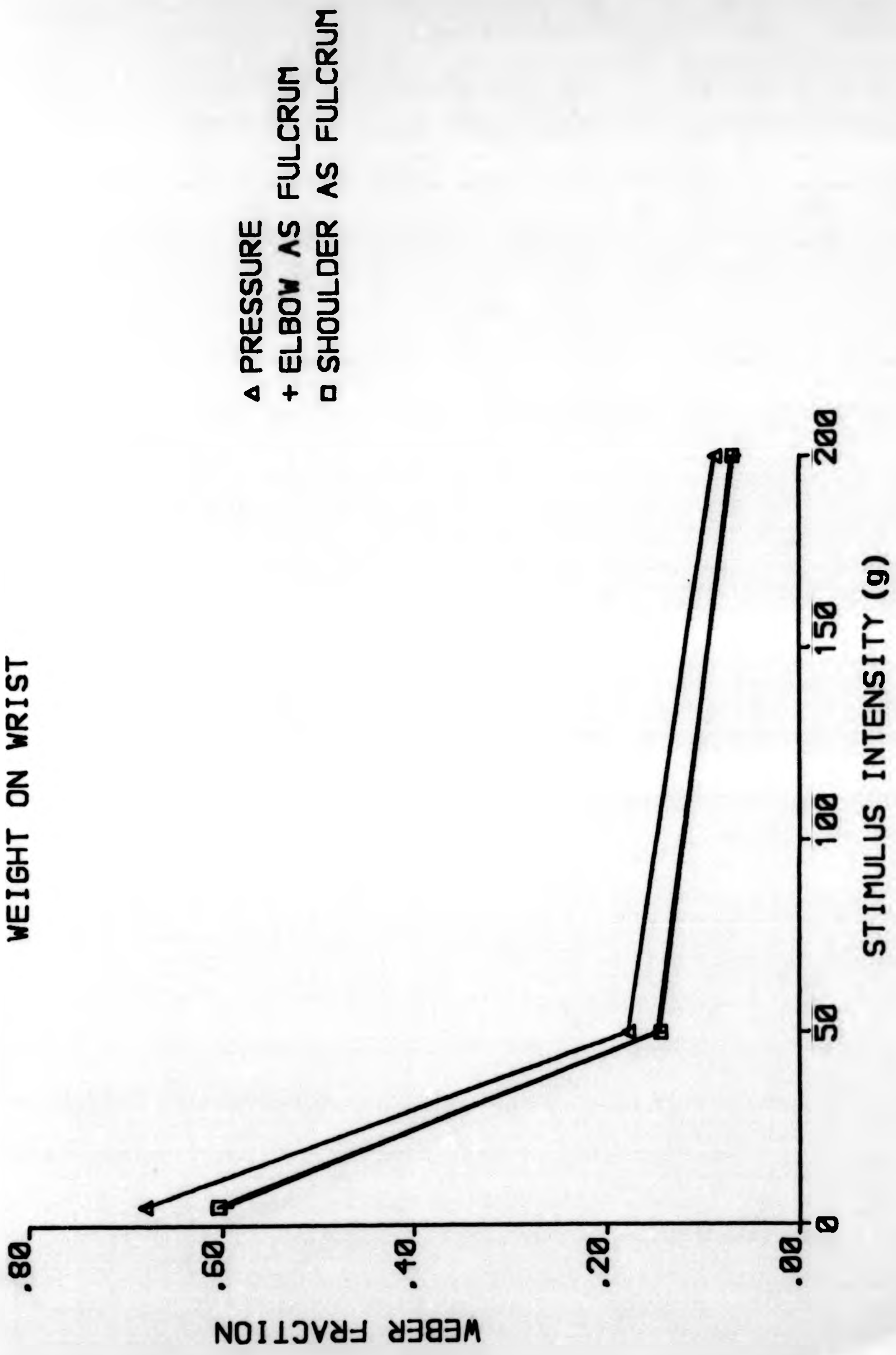


Figure 3.4 Weber fractions for the discrimination of weight on the volar surface of the wrist at three stimulus intensities with three different lifting movements



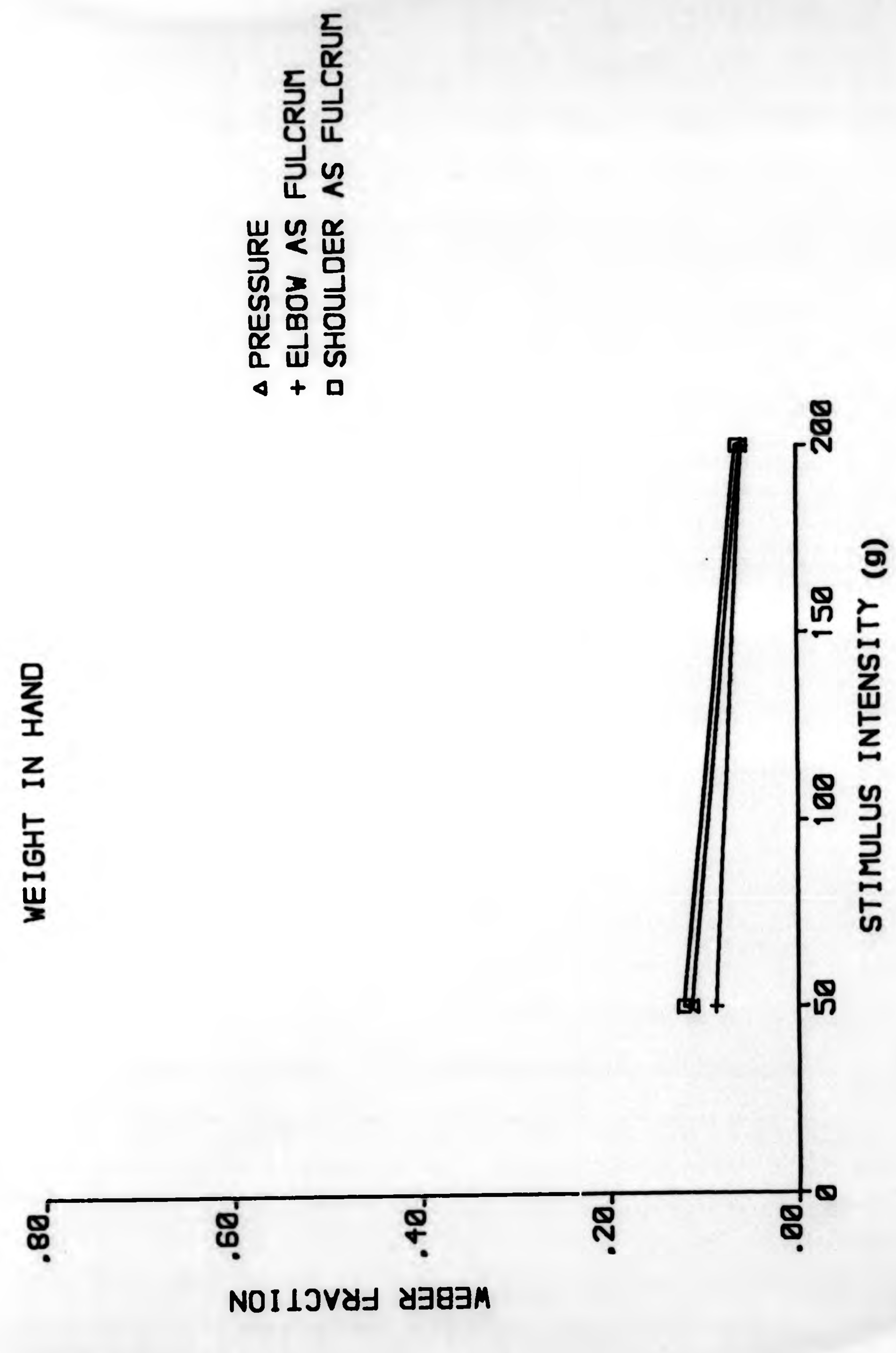
between SI X OOP (F(2,10)=6.15 p=0.0083). The SI effect wascaused by discrimination improving as stimulus intensity increased and the OOP effect by Weber fractions being lower for the standard first order of presentation. The SI X OOP effect was caused by the difference between Weber fractions for standard first and standard second presentations decreasing as stimulus intensity increased.

In order to investigate the interactions, separate ANOVAS were performed upon the three POS conditions; stimuli presented to the palm, to the wrist, and to the elbow.

1) For POS in the palm a significant effect for Weber fractions for SI was found (F2,10)=38.45 p=0.0000) with no significant effects found between MOS or OOP. The SI effect was due to Weber fractions decreasing from approximately 0.32 at 5 g to 0.05 at 200 g. Further inspection of the means and standard deviations suggested unequal variance between Weber fractions obtained at the 5 g intensity level and those obtained at 50 and 200 g.

A three way ANOVA was performed on the Weber fractions for 50 and 200 g intensities. This revealed a significant effect for SI (F(1,5)=18.52 p=0.0077) and MOS (F(2,10)=4.02 p=0.0525). The effect of Weber fractions at 5 g was to mask MOS effects. The significant MOS effect was due to the elbow as fulcrum lifting movement giving the lowest Weber fraction at 50 and 200 g. This can be seen more clearly in Figure 3.3. A t-test revealed that the elbow as fulcrum lifting movement produced significantly lower Weber fractions than the shoulder as fulcrum lifting movement (t=-2.73, df 5, p=0.041,

Figure 3.5 Weber fractions for the discrimination of weight on the volar surface of the hand at two stimulus intensities with three different methods of lifting



2 tail) at 50 g but not at 200 g.

2) For POS on the wrist a significant difference between Weber fractions for SI was found (F(2,10)=56.43 p=0.0000) but no effects for MOS or OOP. The SI effect was due to Weber fractions of approximately 0.65 at 5 g decreasing to 0.075 at 200 g. Inspection of the means and standard deviations suggest unequal variance between Weber fractions obtained at 5 g and those of 50 and 200 g. A three way analysis of variance was performed on the Weber fractions for 50 and 200 g intensities. This revealed a significant effect due to SI (F(1,5)=161.48 p=0.0001) and MOS (F(2,10)=9.54 p=0.0048) with a significant interaction between SI X OOP (F(1,5)=12.78 p=0.0160). The effect of Weber fractions at 5 g was to mask MOS effects. The MOS effect was due to the elbow as fulcrum lifting movement giving improvement over non lifting with the shoulder as fulcrum giving small improvement over elbow-as-fulcrum (see Figure 3.4). T-tests revealed that elbow as fulcrum lifting movements produced significantly lower Weber fractions than non lifting at 50 g (t=3.38, df 5, p=0.020, 2 tail) and 200 g (t=3.79, df 5, p=0.013, 2 tail) but not at 5 g. There were no differences between elbow as fulcrum and shoulder as fulcrum lifting movements.

3) For POS on the elbow a significant effect for SI was found (F(2,10)=784.43 p=0.0000) but no effect for MOS or OOP. A significant interaction between SI X OOP (F(2,10)=4.32 p=0.0443) was found. The SI effect was due to the Weber fractions decreasing from approximately 0.7 at 5 g to 0.05 at 200 g. The interaction was due to difference between standard

<u>Figure 3.6 Weber fractions for the discrimination of weight on the volar surface of the wrist at two stimulus intensities with three different methods of lifting</u>

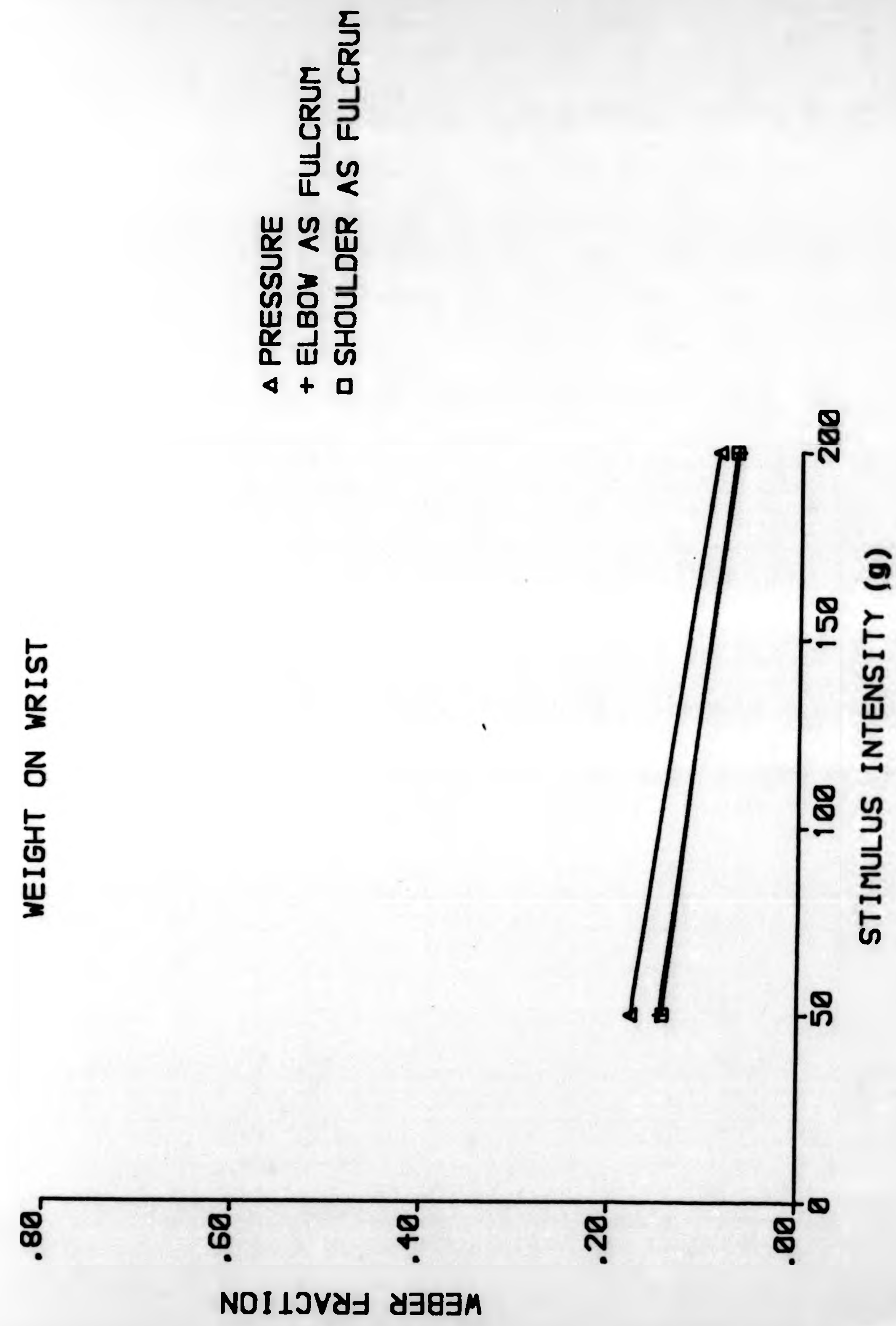
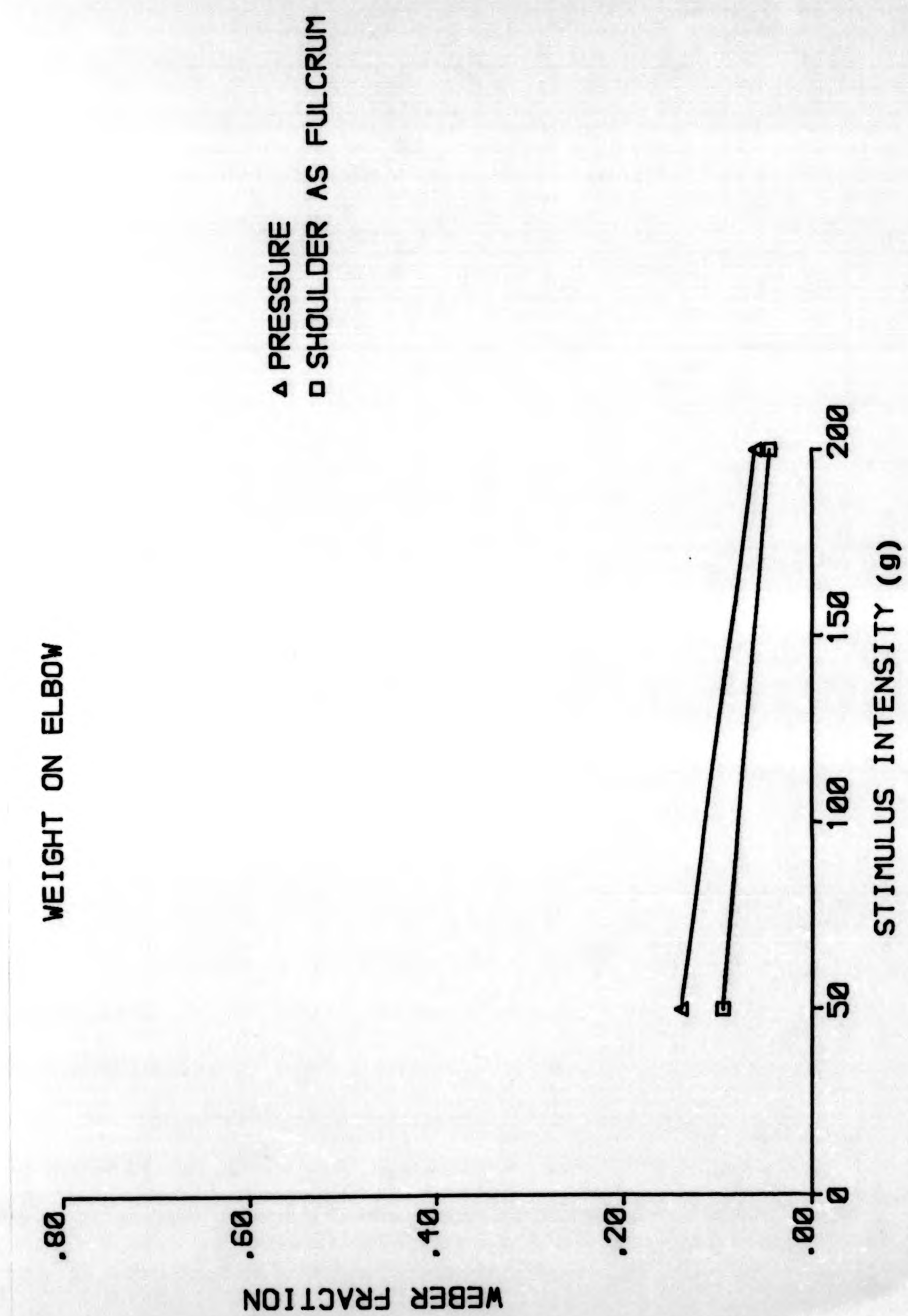


Figure 3.7 Weber fractions for the discrimination of weight on the volar surface of the elbow at two stimulus intensities with three different methods of lifting



first and standard second presentations diminishing as the stimulus intensity increases. Inspection of the means and standard deviations suggested unequal variance between Weber fractions obtained at 5 g and those of 50 and 200 g. A three way ANOVA was performed on the Weber fractions for 50 amd 200 g stimulus intensities. This revealed a significant effect due to SI ($F(1,5)=71.39$ $p=0.0004$) but not for MOS (see Figure 3.5). However, t-tests revealed that the shoulder as fulcrum lifting movement produced significantly lower Weber fractions than the passive pressure at 200 g ($t=2.919$, df 5, $p=0.033$, 2 tail). No differences were found at 5 g or 50 g.

In order to compare the Weber Fractions obtained for the MOS condition (wrist as fulcrum) with POS condition (weight in hand) at the three stimulus intensities, t-tests were performed. Within subjects there were significant differences between Weber fractions at 5 and 50 g ($t=8.99$, df5, $p=0.000$, 2 tail) and 50 and 200 g ($t=5.23$, df5, $p=0.003$, 2 tail). No significant differences were present for MOS at 5 g though at 50 and 200 g the Weber fractions were lower than those afforded by passive pressure or shoulder as fulcrum lifting movements.

3.4 Discussion

It was found that sensitivity to weight differs on different parts of the upper limb and that sensitivity improves as stimulus intensity increases. In this instance it was found that discrimination between weights on a supported upper limb was most sensitive upon the palm, followed by the volar surface of the wrist, with the volar surface of the elbow worst. Sensitivity increased as the stimulus intensity increased from 5 to 50 to 200 g. However an interaction was apparent between stimulus intensity and position of stimulus. The sensitivity of palm and volar surface of elbow were similar at 200 g but greatly different at 5 g. This can be explained by the distribution of different types of cutaneous receptors in the upper arm (Vallbo & Johansson, 1978).

In keeping with Oberlin (1936) Weber fractions were found to decrease as stimulus intensity increased. Unlike Oberlin the shoulder-as-fulcrum lifting movement was not found to produce the lowest Weber fractions at all stimulus intensities. At 5 g no movement aided discrimination, at 50 g the elbow-as-fulcrum lifting movement gave significantly better discrimination than shoulder-as-fulcrum. Only at 200 g did the shoulder-as-fulcrum lifting movement aid discrimination. The deltoid muscle group may well be sensitive to higher stimulus intensities as there was a significant improvement in discrimination when the weights were placed upon the volar surface at the elbow and a lifting movement took place. Light weights may have no effect compared to the weight of the arm when the arm is lifted. Typical male arm weights are 1.73 kg for upper arm, 1.055 kg for the forearm and 0.426 kg for the hand (Clauser, McConville & Young, 1969).

The physiological explanation propounded by Oberlin (1936) and Holway & Hurvich (1937) of why shoulder-as-fulcrum lifting movements at high stimulus intensity produce the lowest thresholds needs further explanation or modification.

It is incorrect to say that the more receptors brought into play the better the discrimination at all stimulus intensities and for all lifting movements. The receptors brought into play by a shoulder-as-fulcrum lifting movement, for example those in the powerful shoulder and upper arm muscles (deltoids), may not aid the signalling of the weight of very light objects held in the hand. In fact it was found that for very light weights a lack of movement aided discrimination and that for 50 g weights the elbow-as-fulcrum lifting movement was the most sensitive. Only at 200 g did the shoulder-as-fulcrum lifting movement produce the lowest thresholds. At lower stimulus intensities the receptors in the shoulder muscles may merely signal kinesthetic information and thus possibly add noise to the system. As such they may interfere with the transmission of information from those receptors in more distal parts of the limb receptive to the stimulus weight.

The direction of the TOE was negative at the three stimulus intensities tested. This is surprising as it is contrary to the classical finding that the direction of the TOE is negative at higher stimulus intensities and positive at low stimulus intensities for the discrimination of lifted weights (Bartlett, 1939; Needham, 1934; Woodrow, 1933). A number of factors have been found to interfere with the directon of the TOE; the length of the inter-stimulus interval (ISI) and the intensity of interpolated weights into the ISI. Needham (1935) and Köhler (1923) found that the TOE is positive with short ISIs and negative with longer ISIs.

Lauenstein (1933) and Guildford & Park (1931) found it to be positive when a high interpolated stimulus was introduced and negative when a low interpolated stimulus was introduced into the ISI. However in all the experimental conditions, and at all the stimulus intensities, a constant ISI was maintained. It could be argued that any movement during the ISI could affect the TOE in the negative direction. However subjects were instructed not to lift or move any portion of their upper limb during the ISI in the active conditions. The fact that there was no difference between the TOEs in passive and active conditions further supports the conclusion that the negative TOE at 5 g was not due to interpolation of movement during the ISI. In fact the interaction between stimulus intensity and the TOE was the result of an increase in the negative TOE at the very low stimulus intensity of 5. This is contrary to the classical findings of positive TOEs at low stimulus intensities but is supported in part by the findings of Björkman, Lundberg and Tarnblöm (1960) who found that when using magnitude estimation the TOE remained negative at low stimulus intensities.

Although statistically significant results were not forthcoming in all conditions, perhaps due to small subject numbers, enough doubt has been cast to question the findings of the 1930's both in terms of methodology and of physiological theorising. The Weber fractions found in this experiment were much finer than those of Holway & Hurvich (1937) suggesting that their methodology could have been improved. Physiological theory now accepts that "active touch" involves both afferent and efferent signals and not a simple sensory input system. The concepts of facilitation and inhibition in the nervous system must be taken into account in any theorising about complex activity.

3.5 Summary

DLs for weight were measured quickly using a computer generated variation of the "staircase" sequential tracking procedure. This was done to investigate sensitivity of three different locations of the upper limb in both passive and active discrimination and to investigate the direction of the time-order error at three stimulus intensities. In the passive condition weights were presented to the volar surface of hand, wrist and elbow, with the arm being supported on a bench top. In the active conditions weights presented to the same positions on the upper limb as in the passive conditions but with wrist-, elbow- and shoulder-as-fulcrum lifting movements used.

Contrary to previous findings the shoulder-as-fulcrum lifting movement was not found to facilitate discrimination at all three stimulus intensities. The shoulder-as-fulcrum lifting movement only facilitated discrimination at 200 g, the elbow-as-fulcrum lifting move ment facilitated dscrimination at 50 g and at 5 g no movement facilitated discrimination.

Contrary to previous findings that the direction of the TOE was positive at low stimulus intensities, in this experiment the TOE remained negative at 5 g, 50 g and 200 g.

It was suggested that the physiological theorising of the 1930s was based on unreliable psychophysical methods of investigation into weight discrimination. Current theorising must take account of the greatly expanded knowledge of the physiology of touch, kinesthesis and motor control.

CHAPTER 4: TWO-HANDED WEIGHT DISCRIMINATION :TEMPORAL SIMULTANEITY

4.1 Introduction

Weber (1834) suggested that the perception of the weight of lifted objects depended both upon the sensations arising from the skin and the sensations accompanying muscular activity (1978, p. 55). He found that subjects could discriminate between weights by a factor of approximately 1/3 using pressure sensing and by approximately 1/14 using pressure sensing plus muscle sensing. In addition he found, using pressure sensing, that weights felt heavier on the left hand side when compared with the same weights on the right hand side. He also stated that muscular strength was greater on the right hand side but did not give details of any experiments carried out in support of such an observation (1978, p. 57). It would be expected that at least some, if not all, of these factors would affect the perception of weight of objects and the discrimination between objects lifted by the left and right hands.

Shen (1935) argued that the preferred hand is capable of exerting a greater force than the non-preferred hand, with the result that weights would feel heavier in the non-preferred hand and lighter in the preferred hand. In order to test this hypothesis he adopted a two-handed simultaneous weight lifting paradigm. However, he found that when presenting right handed subjects, eight male and two female, with equally heavy weights to both hands, some subjects gave more left heavier responses and some subjects gave more right heavier responses. Contrary to his expectation, handedness could not explain the effect found. This result is not surprising in light of recent reviews of research into manual asymmetries (Porac & Coren, 1981). There is no clear evidience to support the suggestion that the preferred hand is capable of exerting greater force. For example, grip strength has been found to be stronger in the non-preferred hand (Barnsley & Rabinovitch, 1970). One factor that may have affected Shen's finding was that he did not take account of the possibilty of sex differences. There is some evidence to suggest that males perform better than females in a number of perceptual and motor tasks (Fairweather, 1976; Maccoby, & Jacklin, 1974)

In a second experiment Shen (1936) investigated the effect of handedness using a different methodology and only right handed male subjects. He found that the right hand under-estimated, and the left hand over-estimated, the weight of lifted objects. This effect was explained in terms of the ability of the preferred hand to exert greater force. Although, Shen did not test left handed subjects, he predicted less clear results would emerge for them (op. cit. p. 75). He did not discuss the possibilty that the use of male subjects may have accounted for the handedness effect found. This may be an important consideration as there is evidence to suggest that males are more strongly lateralised than females (De Renzi, 1982). This may result in differences in performance of right and left hands in male and female subjects.

In recent reviews of research on manual asymmetry unequivocal evidence is not forthcoming to support the claim that pressure sensing is better on the left side (Young & Ratcliffe, 1983) or that the preferred hand can exert greater force (Porac & Coren, 1981). Sensitivity to pressure has been found to differ between right and left hands with either a left or a right hand advantage (Sinclair, 1981; Young & Ratcliffe, 1983). Grip strength and manual proficiency have not been found to correlate highly with hand preference (Porac & Coren, 1981). However the consensus of opinion is in favour of asymmetry if high levels of visuo-spatial or manipulo-spatial functioning occurs (Corkin, 1978; Le Doux, 1983)).

Perceptual tasks involving central or higher order processing dispay asymmerties between left and right hand performance (Sinclair, 1981). There is evidence to suggest that objects of the same size will appear smaller in the preferred hand (McPherson & Renfrew, 1953). This may have an important influence upon the weight of the object as apparent size and weight have been shown to be linked. The size-weight illusion (Charpentier, 1891) is an example of this interdependence. If two objects are of equal weight and of different size the smaller will appear heavier and the larger lighter. In two-handed discrimination if two objects of equal weight are presented to left and right hands because the weight held in the preferred hand will appear smaller it will also appear heavier. Contrary to the view of Shen, objects lifted using the preferred hand may feel heavier than objects held in the non-preferred hand.

On the basis of this evidence it is not clear whether manual asymmetries will exist for weight discrimination or if they do whether weights will appear heavier on the right or left hand side. As discussed in Chapter 1 weight discrimination has been conceived for the most part as a simple perception based upon bodily sensations, whether originating centrally or peripherally. Even if weight discrimination is considered a manipulo-spatial task, it is not clear how hand preference will interfere in a systematic way with the discrimination of simultaneously lifted weights using left and right hands.

The notion that less effort is required to lift and manipulate objects using the preferred hand is a common one. This received theory of weight perception, expressed in different variants based upon either "corollary discharge" (McCloskey, Ebeling & Goddwin, 1974), a "sense of effort" (Waller, 1891) or "sensations of innervation" (Wundt, 1894), would predict that weights lifted with the preferred hand would appear lighter than those weights lifted with the non preferred hand. Subjects displaying a hand preference would feel objects of the same weight as being lighter in their preferred hand and heavier in their non-preferred hand. This would result in a bias, or constant error, being introduced into a two handed discrimination test. For example, in a discrimination test where a standard (lighter) weight and a comparison (heavier) weight was presented one to each hand, an increase in the subjective difference between weights would occur when the standard (lighter) weight is presented to the preferred hand and the comparison (heavier) weight is presented to the non preferred hand. Conversely, when the standard weight is presented to the non preferred hand and the comparison weight is presented to the preferred hand a decrease in the subjective difference would occur. Differential thresholds (DLs) for lifted weights would reflect this by being lower in the former condition than in the latter. Thus one possible source of error in two handed discrimination of lifted weights is that introduced by handedness. Hand preference may affect performance because of the different amounts of effort required to lift each hand.

Fechner (1860) was the first to discover two sources of error in discrimination experiments, those of time and space. Although the "space order error" occurs when the two stimulus weights are separated by time and space, it would be misleading to apply the term when the weights are lifted simultaneously using both arms. Fechner (1966, p. 75) does not make it clear whether his space-order error applies to one- or two-handed lifting, or both. However, he does argue against the use of two-handed discrimination on the grounds that attention cannot be directed to both hands at once (1966, p. 73) which implies the use of two-handed simultaneous lifting. He also argues that hand sensitivity may be unequal across hands (1966, p. 74) which may apply to both one-handed consecutive and two-handed consecutive and simultaneous lifting methods. To avoid confusion, the space error (SE) will be taken to refer to those errors arising in two- handed simultaneous lifting and the space-order error (SOE) to those errors arising a two-handed consecutive lifting.

Theories or models of weight perception or weight discrimination, have generally been derived from the observation of one-handed lifting of weights. This reflects a more general interest in the investigation of the movement and control of one limb, rather than of two limbs together (Kelso, Putman & Goodman, 1983). Major problems arise for the received theory of weight perception when two handed simultaneous lifting is considered. If there is only one sense of effort, how can it be directed to both arms at once? If there are two simultaneous senses of effort how can they co-exist together? How can the co-ordination of two handed movements be achieved? Recent theories of motor control (Wing, 1982; Kelso, Putnam and Goodman, 1983) avoid a similar but related problem in their theorising by postulating a superordinate control mechanism that activates two independent processors which are linked to left and right arm activity (Peters, 1985). In any event, it would be expected that discrimination would be poor in a two handed simultaneous lifting movement if either the received or motor skills theory of Peters was applied.

It has been argued in Chapter 1 that the mechanisms subserving weight perception must be composed of motor and sensory components. However the motor components are normally accounted for by higher level processing with a complex interaction occuring before the weight of an object can be ascertained. Weight constancy, illusions and adaptation could not be explained without recourse to higher cortical functioning. It has been recently argued that the motor control elements of two handed movements function as a single unit (Kelso, Southard & Goodman, 1979). If this were so, the normal relationship between efference and afference for each hand would be disrupted. On the basis of this model, discrimination would be poor in two handed simultaneous lifting.

This experiment was aimed at investigating differences between left and right handed, male and female subjects in a two-handed simultaneous weight discrimination paradigm. If a systematic bias is introduced by hand preference then it will affect DLs in two-handed discrimination in a predictable way, with the direction of bias being reversed for right and left handed subjects. If females are less lateralised than males then this may be reflected by less variable DLs and a less strong bias for females.

4.2 Method

4.2.1 Subjects

Sixty undergraduate psychology students acted as subjects as part of a course requirement. There were 35 female subjects and 25 male subjects. Ages ranged between 17 and 39 with a mean of 19.8.

4.2.2 Apparatus

Two sets of stimulus weights were used, each comprising 7 standard weights and 7 comparison weights. The standard weights were 50 g and the comparison weights ranged from 52 g to 64 g in 2 g intervals. All the weights were identical cylinders (4.5 cm x 2.5 cm) constructed out of aluminium by removing a central core along the longer axix. This ensured equal distribution of the material.

An Apple Microcomputer, a monitor and disk drive were used to generate two randomly interspersed UDTR rules, input and record subjects' responses via push buttons and calculate DLs. Two carousels were used to present stimuli to subjects in the manner described in Chapter 2.

4.2.3 Procedure

DLs were calculated for two conditions; standard (lighter) weight presented to the right hand (SR) and standard weight presented to the left hand (SL).

Subjects were given a standard set of instructions before the experiment started via the VDU. During the test sessions the command to lift and lower the stimulus weights and the command to respond were flashed upon the screen. This enabled control of a 3 sec stimulus presentation time. The experimenter ensured that subjects followed the commands. A bar was placed across the top of the carousels to limit height of lift to 21 cm.

Subjects were required to respond 'heavier' in a forced choice manner by pressing the right hand button if the right hand weight was heavier and the left hand button if the left hand weight was heavier.

Hand preference was measured using the Edinburgh Handedness Inventory (EHI) and expressed as a laterality quotient (LQ) between -100 (strong left hand preference) to +100 (strong right hand preference) (Oldfield, 1970). The experimenter adminstered the EHI at the start of the test session and ensured its correct completion. The test session lasted approximately half an hour.

4.3 Results

Figure 4.1 shows the distribution of sex and hand preference amongst the sixty subjects tested. Sixteen female subjects were left handed, with LQs ranging from -100 to -20,

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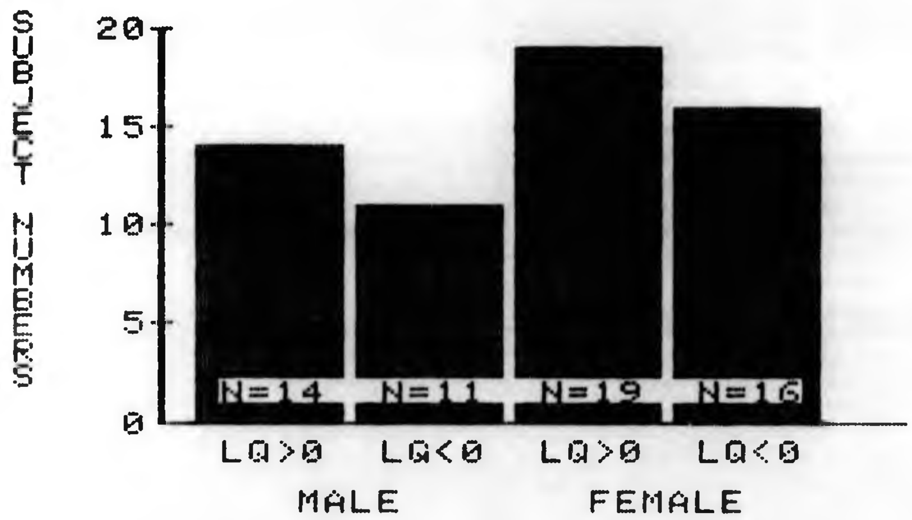
Figure 4.1 Distribution of sex and hand preference amongst subjects



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and nineteen were right handed, with LQs ranging from +30 to +100. Eleven male subjects were left handed, with LQs ranging from -88 to -14, and fourteen were right handed, with LQs ranging from +5 to +100. All subjects with positive LQs used only their right hand for writing and drawing and all subjects with negative LQs used only their left hand for writing and drawing.

The mean differential thresholds (DLs) and standard deviations, in grams, for the two experimental conditions, standard weight presented to the left hand (SL) and standard weight presented to the right hand (SR) are presented in Table 4.1.

Correlations were calculated between LQ, SL, SR, Mean of SL & SR, and difference between SL & SR for male and female subjects.

Table 4.1 Mean and standard deviations for differential thresholds (in grams) for 60 subjects in a two-handed simultaneous weight discrimination paradigm

SEX	HAND PREFERENCE	SIDE OF PRESENTATION OF STANDARD WEIGHT		
		SL	SR	Mean
MALE	LQ>0	6.217(2.767)	5.139(3.132)	5.678
	LQ<0	7.351(3.356)	3.417(2.880)	5.384
FEMALE	LQ>0	4.704(2.426)	5.953(2.856)	5.329
	LQ<0	5.434(3.793)	5.572(3.654)	5.503

No significant correlations were found to exist between hand preference, as measured on the EHI, and the DLs for the two conditions, SL & SR. A significant negative correlation was found between SL and SR for female subjects ($r=-0.7563$ $n=35$ $p<0.01$)) and for male subjects ($r=-0.6048$ $n=25$ $p<0.01$). This was due to subjects having high DLs in one presentation condition and low DLs in the other presentation condition.

An analysis of variance (ANOVA) was performed upon the DLs with two between subject variables, sex (with two levels, male & female) and hand preference (with two levels, left & right) and one within subject variable, side of presentation (with two levels, SL & SR). No significant main effects were found and only one significant interaction was found between side of presentation X sex ($F(1,56)=4.38$ $p=0.0408$). Figure 4.2 shows clearly why this interaction occurred. It was due to DLs for SR being lower than DLs for SL for both left and

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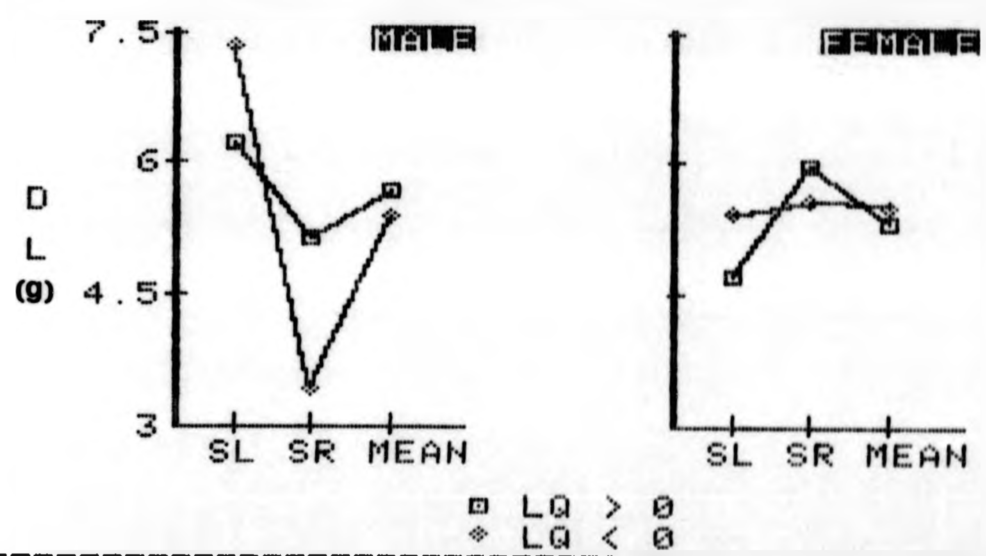
Figure 4.2 Differential thresholds for simultaneously lifted weights



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right handed male subjects and DLs for SR being higher than DLs for SL for both right and left handed female subjects. On the basis of these findings the direction of effect can be predicted. One tailed t-tests revealed that there were significant differences between DLs for male and female subjects in SL ($t=-2.07$, $df=58$, $p=0.022$, 1 tail) and SR ($t=1.69$, $df=58$, $p=0.048$, 1 tail).

4.4 Discussion

The time taken to complete an EHI and present subjects with not more than 48 stimulus pairs of weights for two randomly interspersed "staircase" procedures was not more than half an hour. On average less than twenty minutes were devoted to the stimulus presentations and recording of responses. The apparatus considerably speeded up the measurement of DLs for lifted weights.

The results of this experiment clearly showed that differential thresholds calculated with two-handed simultaneous weight lifting, displayed a bias in one or other direction. This was especially true for left handed male subjects. Right handed male and female subjects showed smaller biases and left handed female subjects showed the least bias. Handedness, as measured by the EHI, was not a good predictor of the direction of this bias. That is, the preferred hand neither showed consistent under or over estimaton of weight. This finding is in agreement with Shen (1935) but in disagreement with Shen (1936). Left handed subjects did not show less of a bias as predicted by Shen (1936) since left-handed males showed the strongest effect.

The surprising effect which emerged from this experiment was a difference in direction of bias between the sexes. Male subjects produced significantly lower DLs when the lighter weight was in their right hand and females lower DLs when the lighter weight was in their left hand. In terms of the absolute weight of the stimuli, male subjects found weights lighter in their right hands and heavier in their left hands. Female subjects showed the opposite effect, though not as strongly, with weights feeling lighter in their left hands and heavier in their right. These findings are consistent with those reports which found that a systematic relationship does not exist between hand preference and manual performance. They are also partly consistent with the sex difference literature that suggests there are differences in performance between the sexes in a variety of perceptual tasks (Maccoby & Jacklin, 1974). This may reflect the fact that females are less lateralised in brain function than males (Harris, 1978; De Renzi, 1982).

It is clear that two handed simultaneous discrimination resulted in very poor discrimination, with a large bias and with very high standard deviations across subjects. Under certain circumstances many subjects were not able to discriminate between the 60 g and 50 g weights. Only with the benefit of a balanced design did their overall ability to discriminate reach reasonable levels. It would be premature to call the bias found here a 'constant error' as the direction of effect did not bear a systematic relationship with hand preference.

One possible explanation of the results is in terms of the bimanual theory of motor control advocated by Kelso, Southard and Goodman (1979). In this theory a single high level integrative mechanism is responsible for co-ordinating the activity of both upper limbs. Such a mechanism would allow the muscle activity of both hands to be organised into a single functional unit in order to produce simultaneity of movement. Under such conditions the afference necessary to signal the weight of the lifted object in each hand would not find a suitable comparison efference. It is thus likely that such a system cannot cope with the demands of simultaneity of both motor output and sensory input.

An alternative explanation of the bias introduced in two-handed simultaneous discrimination is in terms of hand sensitivity. Weber (1934) argued that parts of the body that are more sensitive to pressure are also more sensitive to weight. Thus it is the sensitivity of each hand that determines the direction of the bias. Fechner (1860) also subscribed to an explanation in terms of hand sensitivity. However, hand preference would only predict the direction of bias if there was a strong relationship between hand preference and hand sensitivity. On the basis of the findings in this experiment male and females would have to have different relative sensitivity between left and right hands. The possibility that hand preference and hand sensitivity differ on the basis of sex and the possibility that they bear a systematic relationship with two-handed simultaneous discrimination was investigated and is described in Chapter 4.

Another possible explanation of the bias introduced by two-handed simultaneous lifting is in terms of attention. Weber (1834) and Fechner (1860) advocated such an explanation by arguing that attention in two-handed simultaneous weight lifting inevitably centres on one or other hand. This explanation has received current support in the motor skills model propounded by Peters (1985). This model advocates a single high and two low level control mechanisms. The high level mechanism co-ordinates and integrates two handed movements into a unified act whilst the lower levels have more direct control of each limb. Peters suggests that attention is an important factor in the interaction between the two levels. Thus to achieve a two-handed simultaneous lifting movement attention is first turned to the high level mechanism. To attend to the weight of the object in each hand in order to perform the discrimination, attention must turn to the low level mechanisms. Such attentional shifts may not be conducive to weight discrimination. In order to investigate the effects of attention an experiment was devised to enable the subject to shift attention from one hand to the other. This was achieved in a two-handed consecutive weight discrimination paradigm and is described in Chapter 6.

4.5 Summary

Manual asymmetries could bias the performance of two-handed simultaneous weight discrimination. If the preferred hand was capable of exerting greater force than the non-preferred hand, objects of the same weight might feel lighter in the preferred hand and heavier in the non-preferred hand. If the preferred hand underestimated the size of objects of equal size and weight then objects might feel heavier in the preferred hand and lighter in the non-preferred hand. Sex differences have been found in both perceptual and motor skills probably reflecting the differing degree of hemispheric specialisation between males and females.

The hand preference of sixty subjects, 25 male and 35 female, was measured using the Edinburgh Handedness Inventory. 14 males and 19 females were found to display a right hand preference and 11 males and 16 females a left hand preference. Differential thresholds (DLs) were quickly calculated in a two-handed weight discrimination paradigm using microcomputer generated sequential tracking procedures and two weight bearing carousels. A significant bias was found to exist in this paradigm but no significant correlation was found to exist between hand preference and the direction of the bias. A significant sex difference was found with male subjects having significantly lower DLs when the lighter weight was in their right hand and females lower DLs when the lighter weight was in their left hand. In terms of the weight of the stimuli, male subjects found weights lighter in their preferred hands and heavier in their non-preferred hands. Female subjects showed the opposite effect, though not as strongly, with weights feeling lighter in their left hands and heavier in their right. These results are discussed in terms of differential hemispheric specialisation between the sexes.

The direction of bias in a two-handed discrimination paradigm may be explained in terms of hand sensitivity or attentional factors. Chapter 5 investigates the former possibility and Chapter 6 the latter.

CHAPTER 5: TWO-HANDED WEIGHT DISCRIMINATION : HAND SENSITIVITY

5.1 Introduction

The investigation of sensitivity and performance of left, right and both hands in a variety of perceptual and motor tasks has been carried out since the 19th century. Interest in these investigations was fuelled by the development of the concept of cerebral dominance through the work of Broca in the 1860's. However, Weber (1834) distinguished between the skin (passive touch) sense and the muscle sense (active touch) in the perception of the weight of objects and between sensitivity of right and left sides of the body to pressure. It would seem logical to consider the literature on manual asymmetries, and their relationship with weight discrimination, in such a way.

The discrimination between the weight of objects can be performed by passive touch. Weber (1834) found that on average subjects could discriminate between 1/3 by this method. He also suggested that weights could be more accurately discriminated and that weights felt heavier on the left side. He argued that this was because the cutaneous nerves are more sensitive to pressure on the left side than on the right. However, in recent reviews of the literature on tactile sensitivity (Corkin, 1978; Sinclair, 1981; Young & Ratcliffe, 1983) no clear support for asymmetry of tactile sensitivity is found. Corkin (1978) in a review of left and right sided sensitivity to pressure found that high level abilities in tactile perception displayed asymmetrical effects whereas low level abilities did not. Sinclair (1981) produced evidence both for and against asymmetrical effects and Young and Ratcliffe (1983) have cited evidence for a left hand advantage in shape recognition. Thus there is no clear evidence to suggest that weight discrimination, when mediated by the cutaneous sense, may be better on one side of the body than the other.

As far as the role of "active touch" in weight discrimination is concerned Weber found that on average subjects could discriminate between 1/14 when allowed to lift the objects to be compared. Fechner (1860) measured the sensitivity for lifted weights of the left and right hands in a one-handed discrimination test and of both hands in a two-handed discrimination test. He reported a small difference in sensitivity between left and right hands, with only a slight right hand advantage (1966, p. 79). He also found two handed discrimination to be poorer than one handed discrimination. In both one- and two-handed procedures constant errors are introduced, temporal (and possibly spatial depending on stimulus presentation procedures) in the case of a one handed test and spatial in case of the two handed test. Fechner was aware of these errors (1966, pp. 73-75) though he did not give details of how he overcame them nor of whether he used only right handed subjects.

In recent reviews of "active touch" (Corkin, 1978; Young & Ratcliffe, 1983; Beaumont, 1983; Le Doux, 1983), a left hand advantage is normally found in tasks requiring "manipulospatial" processing. The introductory chapter drew attention to the fact that an adequate conceptual framework, into which weight perception may be fitted, is still lacking. Lifting a weight with a view to judging how heavy it is, requires the ability to move the upper limb in both time and space. In this sense it may be conceived of as being a manipulospatial task.

It has been suggested that there may be a relationship between hand preference and hand sensitivity. The evidence to support such a claim is in part due to anatomical investigations which have found that there are fewer motor and sensory fibres projecting to and from the non-preferred hand (Witelson, 1980). Investigators into weight perception (e.g. Weber, 1834; Shen, 1936; McCloskey et al, 1974) have suggested that weights feel lighter in the preferred hand and heavier in the non-preferred hand. This would not affect discrimination in a one-handed discrimination paradigm (unless one assumes, as Weber did, that there was a relationship between sensitivity and apparent weight), but would undoubtably affect performance in a two-handed discrimination paradigm. It would affect it by increasing the subjective difference between weights simultaneously lifted in left and right hands when the lighter weight was in the preferred hand and the heavier weight in the non preferred hand, and decreasing it when the heavier weight was in the preferred hand and the lighter weight in the non preferred hand. Shen found evidence both for (Shen, 1936) and against (Shen, 1935) such an effect. However, he only tested small numbers (n=10) of right handed subjects.

Ross & Roche (1984) tested both right and left handed subjects and found that the degree of hand preference (as measured by the Edinburgh Handedness Inventory) and differential thresholds for the discrimination of lifted weights were correlated in males but not in females. Discrimination was found to be better for subjects with a strong hand preference when tested with the preferred hand, and worse when tested with the non-preferred hand.

In Chapter 4, the error or bias introduced by the two-handed simultaneous discrimination paradigm could not be explained in terms of hand preference. The direction of the bias was sex related. As pointed out in the discussion of Chapter 4, if weights did feel heavier in the non preferred hand and lighter in the preferred hand, then the direction of the error would have been towards higher thresholds when the standard (lighter) weight was in the non preferred hand and lower thresholds when the standard weight was in the preferred hand. However this assumes that the preferred hand is more sensitive at discriminating between lifted weights. Ross & Roche (1984) did not compare the sensitivity of preferred and non-preferred hands of subjects. It still needs to be shown that the EHI is a good predictor of hand sensitivity. Reviews of manual preference and manual performance (e.g. Annett, 1982; Porec & Coren, 1981) did not find any simple relationship between the two.

The aims of the present experiment were: 1) To investigate the effect of handedness upon a one-handed weight discrimination paradigm using both right and left handed subjects. 2) To investige sex differences in weight discrimination using both male and female subjects. 3) To investigate hand preference effects by testing both right and left hands of subjects. 4) To see if hand sensitivity, as measured by a one-handed discrimination paradigm, correlates with the bias found in a two-handed simultaneous discrimination paradigm (Chapter 4).

5.2 Method

5.2.1 Subjects

Sixty six undergraduate students acted as subjects as part of a course requirement. There were 25 male and 41 female subjects. Ages ranged from 17 to 54 with a mean of 21.

5.2.2 Apparatus

The same apparatus described in Chapter 4 was used.

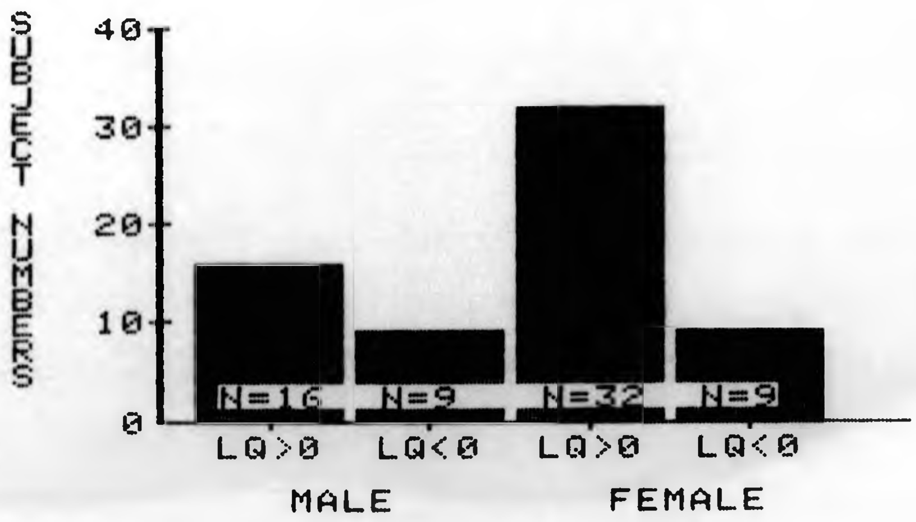
5.2.3 Procedure

Subjects sat front of the carousels and the arm rests were placed in position. Each subject filled out the EHI and then was tested in three conditions in turn, the order of which was counterbalanced. Two of the three conditions involved one-handed consecutive weight discrimination paradigms with DLs measured for right (RH) and left (LH) hands. The third test was a two-handed (BH) consecutive paradigm similar to the one described in Chapter 4. DLs were calculated using the UDTR Method for two order of presentation conditions; standard (lighter) weight first (SF) and standard weight second (SS) for the one-handed consecutive paradigm and standard (lighter) weight right (SR) and standard weight left (SL) for the two-handed simultaneous paradigm.

Subjects were given the same set of instructions via the VDU as given in Chapter 4 for the two-handed simultaneous discrimination and an additional set for the one-handed discrimination, before each test was started. During the test session the command to lift and lower the stimulus weights and the command to respond were flashed upon the screen. This enabled control of a 3 sec stimulus presentation time for all the paradigms and a 5 sec inter stimulus interval for the consecutive paradigms. The experimenter ensured that subjects followed the commands.

In the consecutive paradigms subjects pressed the button on the non-lifting side to obtain the second stimulus weight. Subjects were required to press the right hand button to record a "right heavier response" and the left hand button to record a "left heavier response". The test session lasted approximately 1 hour and 20 minutes.

Figure 5.1 Distribution of sex and hand preference amongst subjects



5.3 Results

Figure 5.1 shows the numbers of subjects divided by sex and hand preference. Of the sixty six subjects tested, nine female subjects were left handed, with LQs ranging from -100 to -13, and thirty two were right handed, with LQs ranging from +13 to +100. Nine male subjects were left handed, with LQs ranging from -100 to -14, and sixteen were right handed, with LQs ranging from +50 to +100. All subjects with positive LQs used only their right hand for writing and drawing and all subjects with negative LQs used only their left hand for writing and drawing.

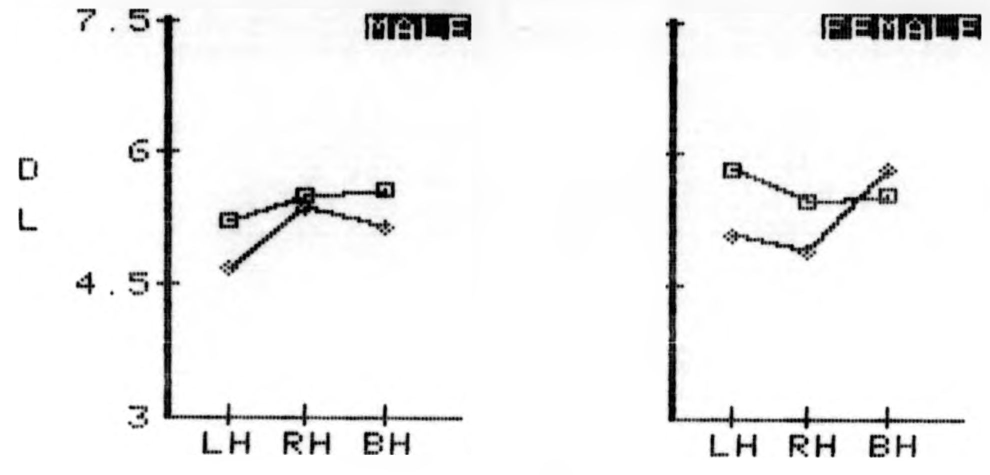
The mean differential thresholds (DLs) (in g) for the three experimental conditions (LH, RH, BH) are shown in table 5.1. The order of presentation conditions for the standard weight presented first (SF) and standard weight presented second (SS) for the one-handed discrimination are also shown. The side of presentation conditions for standard weight presented to the left hand (SL) and standard weight presented to the right hand (SR) for the two-handed discrimination are also shown.

An analysis of variance (ANOVA) was performed on the DLs from the one-handed paradigm with two between subject variables, sex (S), with two levels - male and female and hand preference (HP), with two levels - left and right and two within subject variables, hand (H), with two levels - left and right and order of presentation (OOP), with two levels - SF and SS.

Table 5.1 Mean differential thresholds and standard deviations (in grams) for 66 subjects in one-handed consecutive and two-handed simultaneous weight discrimination paradigms

SEX	EHI	HAND	Order/side* of presentation		
			SF/SL*	SS/SR*	Mean
		LH	3.888(0.626)	6.563(1.968)	5.225
male	LQ > 0	RH	5.500(1.566)	5.513(1.637)	5.506
		BH*	6.325(2.888)	4.825(2.949)	5.575
		LH	3.344(0.910)	5.989(2.205)	4.667
male	LQ < 0	RH	4.589(0.945)	6.122(2.174)	5.356
		BH*	6.644(4.077)	3.633(2.259)	5.139
		LH	4.166(0.956)	7.497(2.044)	5.831
female	LQ > 0	RH	4.644(0.812)	6.303(1.615)	5.473
		BH*	5.566(3.733)	5.531(3.574)	5.548
		LH	4.311(1.066)	5.844(1.552)	5.078
female	LQ < 0	RH	4.022(0.790)	5.789(1.645)	4.906
		BH*	4.133(3.511)	7.489(3.209)	5.811

Figure 5.2 Mean differential thresholds for one and two handed discrimination



A significant main effect was found for HP (F(1,62)=4.90 p=0.0305) due to left handed subjects performing better than right handed subjects with both right and left hands. In Figure 5.2 it can be clearly seen that the DLs for left handed subjects (LQ < 0) are lower than the DLs for right handed subjects (LQ > 0) with the exception of the DL for two-handed discrimination (BH) in female subjects. A significant main effect was found for OOP (F(1,62)=67.32 p=0.0000) due to DLs for SF presentations being lower than ones for SS presentations. In Figure 5.3.A this effect can be clearly seen for male subjects and in Figure 5.3.B for female subjects. A significant interaction between H X S was found (F(1,62)=4.7 p=0.0341) due to females with both a left (LQ<0) and a right hand preference (LQ>0) being better with their right hand (RH) and males with both a right and left hand preference being better with their left hands (LH). This interaction can be seen more clearly in Figure 5.2. A

Figure 5.3.A Differential thresholds for one-handed weight discrimination in male subjects

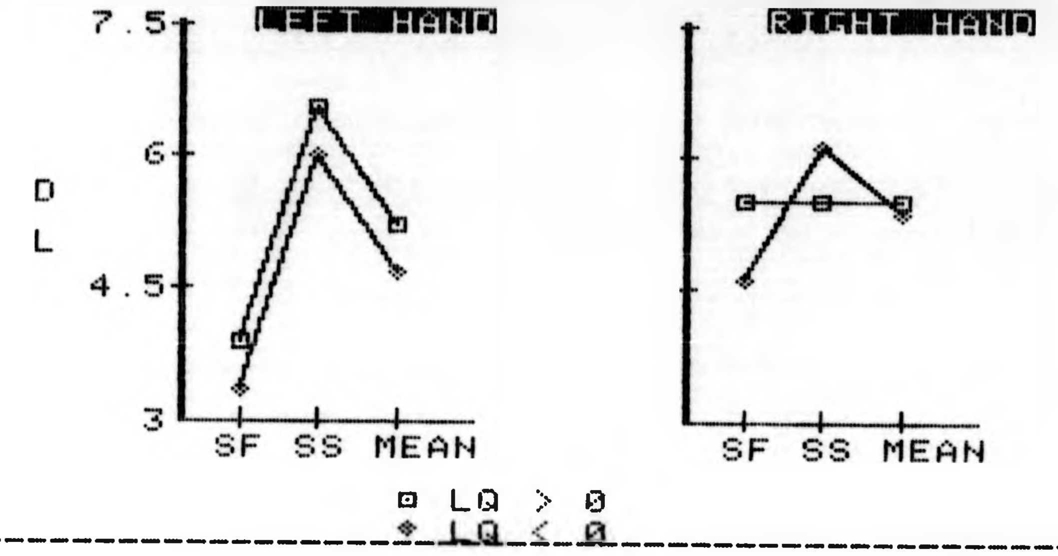
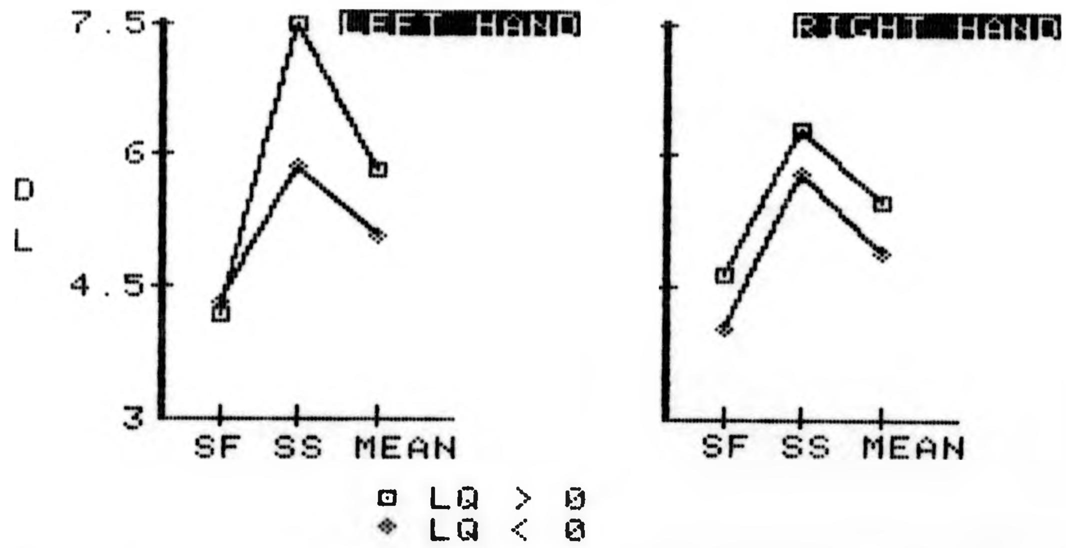


Figure 5.3.B Differential thresholds for one-handed weight discrimination in Female subjects



significant interaction between OOP X H (F(1,62)=11.18 p=0.0014) was found due to the difference between SF and SS being more pronounced for the left hand. This interaction can be more clearly seen in Figures 5.3.A & B.

A significant three way interaction between OOP X H X HP (F(1,62)=4.92 p=0.0303) was found due to the difference between SF and SS being more pronounced for the left hand in right handed subjects. This can be seen in Figures 5.3.A and 5.3.B.

In order to compare one- and two-handed discrimination an ANOVA was performed on the mean thresholds for LH, RH and BH. There were two between subject variables, sex (S), with two levels - male & female) and hand preference (HP), with two levels - left and right and one within subject variable with three levels - LH, RH, & BH. No significant effects were found, though two handed discrimination did produce slightly higher thresholds than one handed discrimination. This can be seen in Figure 5.2.

An ANOVA was performed on the DLs for the two-handed simultaneous discrimination test. No significant main effects were found and one interaction between OOP X S ($F(1,62)=5.17$ $p=0.0264$) was found. This was due to the DLs for SL being higher than DLs for SR in male subjects and DLs for SR being higher than DLs for SL in female subjects. This can be seen

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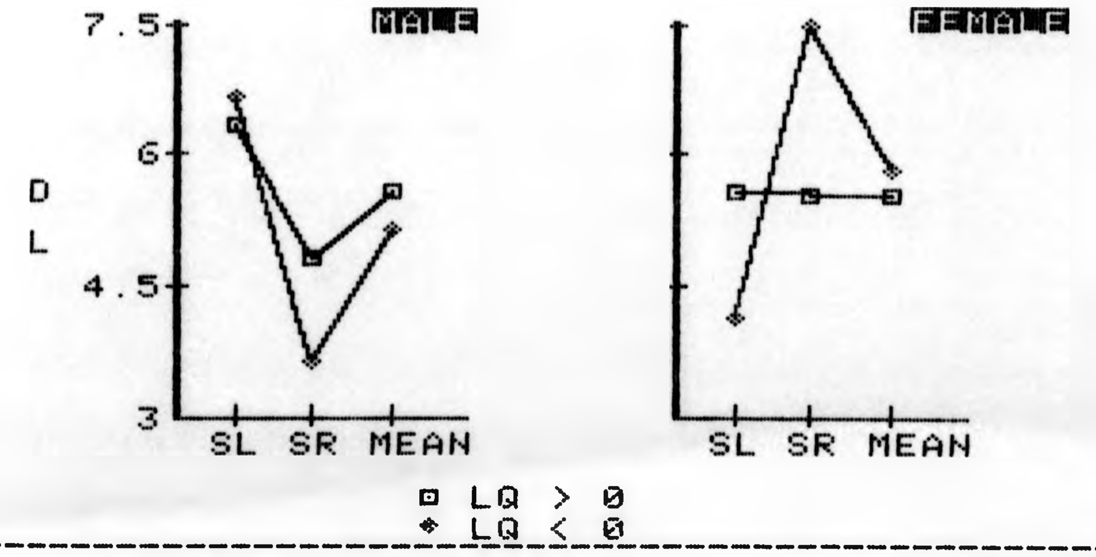
Figure 5.4 Differential thresholds for two handed weight discrimination



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in Figure 5.4. Right handed female subjects did not display this effect with little difference between SL and SR.

A correlation was performed between hand preference and DLs for male and female subjects. For male subjects no significant correlation was found between hand preference and the differential thresholds calculated for weights lifted using either right or left hands. Female subjects did show a significant correlation ($r=0.3719$, $n=41$ $p<0.05$) between hand preference and right hand performance but not between hand preference and left hand performance.

In order to test whether hand sensitivity and direction of space error were related a correlation was performed on the difference score between DLs for RH and LH in the one-handed discrimination and the difference score between SL and SR in the two-handed discrimination. No significant effect was found for either male or female subjects.

5.4 Discussion

The time taken to administer an EHI and present subjects with not more than 48 stimulus pairs of weights for three pairs of randomly interspersed "staircase" procedures was not more than one hour and twenty minutes. On average twenty five minutes were devoted to the stimulus presentations and recording of responses for the consecutive paradigms and twenty minutes for the simultaneous paradigm. The apparatus considerably shortened the time taken to measure DLs for lifted weights. Six DLs were measured in just over an hour.

In the one-handed discrimination paradigms, DLs were found to be lower when the standard weight was presented first than when the standard weight was presented second. This reflects a constant error known as the time error (Fechner, 1860, Needham, 1934; Ross, 1964). More recently it has been renamed the time order error (TOE) to avoid confusion with errors occurring in time estimation (Hellström, 1985). The TOE is a bias towards finding one of two consecutively presented stimuli of equal intensity, less intense. The TOE is defined as being positive when the second stimulus is found less intense and negative when the first stimulus is found less intense. In the one-handed weight discrimination paradigm there were more second heavier responses, resulting in the threshold being lowered when this was the correct response (i.e. when the comparison (or heavier) weight was second) and resulting in the threshold being raised when this was the incorrect response (i.e. when the standard (or lighter) weight was presented second). This negative direction of the TOE is well known (e.g. Brown, 1910; Needham, 1934; Ross, 1964) with the bias being to more second heavier responses. A change in direction of the TOE has been attributed to many factors (e.g. length of inter stimulus interval (ISI), stimulus intensity, difficulty of task). However in the experiments described it always remained negative. In fact the evidence suggests that between subject differences may account for the size of effect in that the magnitude of the TOE is largest for male subjects using their non-preferred hand.

The finding that sensitivity to lifted weights may differ systematically when weights are presented in different first than when the standard weight was presented second. This reflects a constant error known as the time error (Fechner, 1860, Needham, 1934; Ross, 1964). More recently it has been renamed the time order error (TOE) to avoid confusion with errors occurring in time estimation (Hellström, 1985). The TOE is a bias towards finding one of two consecutively presented stimuli of equal intensity, less intense. The TOE is defined as being positive when the second stimulus is found less intense and negative when the first stimulus is found less intense. In the one-handed weight discrimination paradigm there were more second heavier responses, resulting in the threshold being lowered when this was the correct response (i.e. when the comparison (or heavier) weight was second) and resulting in the threshold being raised when this was the incorrect response (i.e. when the standard (or lighter) weight was presented second). This negative direction of the TOE is well known (e.g. Brown, 1910; Needham, 1934; Ross, 1964) with the bias being to more second heavier responses. A change in direction of the TOE has been attributed to many factors (e.g. length of inter stimulus interval (ISI), stimulus intensity, difficulty of task). However in the experiments described it always remained negative. In fact the evidence suggests that between subject differences may account for the size of effect in that the magnitude of the TOE is largest for male subjects using their non-preferred hand.

The finding that sensitivity to lifted weights may differ systematically when weights are presented in different positions reflects a constant error known as the space order error (Fechner, 1860). He defined the error as being positive when the stimulus presented on the right is underestimated relative to the stimulus presented on the left. In the experiment described in Chapter 3, hand preference was not found to account for the space error in a two-handed simultaneous paradigm. A significant sex effect was found. That is male subjects were found to have higher DLs when the standard weight was in the left hand and female subjects higher DLs when the standard weight was in the right hand. This sex difference was again present in this experiment amongst a different group of subjects. A tentative explanation may be advanced in terms of hemispheric specialisation. The literature suggests that females are less lateralised than males with respect to spatial functioning (Harris, 1978; De Renzi, 1982). If weight discrimination is conceived as a manipulospatial task then the pre-potency of the contralateral pathways to and from the hemisphere specialising in such functioning will give males a predictable bias. The fact that females were less biased could be explained by less pre-potency.

In reviews of the literature on human handedness or manual preference and manual performance (Hicks & Kinsbourne, 1978; Porec & Coren, 1981) it has been found difficult to specify the relationship in any particular manual task between hand preference and hand proficiency. However, it has been claimed that right handers seem more skil ful at manual tasks with their right hand than left handers with their left hand and that left handers display greater within and between subject variability (Hicks & Kinsbourne, 1978 pp 537). This however runs contrary to common phenomena of left handed sportsmen and sportswomen excelling in sports with a large visuo-spatial or manipulo-spatial component and indeed to the observation made many hundreds of years ago that of

> "...seven hundred chosen men lefthanded;
> every one could sling stones at an hair
> breadth and not miss." Judges, XX, 16

As far as weight discrimination is concerned it has been found in this study that left handed subjects performed significantly better than right handed subjects with both their preferred and non preferred hands. This advantage in performance for subjects with a left hand preference has been found recently in a peg pulling task (Kilshaw & Annett, 1983). It again suggests the importance of hemispheric specialisation in motor tasks requiring manipulation of objects in time and space such as peg pulling or weight discrimination.

A tentative explanation of the finding that left handers are better than right handers with their preferred hand at manupulospatial tasks could be in terms of the small proportion (10%) of the right handed population having the hemisphere processing spatial information contralateral to their preferred hand (Milner, 1974). A much higher proportion (40%) of the left handed population have their preferred hand contralateral to their spatial hemisphere (Milner, 1974). Amongst the right handed population 90% have language lateralised to the left hemisphere resulting in their preferred hand being contralateral to their language hemisphere. The finding that right handed male subjects were better with their non-preferred hand would similarly be explicable in terms of it being contralateral to the spatial processing hemisphere.

It would seem that as far as weight discrimination goes no simple relationship exists between hand preference and proficiency. This could perhaps be due to the relative importance of motor and sensory components in the task. Flowers (1975) argues that any differences in performance between preferred and non preferred hands is due to the superior sensory feedback capability of the preferred hand, not the motor capacity. In this study male subjects performed better than female subjects with their left hands suggesting that it is the increased lateralisation of hemispheric function in males (Harris, 1978) that results in a left hand advantage. This asymmetry has been supported by the neural transmission model of Kimura (1961) which argues that an advantage, of ear or hand, is due to the prepotency of contralateral pathways projecting from the ear or hand, to the cerebral hemisphere subserving the function. Thus a left side advantage reflects right hemispheric functioning. However, as far as passive pressure sensing goes it has been shown that both contralateral and ipsilateral pathways are used (Gazzaniga & Le Doux, 1978; Wall, 1975). Given the contralateral control of movement of upper limbs and the specialisation of the right hemisphere for a variety of spatial tasks a left hand advantage reflects the importance of "active touch" rather than "passive touch" in weight discrimination. Evidence for a left hand advantage in a variety of manipulospatial tasks has been found (Le Doux, 1983). Thus the results of this study would seem to suggest that a large manipulospatial component is present in weight discrimination.

Ross & Roche (1984) found that for weight discrimination male subjects had lower DLs than female subjects with their preferred hand but higher DLs with their non-preferred hand. Their finding was only partly confirmed in this study. No difference was found between the DLs of right handed males and right handed females performing with their right hands. In fact right handed males performed better than right handed females with their left hands contrary to the finding of Ross & Roche (1984). Only left handed male subjects were better than females with their preferred hand and worse with their non preferred hand. Ross & Roche (1984) also found that the DLs of male subjects correlated with hand preference whereas the DLs of female subjects did not. In this study the reverse was found. Only the DLs of female subjects correlated with hand preference. The differences in results between Ross & Roche (1984) and this study may be due to differences in experimental procedures. Ross & Roche used an experimental design that prevented subjects from lifting discrete objects in a normal way. Subjects were required to pull on a handle attached to the weight hidden out of sight. Thus they may have been forced inadvertantly into discriminating between bodily sensations or "sensations of innervation" accompanying the lifting movement. It has been argued that perceiving these sensations is not equivalent to perceiving the weight of the lifted object (Ross & Bischof, 1981; Brodie & Ross, 1984).

The fact that manual preference and weight discrimination appear to have no simple relationship reflects the difficulty in demonstrating any clear relationship between manual preference and manual performance. Furthermore, if manual preference is taken to reflect the organisation of the cerebral hemispheres in terms of specialisation, then the results of this study lend some support to the view that differences in performance of left and right handers cannot be taken to reflect a simple reversal of cerebral organisation (Satz, 1977; Beaumont, 1983). De Freitas & Dubrovsky (1976) found that amongst a left handed subject population performance in a tactile recognition task was not better with the left hand for all subjects. Using a dichotic listening test to ascertain the hemisphere lateralised for language they found the hand contralateral to the cerebral hemisphere subserving spatial functioning proved to be the better at the task. In order to test whether hemispheric specialisation, not hand preference, influences weight discrimination an experiment was performed and reported in Chapter 7.

5.5 Summary

It has been suggested that the preferred hand is the more sensitive at discriminating between lifted weights and the non-preferred hand is the more sensitive at pressure sensing. Given that weight discrimination is subserved by both pressure sensing and kinesthesis it was decided to investigate the relationship between hand preference and hand sensitivity in the discrimination of lifted weights. It has also been suggested that the bias introduced into two-handed simultaneous weight discrimination can be explained either in terms of hand sensitivity or sex differences. The effects of sex, hand sensitivity and hand preference in one- and two-handed weight discrimination paradigms were investigated. Of the sixty six subjects there were 25 male subjects, of whom 16 were right handed and 9 were left handed and 41 female subjects, of whom 32 were right handed and 9 were left handed. Differential thresholds (DLs) were quickly calculated in one- and two-handed weight discrimination paradigms using microcomputer generated sequential tracking procedures and two weight bearing carousels.

The time-order error was found to be negative for both right and left hands of right and left handed male and female subjects with more "second heavier" responses being given. In keeping with the findings of Fechner (1860) very little difference was found between left and right hands in one-handed discrimination. Contrary to the findings of Fechner, two-handed discrimination did not produce appreciably higher thresholds than one-handed discrimination once the TOEs and the SEs were accounted for in balanced designs.

The main effect to emerge was that both male and female left handed subjects performed better than right handed subjects with both right and left hands. A tentative explanation was given in terms of cerebral organisation. A larger proportion of left handed subjects have a neural transmission advantage from preferred hand to spatial processing hemisphere.

Surprisingly no hand preference effects emerged for male subjects. Correlations between hand preference, as measured by the Edinburgh Handedness Inventory (EHI), and DLs for right and left hands were not significant. That is, subjects displaying a strong hand preference did not obtain low DLs with their preferred hand and high DLs with their non-preferred hand. Both right and left handed male subjects performed better with their left hands. Female subjects showed a marginally significant correlation between hand preference and DLs for the right hand but not for the left hand. Both right and left handed female subjects performed better with their right hands. It was suggested that hand preference does not reflect cerebral organisation for the mechanisms subserving weight discrimination.

CHAPTER 6: TWO HANDED WEIGHT LIFTING: TEMPORAL CONTIGUITY

6.1 Introduction

The time-order error (TOE) is a well known phenomenon in the measurement of DLs for lifted weights (Fechner, 1860; Needham, 1934; Ross, 1964) and has normally to be accounted for in experimental designs where two stimuli are separated by time. This is normally achieved by balancing the design to take account of more "second heavier" responses (Brodie & Ross, 1984). It is also a robust phenomenon, as the previous chapters reveal, with negative TOEs being found for lifted weights at high and low stimulus intensities and with different lifting movements. However, it has generally been studied in the context of a one-handed consecutive weight lifting paradigm, not in the context of a two-handed paradigm.

DLs have been found to differ when weights are presented in different spatial positions and reflect a constant error known as the space error or space-order error (Fechner, 1860). Fechner defined the direction of the error as being positive when the stimulus presented on the right is underestimated relative to the stimulus presented on the left. He (1966, p. 75) did not make it clear whether his space-order error applied to one- or two-handed lifting, or both. It was not clear whether or not it would occur across hands in a two-handed consecutive weight lifting task, thus confounding errors of time and space. The results of an experiment comparing space and time errors in a systematic way may shed some light on possible explanations for the TOE, SOE and SE. That is, whether they are due to sensory biases (Hellström, 1985), reflecting sensitivity of right and left hands, or attentional biases, reflecting the difficulty in controlling two-handed movements.

Weber (1834) found that with pressure sensing, weights are most easily compared if placed successively on one hand, least easily compared if placed simultaneously on one hand and of intermediate ease of comparison if placed consecutively on two hands (1978, p. 95). Fechner (1860) argued against the use of a two-handed weight discrimination procedure on the grounds that attention may be turned to only one of the stimuli at any one time. As mentioned in the discussion in Chapter 4, this approach fits with a current model of two-handed motor control (Peters, 1985). In this model there are two hierarchical functional levels. The higher one controls the movement of the two upper limbs in a unitary manner and the lower two levels control each upper limb separately. Thus attention must switch from the higher level when the two hands have to lift the weights simultaneously, to the lower level when the weight in each hand must be compared. A tentative suggestion was that this attentional switch accounted for the bias in two handed simultaneous discrimination. By lifting each hand in turn in a two-handed consecutive paradigm, subjects were asked to turn their attention from one hand to the other as they lifted the weights. The aim of this experiment was to test the suggestion that attentional factors may account for the space error and to investigate the direction of the TOE in two-handed discrimination.

6.2 Method

6.2.1 Subjects

Fifty eight undergraduate psychology students acted as subjects as part of a course requirement. There were 31 female subjects and 27 male subjects. Male subjects' ages ranged between 19 and 40 with a mean of 23.6 and female subjects' ages ranged from 18 to 42 with a mean of 22.4.

6.2.2 Apparatus

The apparatus described in Chapter 4 was used.

6.2.3 Procedure

Subjects were given a standard set of instructions for two-handed simultaneous and two-handed consecutive forced choice discrimination paradigms before the experiment started via the VDU. During the test sessions the command to lift and lower the stimulus weights and the command to respond were flashed upon the screen. This enabled control of a 3 sec stimulus presentation time for all conditions and a 5 sec inter stimulus interval for the consecutive conditions. The experimenter ensured that subjects followed the commands. As in previous chapters hand preference was measured using the Edinburgh Handedness Inventory

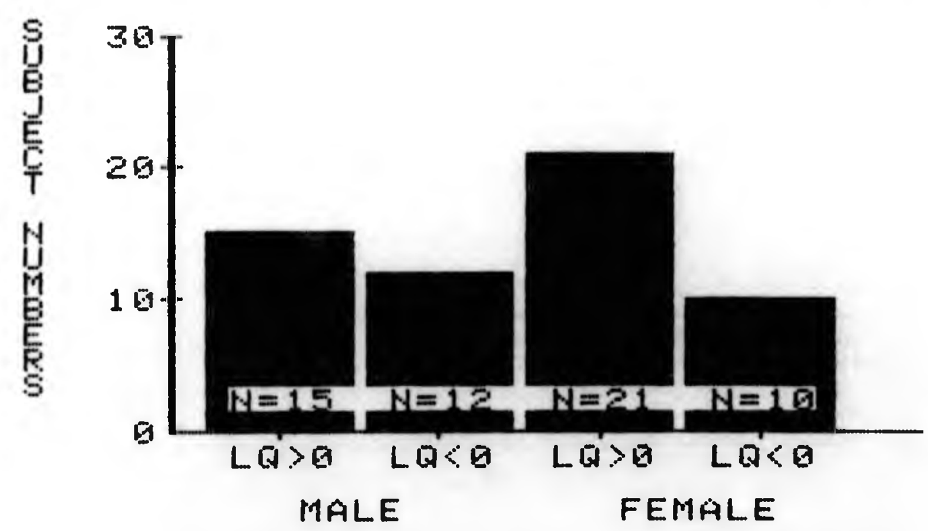
There were three experimental paradigms with two conditions in each. The standard (lighter) weight was presented to the right hand (SR) and standard weight to the left hand (SL) in the simultaneous lifting paradigm. The standard (lighter) weight was presented to the right hand

(SR) and standard weight to the left hand (SL) in the two successive lifting paradigms of the right hand lifted and lowered first (RF) and the left hand lifted and lowered first (LF).

6.3 Results

Figure 6.1 shows the numbers of subjects divided by sex and hand preference. Of the fifty eight subjects tested, ten female subjects were left handed, with LQs ranging from -88 to -23, and twenty one were right handed, with LQs ranging from +33 to +100. Twelve male subjects were left handed, with LQs ranging from -100 to -5, and fifteen were right handed, with LQs ranging from +20 to +100. All subjects with positive

Figure 6.1 Distribution of sex and hand preference amongst subjects



LQs used only their right hand for writing and drawing and all subjects with negative LQs used only their left hand for writing and drawing.

The mean differential thresholds (in g) for the three order of presentation conditions (right hand first - RF, left hand first - LF and simultaneous - SIM), and for the two side of presentation conditions (standard weight presented to the left hand - SL and standard weight presented to the right hand - SR) are shown in Table 6.1.

An analysis of variance was performed upon the DLs with two between subject variables, sex (S), with two levels, male & female and hand preference (HP), with two levels, left & right. There were two within subject variables, order of

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<u>Table 6.1 Mean differential thresholds (with standard deviations) for 58 subjects in a two handed consecutive and two handed simultaneous weight discrimination experiment</u>

SEX	HAND PREFERENCE	ORDER OF PRESENTATION	SIDE OF PRESENTATION OF STANDARD		
			SL	SR	MEAN
		RF	8.462(2.933)	3.477(3.039)	5.969
male	LQ>0	LF	4.688(3.212)	6.387(3.643)	5.537
		SIM	4.805(2.403)	5.300(2.678)	5.053
		RF	6.877(3.430)	4.443(2.631)	5.660
MALE	LQ<0	LF	3.301(2.594)	6.170(3.989)	4.735
		SIM	5.848(3.632)	4.176(3.014)	5.012
		RF	7.709(3.226)	3.173(1.994)	5.441
FEMALE	LQ>0	LF	3.246(1.891)	7.319(3.580)	5.282
		SIM	5.489(3.495)	5.369(3.577)	5.429
		RF	9.111(2.485)	2.541(1.314)	5.826
FEMALE	LQ<0	LF	4.252(2.647)	6.984(3.030)	5.618
		SIM	4.384(2.194)	5.814(2.669)	5.099

presentation (OOP), with three levels - RF, LF and SIM and side of presentation (SOP), with two levels, SL & SR. A significant main effect was found for order of presentation ($F(2,108)=3.11$, $p=0.0485$) due to RH lifting producing the highest DLs and SI lifting the lowest DLs with LH liftings in between the two. This can be clearly seem in Figure 6.2.

Figure 6.2 Mean differential thresholds for two handed discrimination

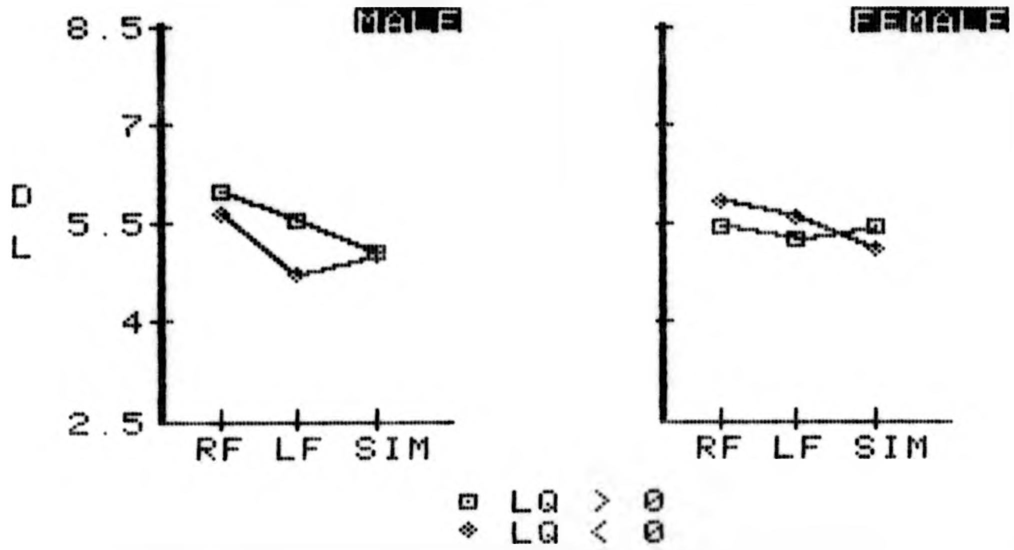
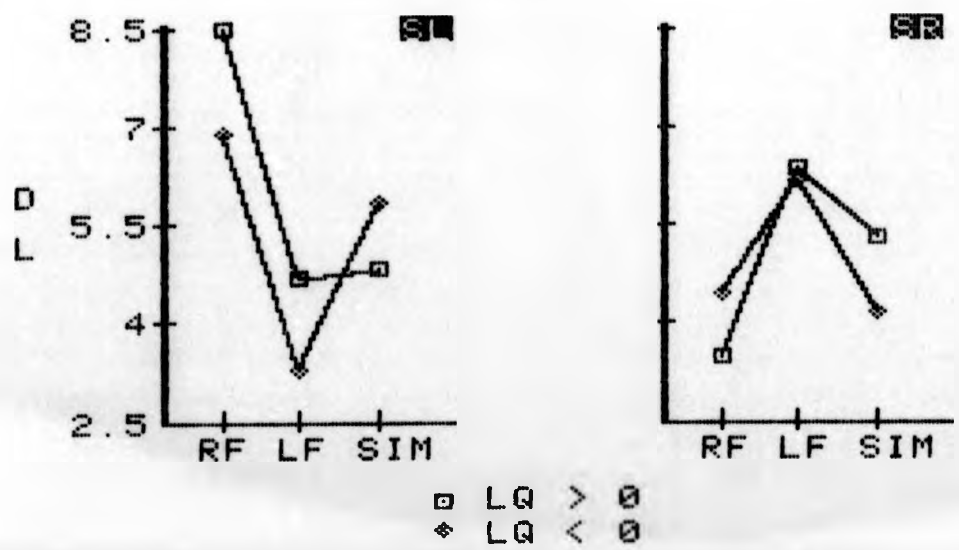
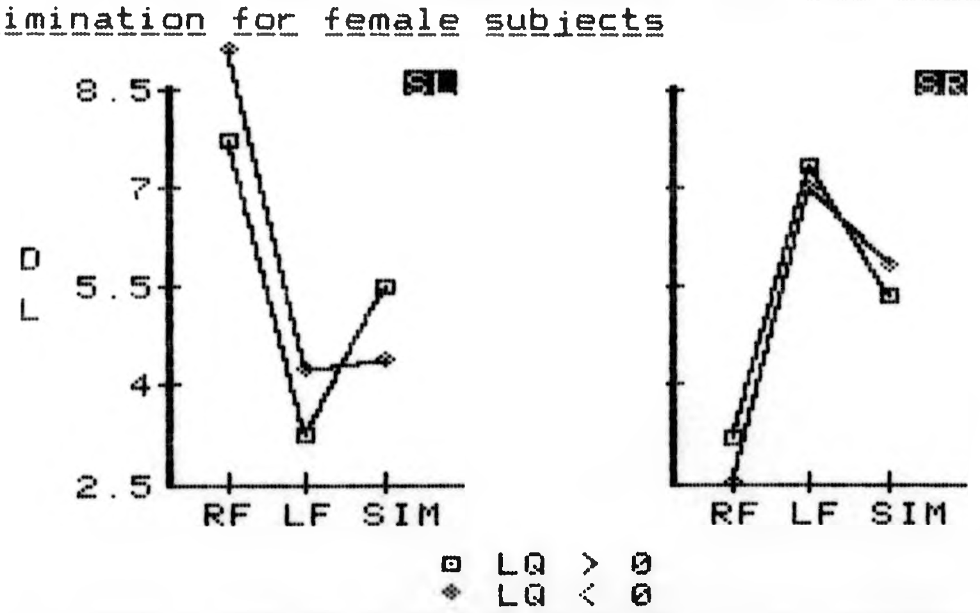


Figure 6.3.A Differential thresholds for two handed weight discrimination for male subjects



A highly significant interaction between OOP X SOP (F(2,108)=50.19, p=0.0000) was found. In the SL condition this was due to DLs being very high in the RF condition, low in the LH condition and intermediate in the SIM condition for both left and right handed, male and female subjects. This effect was reversed for both left and right handed male and female subjects in the SR conditions, where the lowest DLs were produced in the RH condition, the highest in the LH condition and in between in the SIM lifting condition. These effects can be clearly seen in Figures 6.3 A & B. A significant four way interaction was found between OOP X SOP

Figure 6.3.B Differential thresholds for two handed discrimination for female subjects



X S X HP (F(2,108)=4.11,p=0.0190). In the SL condition this was due to left handed female subjects performing worse than right handed female subjects for RF and LF and better for SIM whereas left handed male subjects performed better than right handed male subjects for RF and LF and worse for SIM. In the SR condition this was due to left handed female subjects performing better than right handed female subjects for RF and LF and worse for SIM whereas left handed male subjects performed worse than right handed male subjects for RF and LF and better for SIM. This effect can be seen more clearly in Figures 6.3 A and B.

6.4 Discussion

In the experiments described in Chapters 4 and 5, male subjects were found to have higher DLs when the standard weight was in the left hand and female subjects higher DLs when the standard weight was in the right hand. That is, male subjects found weights lighter in their preferred hands and heavier in their non-preferred hands. Female subjects showed the opposite effect, though not as strongly, with weights feeling lighter in their left hands and heavier in their right. In this experiment this sex difference was not found to be clear cut. Only left handed male and female subjects showed this effect. Right handed male subjects showed higher DLs in the SR presentation condition and right handed female subjects very little difference between SL and SR.

The highly significant effect found in this experiment was between the time error and the space error in the two-handed consecutive discrimination paradigm. For both right and left handed, male and female subjects, the presentation of the standard weight to the left hand (SL) resulted in higher DLs when the right hand weight was lifted first and lower DLs when the left hand weight was lifted first. This effect can be simply explained in terms of a negative TOE. By giving more second heavier responses subjects were reducing their DLs when the comparison (heavier) weight was second and raising their DLs when the comparison weight was first. A negative TOE can again explain the results for both right and left handed male and female subjects when the standard weight was presented to the right hand (SR). By giving more second heavier responses subjects were raising their DLs when the standard weight was second and reducing their DLs when the standard weight was first. That is, a negative TOE was present in the two-handed consecutive weight discriminaton paradigm with no effect due to the SE.

DLs obtained in the two-handed consecutive lifting paradigms were found to be higher than DLs obtained in the two-handed simultaneous lifting paradigm. That is, the attentional shift from one hand to the other does not result in better discrimination. This is surprising as both Weber and Fechner found that consecutive comparisons produced lower thresholds than simultaneous comparisons.

One possible explanation is in terms of the two-level motor control theory posited by Peters (1985). Whether both levels are represented separately in each cerebral hemisphere is not explicit. The channels of motor outflow and sensory inflow for movement and its control are known to occur unilaterally in the contrlateral hemisphere. In two-handed consecutive discrimination the high-level mechanism has to store the "weight" of the object lifted first. When the other hand lifts the weight and the comparison is performed it is between the "weight" stored at a high level of representation in one hemisphere and the current operational or low-level of representation of weight in the other hemisphere. This comparison may well prove difficult and result in poor discrimination.

How remembered weight is represented in the brain is not yet known, but must involve the synthesis of the operational parameters of motor outflow and sensory inflow resulting from the lifting movement. Motor outflow parameters are likely to differ between hemispheres. This would account both for the poor performance in consecutive and simultaneous two-handed discrimination, and the better performance in one-handed consecutive discrimination found in Chapter 5.

The advantage given by simultaneous lifting over consecutive lifting in weight discrimination can be explained by the two tier model of Peters (1985). Two concurrent operational inputs are provided by the two low-level mechanisms involved in individual upper limb control. The super-ordinate control mechanism can monitor both the lower levels using very fast attentional shifts.

6.6 Summary

It has been suggested that simultaneous weight discrimination results in higher DLs than consecutive weight discrimination because of the difficulty in attending to both stimuli at the same time. The constant temporal error (TOE) and the constant spatial error (SE) have been investigated in one-handed weight discrimination paradigms but not two-handed paradigms. The biases of space, time and attention in the measurement of DLs for lifted weights in a two-handed weight discrimination paradigm were investigated.

Fifty eight subjects were tested, ten female subjects were left handed and twenty one were right handed. Twelve male subjects were left handed and fifteen were right handed. Contrary to previous findings it was found that performance was worse with two-handed consecutive weight discrimination than with two-handed simultaneous weight discrimination.

A tentative explanation was given in terms of unilateral hemispheric processing contralateral to the lifting hand. Communication between the two hemispheres can only occur optimally if the comparison to be performed occurs at similar levels in the hierarchy of representations. This can explain why two-handed simultaneous discrimination, although poor, is better than two-handed consecutive discrimination.

It was also found that in a two-handed consecutive weight discrimination paradigm the TOE and the SE are not confounded. A negative TOE explained the biases found in two-handed consecutive weight discrimination.

CHAPTER 7: ONE HANDED CONSECUTIVE WEIGHT LIFTING: THE EFFECT OF HEMISPACE

7.1 Introduction

One of the most influential models which has been advanced to explain the differences between right and left abilities, whether of ear, eye or hand, is the neural transmission model of Kimura (1961). This model explains laterality effects in terms of the prepotency of contralateral afferent pathways over ipsilateral pathways, projecting to the hemisphere specalised for the particular function. However, the concept of hemispace has been introduced recently (Bowers & Heilman, 1980; Bradshaw, Nettleton, Nathan & Wilson, 1983a; Bradshaw, Nathan, Nettleton, Pierson & Wilson, 1983b) in order to explain laterality findings which do not fit the anatomical pathway transmission model. Hemispace refers to the spatial field to the right or left of a saggital vertical midline, whether of the head or trunk. Thus it differs from the visual field which is composed of half fields for left and right eyes.

Bowers and Heilman (1980) found that the pathways from hand to contralateral hemisphere and the mechanisms involved in hemispace to hemisphere representations, interacted for a tactile line bisection task using blindfolded right handed subjects. Although the left hand performed better in left hemispace than the right hand in right hemispace, no overall difference in performance was found between right and left hands. On the basis of this result they argued that each hemisphere is concerned with the processing of information originating from the contralateral spatial field. Thus for right handed subjects, presumably with right hemisphere processing for spatial tasks, a left hemispace advantage is present for both right and left hands. Using a peg moving task Bisiach (1981) found a left hemispace advantage for right handed subjects. He argued that the representation of space is anchored to the sagittal mid-plane of the trunk.

However inconsistent findings have been reported in the current hemispace literature. These may be due to different types of experimental task. Burden, Bradshaw, Nettleton & Wilson (1985) reported a left hemispace advantage for length estimation using touch alone, and for texture matching in children. Bradshaw, Nathan, Nettleton, Pierson and Wilson (1983) found a right hemispace advantage for a vibrotactile response time task and argued that the right hemispace advantage was for motor rather than sensory processing. Bradshaw, Nettleton, Nathan and Wilson (1983) found that they could not replicate Bowers and Heilman's left hemispace advantage for a tactual or visuotactual judgements. Bradshaw (1985) suggested that attentional factors may explain the lack of consistency in the spatial field findings.

On the basis of this evidence it is not clear in what way hand and hemispace will interact, if at all, in weight discrimination. It has been found by Fechner (1860) that for weight discrimination there is a slight hand advantage in favour of the right hand when DLs for both right and left hands of subjects were compared. However, the number of right and left handed subjects was not reported. A more pronounced preferred hand advantage has been claimed by Ross (1984) but no details were given of the empirical investigation supporting the claim. In Chapter 5 of this thesis left handers were found to be better at discriminating between weights than right handers but no simple relatonship was found between hand preference and hand performance. If weight discrimination is conceived of as a motor task then for right handed subjects either a right hemispace advantage might be expected, following Bradshaw et al (1983), or a left hemispace advantage, following Bisiach (1981), or neither following Flowers (1975). If weight discrimination is conceived as a spatial or sensory task than a left hemispace advantage would be expected following Bowers and Heilman (1980, Bradshaw (1985) and Flowers (1975).

However the experiments described have two major shortcomings: 1) They did not control adequately for hemispheric specialisation and 2) They did not use left handed subjects. Amongst right handed populations it is known that between approximately 10% and 20% have right hemisphere superiority for language. Amongst left handed populations between approximately 50% and 60% have right hemisphere superiority for language (Milner, 1974; Hicks & Kinsbourne, 1978). It is thus important to attempt to ascertain the hemispheric specialisation of subjects especially if the task required of them involves a spatial element.

This view is further substantiated by De Freitas & Dubrovsky (1975) who found that left handed subjects displayed a preferred hand advantage in a spatio-tactile task only if they also showed a right ear advantage in a dichotic listening test. If they displayed a left ear advantage on the dichotic listening test a non-preferred hand advantage was found. It is thus important to ascertain differential lateralisation of function as weight discrimination may well be subserved by the spatial hemisphere.

It was argued in Chapter 5 that a clear advantage accrues from having the preferred hand contralateral to the spatial processing hemisphere. Thus a populational effect explains the advantage of left handers over right handers in weight discrimination. About half of the left handed population have the preferred hand contralateral to the the spatial processing hemisphere. This explains the finding of a preferred hand advantage for left handers over right handers in weight discrimination. Conversely about half have the spatial processing hemisphere contralateral to their non-preferred hand. This explains the slight non-preferred hand advantage of right handers over left handers as 90% of the right handed population have the spatial processing hemisphere contralateral to their non-preferred hand. Kilshaw & Annett (1983) found the reverse in a peg moving task. A clear non-preferred hand advantage and a less clear preferred hand advantage was found for left handers over right handers Annett & Kilshaw (1983) explained this effect in terms of a right hemisphere handicap rather than a left hemisphere advantage for right handers. However, the findings of Kilshaw & Annett may well reflect asymmetries in the performance of a visuo-motor task and not of a manipulospatial task involving sensory feedback (Berman, 1973). They also may be confounding hand and hemispace effects.

It has been found that females are less lateralised in brain function that males (Harris, 1978). This may result in differences in discriminatory ability between the sexes. It has been shown in Chapters 4 and 5 of this thesis that there are sex differences in weight discrimination. However, Bowers and Heilman (1980) found no difference between male and female performance in their experimental procedure.

Whether hemispheric specialisation occurs for the representation and processing of the weight of lifted objects is not known. If the neural transmission model is invoked, and weight perception is considered to be a spatial task then an advantage would result in the hand contralateral to the non-language hemisphere. If hemispace is invoked then the representation in the brain and accuracy of representation may depend upon which hemispace the weight is lifted in rather than which hand it has been lifted with. If Bowers' and Heilmans' findings are correct then an interaction between the two will result. In the previous chapters no simple relationship was found between hand preference, as measured by the Edinburgh Handedness Inventory, and performance in a weight discrimination test. These null findings may well be explained by the interaction of hand and hemispace. For example, if the weight was lifted using the preferred hand then the representation would be in the contralateral hemisphere. As the lifting task involves a spatio-temporal element then better performance would occur if the processing occurred in the spatial hemisphere. It might well be expected that subjects' performance would be better with the hand in hemispace contralateral to the non-language hemisphere in a sensorimotor task such as weight discrimination.

7.2 Method

7.2.1 Subjects

Sixty undergraduate students acted as subjects. The majority of right handed subjects were psychology undergraduates acting as part of a course requirement. In order to recruit sufficient numbers of left handed subjects an advert was placed in a student newsletter. Those responding were all undergraduate students and were paid to act as subjects. There were 28 male subjects between the age of 18 and 40 with a mean of 23.9 and 32 female subjects between the age of 18 and 27 with a mean of 20.5.

7.2.2 Apparatus

The same apparatus was used as was described in the previous Chapter 4. The addition of a pair of stereo headphones, a stereo cassette player, cassette tape and response sheets were required to administrer the dichotic listening test.

On the cassette tape were recorded two series of 60 dichotically presented syllables. An example of the randomly organised series is given in the appendices. The syllables consisted of the four stopped consonants 'b', 'd', 'p', 't' followed by the vowel 'o'. The test involved the random presentation of two, out of four possible syllables - BO, PO, DO, TO, to both ears simultaneously. A pair of syllables was presented simultaneously, one to each ear, every 2 sec.

7.2.3 Procedure

Subjects were seated in front of the carousels and VDU and arm rests placed in position. In the test session they were required to fill out the Edinburgh Handedness Inventory and then perform one of two discrimination tasks, either in right or left hemispace using both right and left hands. Equal numbers of subjects performed right hemispace first and equal numbers left hemispace first in order to overcome order effects. In the second half of the test session subjects were required to perform the Dichotic Listening Test and then perform the remaining discrimination test. The experimenter issued the EHI and ensured its correct completion and administered the DLT by issuing the subject with a set of instructions and response sheets. Subjects had to respond to which syllable they "heard". The test was designed to yield a score between -100 for hearing only left ear stimuli to +100 for hearing only right ear stimuli. The headphones were reversed after 60 presentations and the test repeated, to avoid channel or headphone imbalance or attentional effects. An example of the response sheet used in the dichotic listening test is given in the appendices (A.2.2).

A standard set of instructions was flashed upon the VDU for the forced choice discrimination tests and subjects were presented with 3 practise trials for each hand. This ensured subjects understood the instructions and allowed the UDTRs to reach an optimum level. Testing lasted approximately 1 hour. As the prime object of the study was not to investigate the TOE the number of trials for each threshold was reduced to 24 so that 8 DLs and the two tests could be performed within one hour.

7.3 Results

Figures 7.1.A and 7.1.B show that of the 60 subjects tested there were 16 males with a right hand preference with LQs ranging from +20 to +100. Of these 7 displayed a right ear advantage with DLTs ranging from + 9 to + 32 and 9 a left ear advantage with DLTs ranging from -5 to -34. There were 12 with a left hand preference with LQs ranging from -5 to -100, of whom 6 displayed a right ear advantage with DLTs ranging from +2 to +42 and 6 a left ear advantage with DLTs ranging from -11 to - 43. There were 21 females with a right hand preference with LQs ranging from +33 to +100. Of these 11 displayed a right ear advantage with DLTs ranging from +10 to +37 and 10 a left ear advantage with DLTs ranging from -2 to -30. 11 displayed a left hand preference with LQs ranging from -23 to -100, of whom 6 displayed a right ear advantage with DLTs ranging from +1 to +19 and 5 a left ear advantage with DLTs ranging from -1 to -57.

The DLs calculated in right and left hemispace using right and left hands, for subjects grouped on the basis of sex, hand preference and ear preference are presented in Table 7.1.A for male subjects and Table 7.1.B for female subjects.

Figure 7.1.A Distribution of hand and ear preference amongst male subjects (n=28)

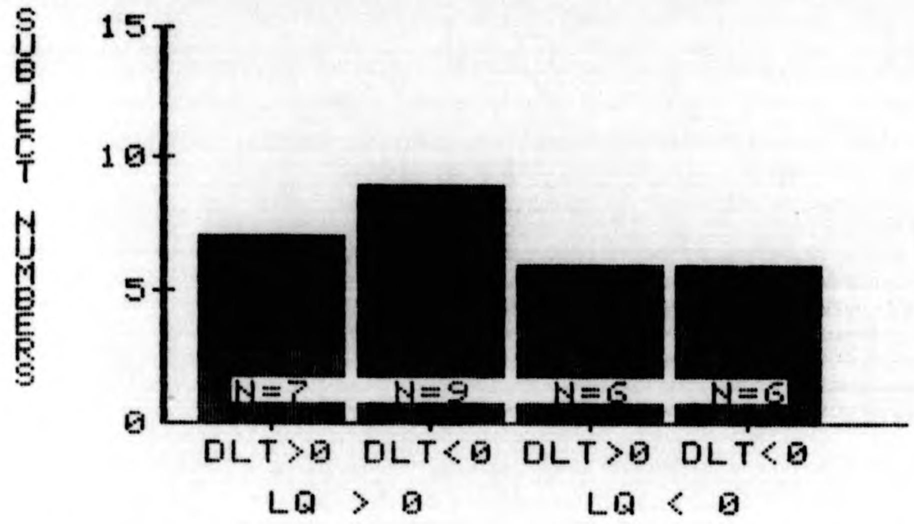


Figure 7.1.B Distribution of hand and ear preference amongst female subjects (n=32)

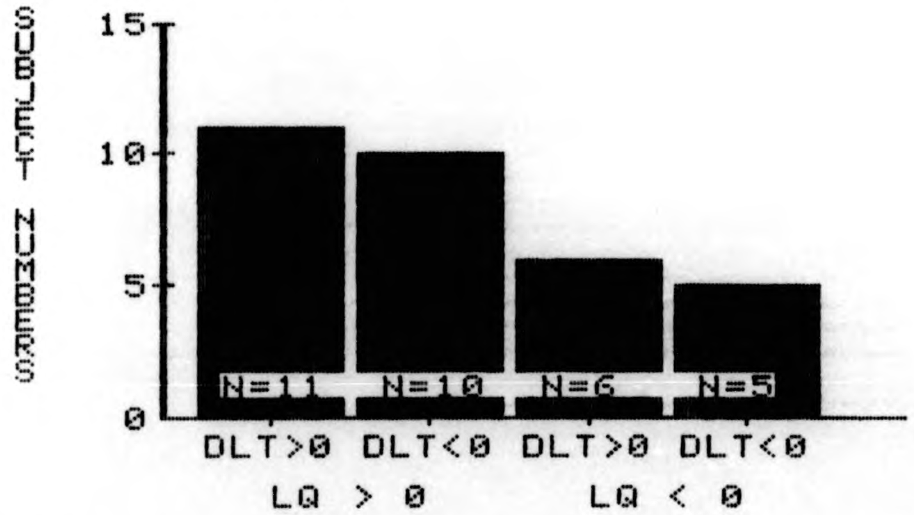


Table 7.1.A Mean differential thresholds (with standard deviations) for male subjects in a one handed consecutive weight discrimination experiment

HAND PREF	EAR PREF	HEMI-SPACE	HAND	DIFFERENTIAL THRESHOLDS Order of presentation standard 1st	standard 2nd	Mean
EHI>0	DLT>0	left	left	4.571(2.234)	7.759(2.492)	6.165
			right	6.160(3.591)	5.833(3.065)	5.996
		right	left	5.117(1.981)	9.626(2.409)	7.371
			right	5.849(3.987)	7.727(3.007)	6.788
	DLT<0	left	left	4.819(2.009	9.126(2.225)	6.972
			right	5.666(2.650)	6.683(1.826)	6.174
		right	left	4.269(2.409)	6.722(2.195)	5.496
			right	3.584(1.891)	4.973(1.748)	4.279
EHI<0	DLT>0	left	left	2.407(1.292)	5.208(2.221)	3.808
			right	2.613(1.243)	4.903(2.772)	3.758
		right	left	3.795(0.952)	6.840(1.267)	5.318
			right	4.763(1.060)	6.515(2.961)	5.639
	DLT<0	left	left	1.788(0.744)	8.693(1.685)	5.241
			right	3.995(2.496)	7.908(2.781)	5.952
		right	left	2.225(1.083)	7.525(2.401)	4.875
			right	2.117(0.786)	7.822(2.217)	4.969

Table 7.1.B Mean differential thresholds (with standard deviations) for female subjects in a one handed consecutive weight discrimination experiment

HAND PREF	EAR PREF	HEMI-SPACE	HAND	DIFFERENTIAL THRESHOLDS Order of presentation standard 1st	standard 2nd	Mean
EHI>0	DLT>0	left	left	3.070(1.064)	7.849(2.898)	5.459
			right	4.359(1.732)	7.046(2.217)	5.703
		right	left	3.822(3.058)	8.068(2.761)	5.945
			right	4.168(2.503)	8.065(3.078)	6.117
	DLT<0	left	left	5.325(2.331	7.706(1.565)	6.516
			right	5.263(2.077)	7.566(2.109)	6.415
		right	left	3.539(2.011)	8.956(2.149)	6.248
			right	3.966(1.821)	5.903(2.428)	4.935
EHI<0	DLT>0	left	left	3.972(1.128)	7.515(2.659)	5.743
			right	5.177(2.590)	7.702(3.120)	6.439
		right	left	3.682(1.703)	10.278(2.326)	6.980
			right	3.295(1.679)	8.180(3.668)	5.738
	DLT<0	left	left	4.500(2.114)	7.250(2.363)	5.875
			right	5.636(2.346)	5.874(1.818)	5.755
		right	left	4.380(2.500)	7.358(1.445)	5.869
			right	4.184(1.986)	5.874(1.986)	5.029

Figure 7.2.A Differental thresholds for lifted weights using right and left hands in right and left hemispace for male subjects

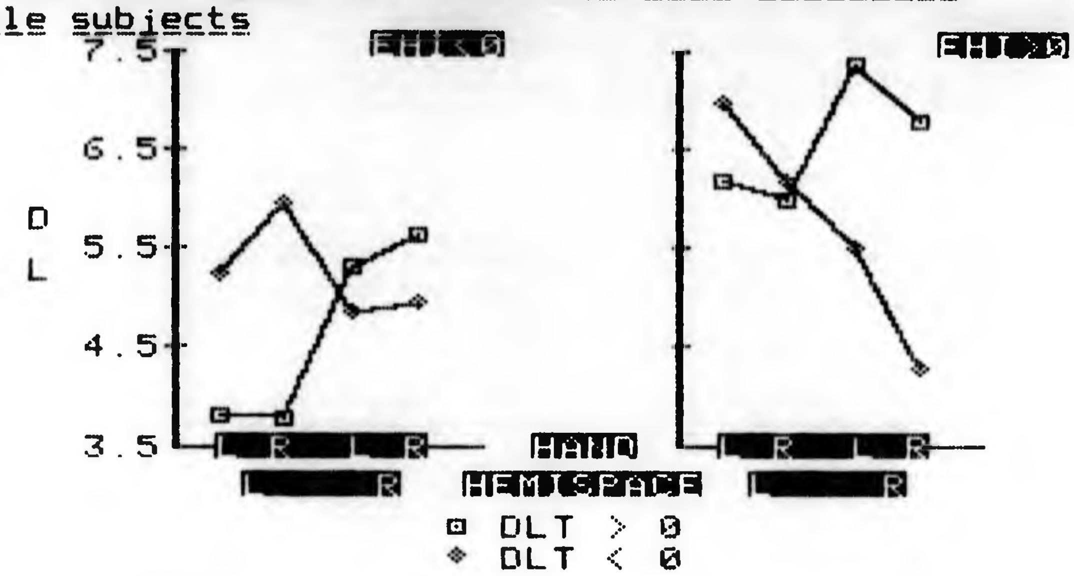
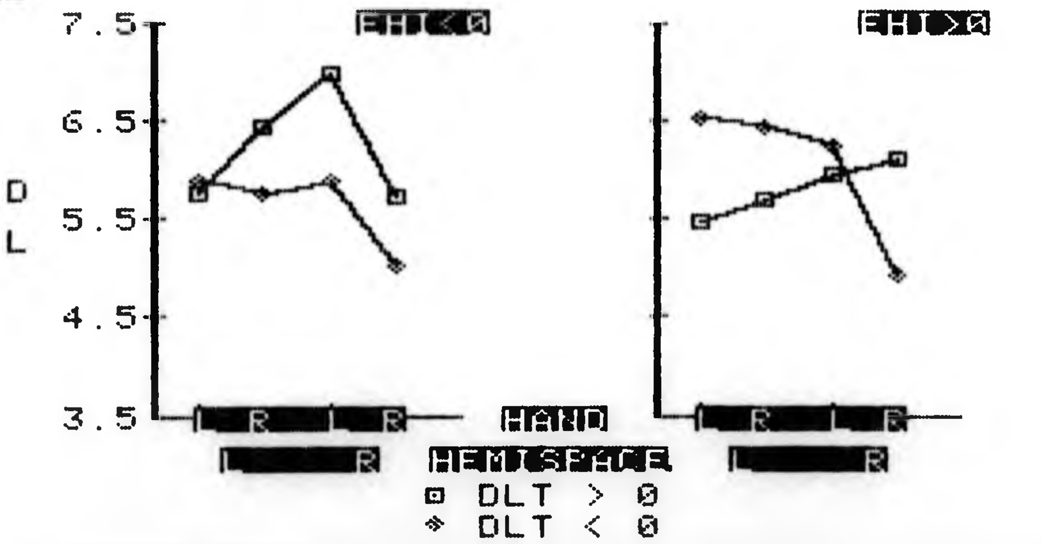


Figure 7.2.B Differental thresholds for lifted weights using right and left hands in right and left hemispace for female subjects



An analysis of variance (ANOVA) was performed upon the DLs for three within subject factors, hemispace (HE), with two levels - right and left, hand (HA), with two levels - right and left and order of presentation (OOP), with two levels - standard first and standard second. There were three between subject factors, sex (S), with two levels - male and female, hand preference (HP), with two levels - right and left and ear preference (EP), with two levels - right and left.

A significant main effect was found for HP (F(1,52)=5.52 p=0.0226), a significant two way interaction between S X HP (F(1,52)=5.74 p=0.0202) and a significant three way interaction between S X HP X EP (F(1,52)=5.05 p=0.0288). Figures 7.2.A and 7.2.B show that the HP effect was due to left handed subjects performing better than right handed subjects. The S X HP effect was due to left handed male subjects performing better than right handed male subjects but no difference between female right and left handed subjects. The three way effect was due to male subjects with left hand and right ear preference performing better than male subjects with left hand and left ear preference. Male subjects with right hand and left ear preference performed better than male subjects with right hand and right ear preference. Female subjects displayed the opposite effect with left hand and right ear preference subjects performing worse than those with left hand and left ear preference. Female subjects with right hand and left ear preference performed worse than those with right hand and right ear preference.

A significant interaction effect was found for HE X EP (F(1,52)=33.48 p=0.0000) due to subjects with a left ear preference performing better in right hemispace and subjects with a right ear preference performing better in left hemispace. A significant three way interaction was found for

S X HE X EP (F(1,52)=6.53 p=0.0136) due to females displaying less of an effect than males.

A significant main effect was found for OOP (F(1,52)=98.78 p=0.0000), and a significant three way interaction between OOP X S X EP (F(1,52)=5.97 p=0.0180). The order of presentation effect was due to the DLs being lower when the standard weight was presented first than when presented second. The three way interaction was due to the difference between standard first and standard second being greater for right ear advantaged males and left ear advantaged females.

A significant interaction was found for HA X OOP (F(1,52)=18.19 p=0.0001) due to the difference between standard first and standard second being greater in the left hand.

In order to investigate the sex interactions an ANOVA was performed for males and females separately with two between subject variables, hand preference (HP), with two levels - right and left and ear preference (EP), with two levels - right and left. There were two within subject variables, hemispace (HE), with two levels - right and left) and hand (HA), with two levels - right and left.

For male subjects a significant main effect for HP was found (F(1,24)=16.33 p=0.0005) due to left handers performing better than right handers. A significant interaction between HP X EP was found (F(1,24)=6.09 p=0.0211) due to left handed subjects with a right ear advantage performing better and right handed subjects with a left ear advantage performing better. A significant two way interaction was found for HE X EP (F(1,24)=27.39 p=0.0000) due to subjects with a left ear preference performing better in right hemispace and subjects with a right ear preference performing better in left hemispace. A significant two way interaction was found for HA X HP (F(1,24)=5.06 p=0.0340) due to subjects performing better with their left hand if left handed and better with their right hand if right handed.

For female subjects the only significant effect was a two way interaction between HE X EP (F(1,28)=6.73 p=0.0149) due to subjects with a left ear advantage performing better in right hemispace and subjects with a right ear advantage performing better in left hemispace.

7.4 Discussion

The finding that DLs were lower when the standard weight was presented first than when the standard weight was presented second reflects a negative TOE. That is, there were more second heavier responses, resulting in the threshold being lowered, when this was the correct response (i.e. when the comparison or heavier weight was second) and resulting in the threshold being raised when this was the incorrect response (i.e. when the standard or lighter weight was presented second). This direction of time error is well known (e.g. Brown, 1910; Needham, 1934; Ross, 1964) and is consistent with the findings in Chapters 3, 5 and 6 of this thesis. The bias has always been towards more second heavier responses.

Previous findings have suggested (Bowers & Heilman, 1980; Bradshaw *et al*, 1983a & b) that a hand and hemispace interaction is likely to be found in a manipulospatial task. This has been confirmed for both male and female subjects in weight discrimination. That is, subjects discriminated better between the weight of lifted objects with both hands in either right or left spatial fields. The effect was not related to hand preference but to ear preference with the performance of both hands being better in the hemispace contralateral to the hemisphere processing spatial information. This would support the notion that weight discrimination involves manipulospatial aspects which are known to be more efficiently processed in this hemisphere (Young & Ratcliffe, 1983) and that information pertaining to the weight of an object is processed in the contralateral hemisphere to the spatial field in which it was lifted.

In this study an overall preferred hand advantage was found for both right and left handers. This is surprising in light of the fact that that Bowers & Heilman (1980) found no such effect. However, an explanation may be given in terms of the motor and sensory pathways to and from the preferred hand giving an advantage in weight discrimination but not in line bisection. This is because it has been found that there are fewer motor and sensory pathways to and from the non-preferred hand (Witelson, 1980) and it has been shown in Chapter 3 that the ability to discriminate between weights is in part determined by the muscle groups brought into play.

Weight discrimination may be the sort of activity that is more sensitive to a sensory motor advantage.

The lack of a clear preferred hand advantage found in Chapter 5 was the result of both hand and hemisphere, hemispace and and hemisphere, and differential hemispheric functioning being confounded. Hicks & Kinsbourne (1978) point out that the relationship between hand preference and hand performance depends upon the type of task performed. The findings of this experiment are consistent with such an observation but with additional constraints. Hand preference is a good indicator of hand performance in weight discrimination only if hemispheric specialisation and the spatial field in which the weights are lifted are taken into account. Although it was found that male subjects performed better with their preferred hand relative to hemispace, cerebral organisation determined whether the preferred or non-preferred hand was the better at discrimination. De Freitas & Dubrovsky (1976) found that left handed subjects displayed a left hand advantage in a tactual-linguistic task if they had speech lateralised to the left hemisphere and displayed a right hand advantage if they had speech lateralised to the right hemisphere. The findings of this study confirm the importance of lateralisation of cerebral function in relation to hand advantage. However, De Freitas and Dubrovsky did not consider sex differences.

There exists a large body of evidence in favour of sex differences in perceptual tasks. Males have been found superior to females on spatial tasks (MacCoby & Jacklin, 1974; Harris, 1978). In this experiment an overall male advantage did not emerge. The sex difference to emerge was that differences in performance of hands in hemispace were more pronounced in male subjects. That is, female subjects were less variable in their discriminatory ability. It also supports the view that females are less lateralised than males (Harris, 1978; De Renzi, 1982). The advantage resulting from the discrimination of lifted objects, with either hand, in the hemispace contralateral to the spatial processing hemisphere is more pronounced in males than females. The disadvantage resulting from the discrimination of lifted objects, with either hand, in the hemispace contralateral to the language processing hemisphere is more pronounced in males than females. Females are more able to process weight information in either cerebral hemisphere.

It was found in the experiment described in Chapter 5 that left handers were better than right handers at discriminating between the weight of lifted objects. This finding has been replicated with a different group of subjects in this experiment. Left handers were found to be faster than right handers, with both hands, in a peg moving task (Kilshaw & Annett, 1983) and in a reciprocal tapping task (Flowers, 1975). However, in this study the advantage is present most clearly in male subjects.

7.5 Summary

It has been found that the ability to discriminate between lifted weights with either hand cannot be related to hand preference. Previous research has shown that the differential lateralisation of spatial function between the cerebral hemispheres can be related to a contralateral hand advantage in a tactile discrimination task. It was hypothesised that the same may be true for weight discrimination. However the research in question did not consider sex differences. These may interfere as females are known to be less differentially lateralised than males.

Two further findings complicate any predictions about the direction of manual asymmetries in weight discrimination. 1) It has been found that motor and sensory channels project contralaterally to and from hand to cerebral hemisphere with an advantage if the hemisphere is specialised in processing the type of information transmitted. An advantage in weight discrimination may result for the hand from which information is projected to the hemisphere subserving spatial processing. This would result in the surprising finding of most right handers performing better with their non-preferred hand. 2) It has been found that information originating from a spatial field is projected to the contralateral cerebral hemisphere. An advantage may result for both hands projecting information from the hemispace contralateral to the hemisphere subserving spatial processing. This would result in the surprising finding of right handers performing better with their right hand on the left hand side of their body.

Sixty undergraduate students acted as subjects, 28 male and 32 female, in an experiment measuring DLs for lifted weights. Hand preference was measured using the Edinburgh Handedness Inventory and ear preference was measured using a

Dichotic Listening Test. Subjects discriminated between weights with both right and left hands in right and left hemispace.

As found in previous chapters, the TOE was negative, with more second heavier responses being given and left handed subjects were found to be better than right handed subjects with both hands. Evidence to support both the neural transmission model of Kimura and the hemispace hypothesis of Bradshaw was found. An advantage for both hands was found in the spatial field contralateral to the spatial processing hemisphere for both male and female subjects. The difference in performance between right and left hands in left and right hemispace was more pronounced in male subjects. This probably reflects the fact that females are less lateralised than males. Left handers were found to be better than right handers at weight discrimination confirming the truth in the observation made about a regiment of left handers in Benjamin's army who could "sling stones at an hair breadth and not miss" (Judges, XX, 16).

CHAPTER 8: GENERAL DISCUSSION

It has often been said that any advancement in scientific knowledge can only occur if the equipment or technology is available. This is certainly true in the realm of weight discrimination. For the last 150 years the measurement of DLs for lifted weights has been a tedious and time consuming business. Only with the introduction of a simple paper and pencil self-test apparatus could the investigation of weight discrimination in "unusual" environments take place. Now this situation has been taken one step further. The combination of computer generated sequential tracking procedures and the automatic presentation of stimuli has allowed laboratory based research into weight discrimination to advance one more step.

8.1 Apparatus

The human ability to discriminate between discrete objects on the basis of their weight was measured quickly and efficiently using microcomputer generated sequential tracking procedures (UDTRs) to calculate differential thresholds (DLs). In the experimental procedure described in Chapter 3 the experimenter presented the weights to subjects and recorded the subjects' responses via the computer keyboard. The time taken to measure DLs was very similar to the time taken in previous studies which used the manual presentation of weights and computer generated UDTRs (Brodie & Ross, 1984; Brodie & Ross, 1985). It was considerably more efficient than other procedures for measuring DLs such as the method of constant stimuli. An even greater saving in time was made when the stimulus weights were presented automatically by computer controlled turntables and the subject input his or her reponses via push-buttons. In the experimental procedures described in Chapters 4 and 5, up to 6 DLs were measured in about an hour. In keeping with the findings of Corwin, Kintz & Beaty (1979) 1/6 fewer trials were required than with the method of constant stimuli with a commensurate saving in time. In the experimental procedure described in Chapter 7 the maximum number of trials per threshold was reduced from 48 to 24 as reliablity of DLs in each time-order error (TOE) condition was not of paramount importance. The DLs for each hand were calculated from the average of standard first and standard second presentations. This did not appear to result in any loss of reliablity as the direction of the TOE was still strongly negative; the direction found in all the other experimental chapters.

The use of the apparatus was not entirely unproblematic. For example, the brake shoe lining wore down unevenly in the course of testing. This occasionally resulted in some stimulus weights not stopping in the centre of the opening. When this happened subjects were confronted with a choice of two weights. An extra response button was introduced to overcome the problem of subjects not knowing which weight to lift. Subjects were instructed to press this button when in doubt over which weight to lift. Once the button was pressed the program repeated the presentation of the stimulus pair. The use of stepper motors would have eliminated the need for a braking system, the need for continual maintenance and most importantly, the possibility of presenting the wrong stimulus weight.

8.2 DLs and movements of the the upper limb

Davis (1974) argued that the force required to lift objects varied with the effective lever length of the upper limb. He found that objects lifted with a short effective lever length felt lighter than those lifted with a long effective lever length. However, Davis made a conceptual error in reducing weight discrimination to the discrimination of force by reference to a "sense of effort" (See Chapter 1). In Chapter 3 different methods of lifting the stimulus weights were adopted in order to investigate peripheral factors in weight discrimination and the direction of the time-order error at three stimulus intensities. This was done by measuring DLs at three different locations of the upper limb in both passive and active discrimination. The lifting movement for each pair of stimuli used the same effective lever length. The biomechanical factor (differential input to the arm system in the form of a motor command) advocated by Davis as the prime determinant of weight perception cannot account for the differences found in sensitivity using different lifting movements and at different stimulus intensities. However the differences can be accounted for in peripheral terms without assuming that the psychometric response curve bears a direct relationship to receptor output. The shoulder-as-fulcrum lifting movement facilitated discrimination at 200 g, the elbow-as-fulcrum lifting movement facilitated discrimination at 50 g and no movement facilitated discrimination at 5 g. Within the feedback loop subserving arm movement and thus weight discrimination, the weight of the object may only be registered relative to the operational parameters within which the receptors of any one muscle group normally operate. The deltoid muscle group was found to be most sensitive at 200 g and the biceps muscle at 50 g. If the stimulus intensity is above or below these parameters then discrimination will not be optimal. This was found by Brown (1910) to be the case with a shoulder-as-fulcrum arm movement

Thus Fechner (1860) may well have been right when he suggested that different methods of lifting may affect discrimination; not because the constant factor of arm weight interfered in some way but because of the complexity of interactions between separate muscle groups and arm segments. Further evidence for such a hypothesis is provided by Brodie & Ross (1985). They found that lifting and jiggling gave lower DLs than lifting and holding when using a shoulder-as-fulcrum lifting movement to discriminate between two weights. One possible explanation of this phenomenon is that the receptors in muscles and joints of the arm segments distal to the shoulder, the hand and the forearm, do not engage in signalling the weight of the object when they are kept rigid in the non-jiggling condition. In the jiggling condition these segments are brought into play in an active way thus allowing additional receptor activity to result in finer discrimination.

8.3 The validity of hand-preference questionnaires

Asymmetries have been found to exist between the hands for various sensory and motor activities and in this thesis weight discrimination has been shown to be no exception. However the relationship between hand preference as measured by a questionnaire and performance in a wide variety of tasks is not a simple one (Hicks & Kinsbourne, 1978; Porac & Coren, 1981). In this thesis significant biases were found to exist in two-handed paradigms with weights presented to left and right hands but no significant correlations were found to exist between hand preference and the direction of the bias. Correlations between hand preference, as measured by the Edinburgh Handedness Inventory (EHI), and DLs in one-handed discrimination paradigms for right and left hands were not significant. That is, subjects displaying a strong hand preference did not obtain low DLs with their preferred hand and high DLs with their non-preferred hand.

These findings probably reflect the inadequacy of hand-preference questionnaires in ascertaining differential cerebral functioning (Satz, 1977; Beaumont, 1983). It is now well documented (Milner, 1974; Hicks & Kinsbourne, 1978) that right and left handed populations display differential cerebral lateralisation of certain functons. Left handers do not necessarily display the opposite pattern of hemispheric lateralisation from right handers. Differences in the performance of groups selected on the basis of hand preference cannot be attributed to cerebral organisation, as handedness does not simply reflect cerebral organisation.

However the superiority of the motor and sensory pathways to and from the preferred hand (Witelson, 1980) may explain subtle performance differences in activities requiring the complex interaction of efference and afference. An overall preferred hand advantage was found for weight discrimination in this thesis (Chapter 7). Bowers & Heilman (1980) did not find an overall preferred hand effect in a tactile line bisection task. However they did not take account of the finding that only 90% of the right handed population have language lateralised to the left cerebral hemisphere.

8.4 Sex differences

Sex differences were found in both one and two-handed discrimination paradigms. In two-handed weight discrimination (Chapters 4 & 6) male subjects found weights lighter in their right hand and females found weights heavier in their right hand irrespective of hand preference. In one-handed discrimination (Chapter 7) manual performance asymmetries were less pronounced for females than for males. For example, there was less difference between DLs in left and right hemispace for female subjects than for male subjects.

Failure to take account of sex differences may have resulted in the null finding of Shen (1935). The use of male subjects in Shen (1936) resulted in an incomplete picture of manual asymmetry. Given that females are probably less lateralised in function than males (De Renzi, 1982) research that does not account for sex differences in sensorimotor paradigms must be questioned.

8.5 The superiority of left handed subjects

One of the main effects to emerge in this thesis (Chapters 5 & 7) was that left handed subjects performed better than right handed subjects with both right and left hands. A tentative explanation was given in terms of cerebral organisation; left handed subjects having a neural transmission advantage with pathways from the preferred hand to the spatial processing hemisphere occuring for a larger proportion of the population. However this explanation assumes that the percentage of right handed subjects with a left ear advantage is 90%, following Milner (1974). Amongst the student population tested in the experiment described in Chapter 7 the proportion of right handed subjects displaying a left ear advantage was greater than 50%. A dichotic listening test was not performed upon the subjects whose results are reported in Chapter 5. Whether they were more representative of the general population is open to question.

8.6 Attentional factors in weight discrimination

The biases of space and time introduced in two-handed weight discrimination were investigated in terms of attentional factors. Contrary to previous findings it was found that performance was worse with two-handed consecutive weight discrimination than with two-handed simultaneous weight discrimination.

More interestingly the results of the two-handed weight discrimination paradigm may be viewed in terms of current motor skills models of two hand co-ordination (Wing, 1982; Kelso *et al*, 1983; Peters, 1985). Communication between the two hemispheres can only occur optimally if the comparison to be performed occurs at similar levels in the hierarchy of representations. This can explain why two-handed simultaneous discrimination, although poor, is better than two-handed consecutive discrimination.

Attention must be directed to either the higher level of representation which co-ordinates two handed movements to control and respond to what the two hands are doing or to either of the lower level of representations to control and respond to what one hand is doing. The importance of attentional factors in experiments investigating the interaction of hand or hemispace was also emphasised by Bradshaw (1985).

8.7 Neural transmission and spatial field advantages in weight discrimination

It has been found that motor and sensory channels project contralaterally to and from the hand to the cerebral hemisphere with an advantage if the hemisphere is specialised in processing the type of information transmitted (Kimura, 1961). It has been found that information originating from a spatial field is projected to the contralateral cerebral hemisphere (Bowers & Heilman, 1980; Bradshaw et al, 1983 a & b).

Evidence to support a synthesis of both the neural transmission model of Kimura and the hemispace hypothesis of Bradshaw was found in this thesis. An advantage for both hands was found in the spatial field contralateral to the spatial processing hemisphere for both male and female subjects. The difference in performance between right and left hands in left and right hemispace was more pronounced in male subjects. This probably reflects the fact that females are less lateralised than males. Left handers were found to be better than right handers at weight discrimination confirming the truth in the observation made about a regiment of left handers in Benjamin's army who could "sling stones at an hair breadth and not miss" (Judges, XX, 16). An adequate conceptualisation of weight perception can now be reached. It can be conceived of as a manipulospatial activity subserved by mechanisms processing information about the movement of the upper limbs in time and space. Weight perception is not subserved solely by sensory input channels nor is it subserved solely by motor output monitoring. Weight perception is the result of complex high level integrative activities.

8.8 Populational effects

Annett (1978) has suggested that there would be a higher proportion of left handers amongst a university population. This suggestion has been validated in this study. The proportion of left handers amongst the general population is 10%. The proportion of left handers amongst the first year psychology students has been found to be more than 10%. For example, in 1982 when the data for Chapter 4 were gathered there were 242 students in first year with at least 27 being left handed and used as subjects. In 1983 when the data for Chapter 5 were gathered there were 141 students of which at least 18 were left handed and used as subjects. This has helped in the collection of data from a large number of left handers without recourse to volunteers. Psychology undergraduates at Stirling are required to act as subjects as a course requirement.

In addition it was found (Chapter 7) that the right handed subject population was not representative of the general population. In the general population approximately 10% of right handers (Milner, 1974) have language lateralised to the right cerebral hemisphere. The results of the Dichotic Listening Test in Chapter 7 revealed that amongst the right handed students tested, an unusually high proportion had language lateralised to the right cerebral hemisphere. This may well be consistent with the finding that there are more left handers amongst those of higher intellectual ability (Annett, 1978). As left handers are known to be less strongly lateralised, an overall trend towards less strong cerebral lateralisation of function amongst both right and left handers displaying a high IQ may be being reflected.

The use of left handed volunteers is frowned upon (Kilshaw & Annett, 1983) as those with "sinistral" tendencies will predominate. However this would only be harmful if right or left handedness as measured by a handedness inventory was the only criteria used to reflect cerebral organisation. In Chapter 7 of this thesis it was found that amongst an undergraduate population of right handers the distribution of differential lateralisation for language was atypical. This again suited the purposes of the experiment as it ensured sufficient right handers with a right hemisphere advantage for language. Both right and left handed student populations may be unrepresentative of the general population in terms of cerebral laterality. However their performance in weight discrimination must be applicable to the general population once cerebral lateralisation is accounted for.

The findings of this thesis cannot be applied to members of the general population, who appear to be right or left handed according to a handedness questionnaire but who do not appear differentially lateralised when measured on a dichotic listening test. Further study is required to ascertain the relative performance of hand and hemispace of such a group in weight discrimination.

However the majority of the population do display differential cerebral lateralisation of function. The findings of this study suggest that weight discrimination which can be conceived of as a manipulospatial activity resulting from complex high level integrative activities of motor and sensory mechanisms may well be a reliable indicator of the hemisphere in which the processing of manipulospatial information occurs.

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APPENDIX A.1.1

```
1000  REM  TWO RANDOMLY INTERSPERSED UDTR'S
1010  REM  STANDARD FIRST AND STANDARD SECOND
1020  REM  AT THREE STIMULUS INTENSITIES
1030  TEXT : HOME : VTAB 2
1040  INVERSE
1050  PRINT "INSTRUCTIONS TO EXPERIMENTER"
1060  NORMAL
1070  VTAB 4
1080  PRINT "IN THIS EXPERIMENT YOU ARE REQUIRED TO
1090  PRINT "PRESENT TWO WEIGHTS TO SUBJECTS"
1100  PRINT "THEY HAVE TO JUDGE WHICH WEIGHT FELT
        HEAVIER"
1110  VTAB 10
1120  PRINT "THEY HAVE TO LIFT AND LOWER ONE WEIGHT"
1130  PRINT "IN THE MANNER PRESCRIBED EARLIER"
1140  VTAB 14
1150  PRINT "THE STIMULUS WEIGHTS WILL BE"
1160  PRINT "FLASHED UPON THE SCREEN"
1180  VTAB 21: CLEAR
1190  PRINT "PLEASE TYPE IN THE SUBJECTS FIRST NAME"
1200  INPUT "AND PRESS THE RETURN KEY ";NS$
1210  PRINT "PLEASE TYPE IN THE SUBJECTS SURNAME"
1220  INPUT "AND PRESS THE RETURN KEY ";SS$
1230  HOME : INVERSE : PRINT "ATTENTION EXPERIMENTER":
        NORMAL
1240  PRINT "ARE YOU READY TO BEGIN (HIT Y OR N KEY) ?"
1250  GET N$
1260  IF N$ <  > "Y" GOTO 1000
```

```
1270  REM  INPUTING PARAMETERS
1280  DATA          50,2,48,8,56,58
1290  READ X
1300  READ I
1310  READ N
1320  READ C
1330  READ W(1)
1340  READ W(2)
1350 P = 1: REM  CHOOSE WHICH UDTR
1360 L =  RND (1): IF L > 0.5 THEN P = 3 - P
1370  IF P = 2 THEN  GOTO 1420
1380  IF N(1) >  = N OR (S(1) >  = C AND V(1) >  = C)
        THEN  GOTO 1400
1390  GOTO 1460
1400 P = 2
1410  IF N(2) >  = N OR (S(2) >  = C AND V(2) >  = C)
        THEN  GOTO 2530
1420  IF N(2) >  = N OR (S(2) >  = C AND V(2) >  = C)
        THEN  GOTO 1440
1430  GOTO 1460
1440 P = 1
1450  IF N(1) >  = N OR (S(1) >  = C AND V(1) >  = C)
        THEN  GOTO 2530
1460 N(P) = N(P) + 1
1470  IF P = 1 THEN  GOSUB 1770
1480  IF P = 2 THEN  GOSUB 2150
1490 OLDW(P) = W(P)
1500  VTAB 20
1510  PRINT "TYPE F IF THE FIRST WEIGHT WAS HEAVIER"
```

```
1520  PRINT "TYPE S IF THE SECOND WEIGHT WAS HEAVIER"
1530  GET A$(P)
1540  IF A$(P) <  > "F" AND A$(P) <  > "S" THEN  GOTO
        1510
1550  IF A$(P) = "F" AND P = 1 THEN R(P) =  - 1
1560  IF A$(P) = "F" AND P = 2 THEN R(P) = 1
1570  IF A$(P) = "S" AND P = 1 THEN R(P) = 1
1580  IF A$(P) = "S" AND P = 2 THEN R(P) =  - 1
1590  IF W(P) = X THEN R(P) =  - 1
1600  IF W(P) = X + 6 * (I) THEN R(P) = 1
1610 R$(P) =  STR$ (R(P))
1620 RT$(P) = R$(P) + RT$(P)
1630  IF R(P) =  - 1 THEN W(P) = OLDW(P) + I
1640  IF R(P) = 1 AND AR(P) =  - 1 THEN W(P) = OLDW(P)
1650  IF VOLDW(P) = OLDW(P) THEN  GOTO 1670
1660  IF VOLDW(P) <  > OLDW(P) THEN  GOTO 1680
1670  IF R(P) = 1 AND AR(P) = 1 THEN W(P) = OLDW(P) -
        I: GOTO 1690
1680  IF R(P) = 1 AND AR(P) = 1 THEN W(P) = OLDW(P)
1690  IF VOLDW(P) > VVOLDW(P) AND OLDW(P) > W(P) THEN
        S(P) = S(P) + 1
1700  IF VOLDW(P) > VVOLDW(P) AND OLDW(P) > W(P) THEN
        SS(P) = SS(P) + OLDW(P)
1710  IF OLDW(P) < W(P) AND OLDW(P) < VVOLDW(P) THEN
        V(P) = V(P) + 1
1720  IF OLDW(P) < W(P) AND OLDW(P) < VVOLDW(P) THEN
        SV(P) = SV(P) + OLDW(P)
1730 AR(P) = R(P)
1740 VVOLDW(P) = VOLDW(P)
```

```
1750 VOLDW(P) = OLDW(P)
1760  GOTO 1350
1770 Q =  INT ( RND (1) * 7): REM  RANDOMLY SELECTING
        STANDARD FROM 7
1780  IF Q > 6 THEN  GOTO 1770
1790  IF Q = 0 THEN SW$ = "3"
1800  IF Q = 1 THEN SW$ = "6"
1810  IF Q = 2 THEN SW$ = "9"
1820  IF Q = 3 THEN SW$ = "12"
1830  IF Q = 4 THEN SW$ = "14"
1840  IF Q = 5 THEN SW$ = "15"
1850  IF Q = 6 THEN SW$ = "18"
1860  HOME : VTAB 10
1870  PRINT "PRESENT WEIGHT ";SW$;" FIRST"
1880  FOR T = 0 TO 2000: NEXT T
1890  VTAB 12: PRINT "REMOVE WEIGHT"
1900  FOR T = 0 TO 2000: NEXT T
1910 F =  RND (1): REM   RANDOMLY S
        ELECTING FROM 2 POSSIBLE COM
        PARISON WEIGHTS
1920  IF F > 0.5 THEN  GOTO 2020
1930  IF W(1) = X THEN CW$ = "19"
1940  IF W(1) = X + I THEN CW$ = "17"
1950  IF W(1) = (X + 2 * I) THEN CW$ = "20"
1960  IF W(1) = (X + 3 * I) THEN CW$ = "7"
1970  IF W(1) = (X + 4 * I) THEN CW$ = "10"
1980  IF W(1) = (X + 5 * I) THEN CW$ = "11"
1990  IF W(1) = (X + 6 * I) THEN CW$ = "16"
2000  GOTO 2080
```

A.1.1 CONTINUED

```
2010  IF W(1) = X THEN CW$ = "21"
2020  IF W(1) = X + I THEN CW$ = "4"
2030  IF W(1) = (X + 2 * I) THEN CW$ = "5"
2040  IF W(1) = (X + 3 * I) THEN CW$ = "8"
2050  IF W(1) = (X + 4 * I) THEN CW$ = "13"
2060  IF W(1) = (X + 5 * I) THEN CW$ = "2"
2070  IF W(1) = (X + 6 * I) THEN CW$ = "1"
2080 TCW$(P) = CW$ + TCW$(P)
2090  VTAB 15
2100  PRINT "PRESENT WEIGHT ";CW$;", "
2110  FOR S = 0 TO 2000: NEXT S
2120  VTAB 17: PRINT "REMOVE WEIGHT"
2130  FOR S = 0 TO 1000: NEXT S
2140  RETURN
2150 G =  RND (1): REM  SAME AGAIN FOR SECOND WEIGHT
2160  IF G > 0.5 THEN  GOTO 2260
2170  IF W(2) = X THEN CW$ = "21"
2180  IF W(2) = X + I THEN CW$ = "4"
2190  IF W(2) = (X + 2 * I) THEN CW$ = "5"
2200  IF W(2) = (X + 3 * I) THEN CW$ = "8"
2210  IF W(2) = (X + 4 * I) THEN CW$ = "13"
2220  IF W(2) = (X + 5 * I) THEN CW$ = "2"
2230  IF W(2) = (X + 6 * I) THEN CW$ = "1"
2240  GOTO 2320
2250  IF W(2) = X THEN CW$ = "19"
2260  IF W(2) = X + I THEN CW$ = "17"
2270  IF W(2) = (X + 2 * I) THEN CW$ = "20"
2280  IF W(2) = (X + 3 * I) THEN CW$ = "7"
2290  IF W(2) = (X + 4 * I) THEN CW$ = "10"
```

A.1.1 CONTINUED

```
2300  IF W(2) = (X + 5 * I) THEN CW$ = "11"
2310  IF W(2) = (X + 6 * I) THEN CW$ = "16"
2320 TCW$(P) = CW$ + TCW$(P)
2330  HOME : VTAB 10
2340  PRINT "PRESENT WEIGHT ";CW$;" FIRST"
2350  FOR S = 0 TO 2000: NEXT S
2360  VTAB 12: PRINT "REMOVE WEIGHT"
2370  FOR S = 0 TO 2000: NEXT S
2380 Q =  INT ( RND (1) * 7)
2390  IF Q > 6 THEN  GOTO 2380
2400  IF Q = 0 THEN SW$ = "3"
2410  IF Q = 1 THEN SW$ = "6"
2420  IF Q = 2 THEN SW$ = "9"
2430  IF Q = 3 THEN SW$ = "12"
2440  IF Q = 4 THEN SW$ = "14"
2450  IF Q = 5 THEN SW$ = "15"
2460  IF Q = 6 THEN SW$ = "18"
2470  VTAB 15
2480  PRINT "PRESENT WEIGHT ";SW$
2490  FOR T = 0 TO 2000: NEXT T
2500  VTAB 17: PRINT "REMOVE WEIGHT"
2510  FOR T = 0 TO 1000: NEXT T
2520  RETURN
2530  HOME : PRINT "END OF TEST ";NS$
2540  FOR P = 1 TO 2
2550 DL(P) = ((SS(P) / S(P) + SV(P) / V(P)) / 2) - X
2560 REVERSALS(P) = S(P) + V(P)
2570  NEXT P
2580 NS$ = NS$ + SS$ +  STR$ (X)
```

A.1.1 CONTINUED

```
2590 D$ =  CHR$ (4)
2600  PRINT D$;"OPEN";NS$
2610  PRINT D$;"DELETE";NS$
2620  PRINT D$;"OPEN";NS$
2630  PRINT D$;"WRITE";NS$
2640  FOR P = 1 TO 2
2650  PRINT " D L ";P"= ";DL(P)
2660  PRINT "NO OF REVERSALS=";REVERSALS(P)
2670  PRINT "NO OF TRIALS=";P"= ";N(P)
2680  PRINT "RESPONSES";P"= ";RT$(P)
2690  PRINT "SI'S ";P"= "TCW$(P)
2700  NEXT P
2710  PRINT D$;"CLOSE";NS$
```

APPENDIX A.1.2

```
10  REM  RIGHT HAND ONLY P(1)=STANDARD FIRST,
       P(2)=STANDARD SECOND
20  REM       SETTING PORTS.
30  LET A =  - 15102
40  LET B =  - 15103
50  LET C =  - 15104
60  LET D =  - 14976
70  LET E =  - 14973
80  LET F =  - 14975
90  REM  BRAKE AND MOTOR OFF
100  POKE A,255
110  POKE C,0
120  REM  VARIABLES FOR TWO RANDOMLY INTERSPERSED
       UDTR'S
130  DATA           50,2,48,8,56,58
140  READ Z
150  READ I
160  READ N
170  READ U
180  READ W(1)
190  READ W(2)
200  GOSUB 1230
210 P = 1: REM  CHOOSE WHICH UDTR
220 O =  RND (1): IF O > 0.5 THEN P = 3 - P
230  IF P = 2 THEN  GOTO 280
240  IF N(1) >  = N OR (S(1) >  = U AND V(1) >  = U)
       THEN  GOTO 260
250  GOTO 330
```

A.1.2 CONTINUED

```
260 P = 2
270  IF N(2) >  = N OR (S(2) >  = U AND V(2) >  = U)
        THEN  GOTO 530
280  IF N(2) >  = N OR (S(2) >  = U AND V(2) >  = U)
        THEN  GOTO 300
290  GOTO 330
300 P = 1
310  IF N(1) >  = N OR (S(1) >  = U AND V(1) >  = U)
        THEN  GOTO 530
330 N(P) = N(P) + 1
340 OLDW(P) = W(P)
350  IF P = 1 THEN  GOSUB 600
360  IF P = 2 THEN  GOSUB 630
370  IF A(P) =  - 1 THEN W(P) = OLDW(P) + I
380  IF A(P) = 1 AND OA(P) =  - 1 THEN W(P) = OLDW(P)
390  IF VOLDW(P) = OLDW(P) THEN  GOTO 410
400  IF VOLDW(P) <  > OLDW(P) THEN  GOTO 420
410  IF A(P) = 1 AND OA(P) = 1 THEN W(P) = OLDW(P) - I:
         GOTO 425
420  IF A(P) = 1 AND OA(P) = 1 THEN W(P) = OLDW(P)
425  IF P = 1 AND N(1) < 6 THEN  GOTO 470
426  IF P = 2 AND N(2) < 6 THEN  GOTO 470
430  IF VOLDW(P) > VVOLDW(P) AND OLDW(P) > W(P) THEN
        S(P) = S(P) + 1
440  IF VOLDW(P) > VVOLDW(P) AND OLDW(P) > W(P) THEN
        SS(P) = SS(P) + OLDW(P)
450  IF OLDW(P) < W(P) AND OLDW(P) < VVOLDW(P) THEN
        V(P) = V(P) + 1
460  IF OLDW(P) < W(P) AND OLDW(P) < VVOLDW(P) THEN
        SV(P) = SV(P) + OLDW(P)
```

A.1.2 CONTINUED

```
470 OA(P) = A(P)

480 VVOLDW(P) = VOLDW(P)

490 VOLDW(P) = OLDW(P)

500  IF N(1) >  = N AND N(2) >  = N THEN  GOTO 530

510  IF S(1) < U OR S(2) < U OR V(1) < U OR V(2) < U
        THEN  GOTO 210

520  HOME

530  VTAB 8: PRINT "END OF TEST"

540  GOSUB 1410

550  HOME

560  PRINT "ASK EXPERIMENTER FOR NEXT TEST"

570  FOR PT = 1 TO 1000: NEXT PT

580  RESTORE : CLEAR

590  GOTO 20

592  HOME : PRINT "DO NOT LIFT WEIGHT YET"

594  VTAB 18: PRINT "IF YOU CANNOY LIFT A WEIGHT
        EASILY"

596  PRINT "PRESS RED BUTTON"

600 Y =  INT ( RND (1) * 3) + 5

610  IF 5 < Y > 7 GOTO 600

620  GOTO 740

630  HOME : PRINT "DO NOT LIFT WEIGHT YET"

640  VTAB 18: PRINT "IF YOU CANNOT LIFT A WEIGHT
        EASILY"

650  PRINT "PRESS RED BUTTON"

660  IF W(P) = Z + I THEN Y = 12

670  IF W(P) = Z + 2 * (I) THEN Y = 13

680  IF W(P) = Z + 3 * (I) THEN Y = 15

690  IF W(P) = Z + 4 * (I) THEN Y = 14
```

A.1.2 CONTINUED

```
700  IF W(P) = Z + 5 * (I) THEN Y = 10
710  IF W(P) = Z + 6 * (I) THEN Y = 11
720  IF W(P) = Z + 7 * (I) THEN Y = 9
740  POKE C,1
750 X =  PEEK (B)
760  IF X = Y GOTO 740
770  FOR K = 0 TO 1000
780  NEXT K
790 X =  PEEK (B)
800  IF X <  > Y THEN  GOTO 790
810  POKE C,0
820  POKE C,2
830  FOR M = 0 TO 200
840  NEXT M
850  POKE C,0
860  HOME
870  FOR TL = 1 TO 100
880  VTAB 1: PRINT "LIFT THE WEIGHT NOW ";NS$
890  NEXT TL
900  FOR TD = 1 TO 100
910  VTAB 4: PRINT "LOWER THE WEIGHT NOW ";NS$
920  NEXT TD
930  POKE E,0
940  IF Y < 8 AND P = 2 THEN  GOTO 1050
950  IF Y > 8 AND P = 1 THEN  GOTO 1050
960  VTAB 10
970  PRINT "PRESS BUTTON 2 FOR NEXT WEIGHT"
990 M =  PEEK (F)
1000  IF M = 4 THEN  GOTO 350
```

A.1.2 CONTINUED

```
1010  IF M <  > 2 THEN  GOTO 960
1030  IF P = 1 THEN  GOTO 630
1040  IF P = 2 THEN  GOTO 600
1050  HOME : VTAB 8
1060  PRINT "PRESS BUTTON 1 IF THE"
1070  VTAB 9: PRINT "FIRST WEIGHT WAS HEAVIER"
1080  VTAB 11
1090  PRINT "PRESS BUTTON 2 IF THE"
1100  VTAB 12: PRINT "SECOND WEIGHT WAS HEAVIER"
1110 Q =  PEEK (F): IF Q = 0 THEN  GOTO 1110
1130  HOME : PRINT "DO NOT LIFT WEIGHT YET"
1140  IF Q = 2 AND P = 2 THEN A(P) =  - 1
1150  IF Q = 1 AND P = 2 THEN A(P) =  + 1
1160  IF Q = 2 AND P = 1 THEN A(P) =  + 1
1170  IF Q = 1 AND P = 1 THEN A(P) =  - 1
1180  IF W(P) = Z + I THEN A(P) =  - 1
1190  IF W(P) = Z + 7 * (I) THEN A(P) = 1
1200 R$(P) =  STR$ (A(P))
1210 RT$(P) = R$(P) + RT$(P)
1220  RETURN
1230  TEXT : INPUT "PLEASE GIVE YOUR FIRST NAME ";NS$
1240  INPUT "PLEASE GIVE YOUR SURNAME ";SS$
1250  HOME
1260  INVERSE : VTAB 2: PRINT "INSTRUCTIONS": NORMAL
1270  VTAB 4: PRINT "1.IN THIS EXPERIMENT YOU ARE
        REQUIRED"
1280  VTAB 6: PRINT "TO LIFT THE TWO WEIGHTS PRESENTED"
1290  VTAB 8: PRINT "AND JUDGE WHICH WAS HEAVIER"
1300  VTAB 10: PRINT "2.USE YOUR RIGHT HAND ONLY"
```

```
1310  VTAB 12: PRINT "TO LIFT THE WEIGHTS"
1320  VTAB 14: PRINT "3.LIFT THE WEIGHTS WHEN
        INSTRUCTED"
1330  VTAB 16: PRINT "4.LIFT THE WEIGHT TILL YOU HIT
        THE BAR"
1340  VTAB 18: PRINT "THEN LOWER IT WHEN INSTRUCTED"
1350  NORMAL : VTAB 22
1360  INVERSE : PRINT "ATTENTION ";NS$: NORMAL
1370  PRINT "IF YOU ARE READY TO BEGIN ASK THE "
1380  PRINT "EXPERIMENTER TO START THE EXPERIMENT"
1390  GET N$: HOME : VTAB 2: PRINT "DO NOT LIFT
        WEIGHTS YET"
1400  RETURN
1410 THRESHOLD(1) = (SS(1) / S(1) + SV(1) / V(1)) / 2
1420 THRESHOLD(2) = (SS(2) / S(2) + SV(2) / V(2)) / 2
1430 REVERSALS(1) = S(1) + V(1)
1440 REVERSALS(2) = S(2) + V(2)
1450  LET NS$ = NS$ + SS$
1460 D$ =  CHR$ (4)
1470  PRINT D$;"OPEN";NS$
1480  PRINT D$;"DELETE";NS$
1490  PRINT D$;"OPEN";NS$
1500  PRINT D$;"WRITE";NS$
1510  PRINT "THRESHOLD(1)=";THRESHOLD(1)
1520  PRINT "THRESHOLD(2)=";THRESHOLD(2)
1530  PRINT "NO OF REVERSALS=";REVERSALS(1)
1540  PRINT "NO OF REVERSALS=";REVERSALS(2)
1550  PRINT "NO OF TRIALS(1)=";N(1)
1560  PRINT "NO OF TRIALS(2)=";N(2)
```

A.1.2 CONTINUED

```
1570  PRINT "RESPONSES(1)=";RT$(1)
1580  PRINT "RESPONSES(2)=";RT$(2)
1590  PRINT D$;"CLOSE";NS$
1600  RETURN
```

APPENDIX A.1.3

```
10  REM     SETTING PORTS.    BRAKE AND MOTOR OFF.
20  LET A =  - 15102
30  LET B =  - 15103
40  LET C =  - 15104
50  LET D =  - 14976
60  LET E =  - 14973
70  LET F =  - 14975
80  POKE A,255
90  POKE C,0
100  GOSUB 1230
110  DATA          50,2,48,8,56,58
120  READ Z
130  READ I
140  READ N
150  READ U
160  READ W(1)
170  READ W(2)
175  IF HQ$ = "L" THEN W(1) = W(1) + I
180  IF HQ$ = "L" THEN W(2) = W(2) - I
190 P = 1: REM  CHOOSE WHICH UDTR
200 O =  RND (1): IF O > 0.5 THEN P = 3 - P
210  IF P = 2 THEN  GOTO 260
220  IF N(1) >  = N OR (S(1) >  = U AND V(1) >  = U)
       THEN  GOTO 240
230  GOTO 300
240 P = 2
250  IF N(2) >  = N OR (S(2) >  = U AND V(2) >  = U)
       THEN  GOTO 500
```

A.1.3 CONTINUED

```
260  IF N(2) >  = N OR (S(2) >  = U AND V(2) >  = U)
       THEN  GOTO 280
270  GOTO 300
280 P = 1
290  IF N(1) >  = N OR (S(1) >  = U AND V(1) >  = U)
       THEN  GOTO 500
300 N(P) = N(P) + 1
310 OLDW(P) = W(P)
320  IF P = 1 THEN  GOSUB 570
330  IF P = 2 THEN  GOSUB 690
340  IF A(P) =  - 1 THEN W(P) = OLDW(P) + I
350  IF A(P) = 1 AND OA(P) =  - 1 THEN W(P) = OLDW(P)
360  IF VOLDW(P) = OLDW(P) THEN  GOTO 380
370  IF VOLDW(P) <  > OLDW(P) THEN  GOTO 390
380  IF A(P) = 1 AND OA(P) = 1 THEN W(P) = OLDW(P) - I:
        GOTO 395
390  IF A(P) = 1 AND OA(P) = 1 THEN W(P) = OLDW(P)
395  IF P = 1 AND N(1) < 6 THEN  GOTO 440
396  IF P = 2 AND N(2) < 6 THEN  GOTO 440
400  IF VOLDW(P) > VVOLDW(P) AND OLDW(P) > W(P) THEN
       S(P) = S(P) + 1
410  IF VOLDW(P) > VVOLDW(P) AND OLDW(P) > W(P) THEN
       SS(P) = SS(P) + OLDW(P)
420  IF OLDW(P) < W(P) AND OLDW(P) < VVOLDW(P) THEN
       V(P) = V(P) + 1
430  IF OLDW(P) < W(P) AND OLDW(P) < VVOLDW(P) THEN
       SV(P) = SV(P) + OLDW(P)
440 OA(P) = A(P)
450 VVOLDW(P) = VOLDW(P)
```

A.1.3 CONTINUED

```
460 VOLDW(P) = OLDW(P)
470  IF N(1) >  = N AND N(2) >  = N THEN  GOTO 490
480  IF S(1) < U OR S(2) < U OR V(1) < U OR V(2) < U
       THEN  GOTO 190
490  HOME
500  VTAB 8: PRINT "END OF TEST"
510  GOSUB 1410
520  HOME
530  PRINT "ASK EXPERIMENTER FOR NEXT TEST"
540  FOR PT = 1 TO 1000: NEXT PT
550  RESTORE : CLEAR
560  GOTO 10
570  HOME : PRINT "DO NOT LIFT WEIGHTS YET"
580  VTAB 18: PRINT "IF YOU CANNOT LIFT EITHER WEIGHT
       EASILY"
590  PRINT "PRESS RED BUTTON"
600 Y =  INT ( RND (1) * 3) + 5
605  IF 5 < Y > 7 THEN  GOTO 600
610  IF W(1) = Z + I THEN H = 12
620  IF W(1) = Z + 2 * (I) THEN H = 13
630  IF W(1) = Z + 3 * (I) THEN H = 15
640  IF W(1) = Z + 4 * (I) THEN H = 14
650  IF W(1) = Z + 5 * (I) THEN H = 10
660  IF W(1) = Z + 6 * (I) THEN H = 11
670  IF W(1) = Z + 7 * (I) THEN H = 9
680  GOTO 770
690  IF W(2) = Z + I THEN Y = 12
700  IF W(2) = Z + 2 * (I) THEN Y = 13
710  IF W(2) = Z + 3 * (I) THEN Y = 15
```

A.1.3 CONTINUED

```
720  IF W(2) = Z + 4 * (I) THEN Y = 14
730  IF W(2) = Z + 5 * (I) THEN Y = 10
740  IF W(2) = Z + 6 * (I) THEN Y = 11
750  IF W(2) = Z + 7 * (I) THEN Y = 9
760 H =  INT ( RND (1) * 3) + 5
765  IF 5 < H > 7 THEN  GOTO 760
770  POKE C,5
780 X =  PEEK (B)
790  IF X = Y GOTO 770
800 G =  PEEK (D)
810  IF G = H GOTO 770
820  FOR K = 0 TO 1000
830  NEXT K
840 X =  PEEK (B)
850  IF X <  > Y THEN  GOTO 840
860  POKE C,6
870  FOR M = 0 TO 200
880  NEXT M
890  POKE C,4
900 G =  PEEK (D)
910  IF G <  > H THEN  GOTO 900
920  POKE C,8
930  FOR T = 0 TO 200
940  NEXT T
950  POKE C,0
960  POKE E,0
970  HOME
980  FOR TL = 1 TO 100
990  VTAB 2: PRINT "LIFT THE WEIGHTS NOW ";NS$
```

A.1.3 CONTINUED

```
1000  NEXT TL
1010  VTAB 4: FOR TD = 1 TO 100
1020  VTAB 4: PRINT "LOWER THE WEIGHTS NOW "
1030  NEXT TD
1040  VTAB 8
1050  PRINT "PRESS THE LEFT BUTTON IF THE"
1060  VTAB 9: PRINT "LEFT WEIGHT WAS HEAVIER"
1070  VTAB 11
1080  PRINT "PRESS THE RIGHT BUTTON IF THE"
1090  VTAB 12: PRINT "RIGHT WEIGHT WAS HEAVIER"
1100 Q =  PEEK (F): IF Q = 0 THEN  GOTO 1100
1110  IF Q = 4 THEN  GOTO 320
1120  HOME
1130 Q =  PEEK (F): IF Q = 1 OR Q = 2 THEN  PRINT "DO
        NOT LIFT WEIGHTS YET"
1140  IF Q = 2 AND P = 2 THEN A(P) =  - 1
1150  IF Q = 1 AND P = 2 THEN A(P) =  + 1
1160  IF Q = 2 AND P = 1 THEN A(P) =  + 1
1170  IF Q = 1 AND P = 1 THEN A(P) =  - 1
1180  IF W(P) = Z THEN A(P) =  - 1
1190  IF W(P) = Z + 7 * (I) THEN A(P) = 1
1200 R$(P) =  STR$ (A(P))
1210 RT$(P) = R$(P) + RT$(P)
1220  RETURN
1230  TEXT : INPUT "PLEASE GIVE YOUR FIRST NAME ";NS$
1240  TEXT : INPUT "PLEASE GIVE YOUR SURNAME ";SS$
1245  PRINT "WHICH IS YOUR PREFERRED HAND, LEFT OR
        RIGHT?": GET HQ$
1250  IF HQ$ <  > "R" AND HQ$ <  > "L" THEN  GOTO 1245
```

A.1.3 CONTINUED

```
1255  HOME
1260  INVERSE : VTAB 2: PRINT "INSTRUCTIONS": NORMAL
1270  VTAB 4: PRINT "1 IN THIS EXPERIMENT YOU ARE
        REQUIRED"
1280  VTAB 6: PRINT "TO LIFT THE TWO WEIGHTS PRESENTED"
1290  VTAB 8: PRINT "SIMULTANEOUSLY"
1300  VTAB 10: PRINT "2 USE BOTH LEFT AND RIGHT HANDS"
1310  VTAB 12: PRINT "TO LIFT THE WEIGHTS
1320  VTAB 14: PRINT "3 LIFT THE WEIGHTS AT THE SAME
        TIME"
1330  VTAB 16: PRINT "AND IN THE SAME WAY EACH TIME"
1340  VTAB 18: PRINT "4 LIFT WEIGHTS TILL YOU HIT THE
        BAR"
1350  VTAB 20: PRINT "THEN LOWER THEM WHEN INSTRUCTED"
1360  NORMAL : VTAB 22
1370  INVERSE : PRINT "ATTENTION ";NS$: NORMAL
1380  PRINT "INFORM EXPERIMENTER IF READY TO BEGIN"
1390  GET N$: HOME : VTAB 2: PRINT "DO NOT LIFT
        WEIGHTS YET"
1400  RETURN
1410 THRESHOLD(1) = (SS(1) / S(1) + SV(1) / V(1)) / 2
1420 THRESHOLD(2) = (SS(2) / S(2) + SV(2) / V(2)) / 2
1430 REVERSALS(1) = S(1) + V(1)
1440 REVERSALS(2) = S(2) + V(2)
1450  LET NS$ = NS$ + SS$
1460 D$ =  CHR$ (4)
1470  PRINT D$;"OPEN";NS$
1480  PRINT D$;"DELETE";NS$
1490  PRINT D$;"OPEN";NS$
```

A.1.3 CONTINUED

```
1500  PRINT D$;"WRITE";NS$
1505  PRINT "STD RIGHT - 1, STD LEFT - 2"
1510  PRINT "THRESHOLD(1)=";THRESHOLD(1)
1520  PRINT "THRESHOLD(2)=";THRESHOLD(2)
1530  PRINT "NO OF REVERSALS=";REVERSALS(1)
1540  PRINT "NO OF REVERSALS=";REVERSALS(2)
1550  PRINT "NO OF TRIALS(1)=";N(1)
1560  PRINT "NO OF TRIALS(2)=";N(2)
1570  PRINT "RESPONSES(1)=";RT$(1)
1580  PRINT "RESPONSES(2)=";RT$(2)
1590  PRINT D$;"CLOSE";NS$
1600  RETURN
```

A.2 The Edinburgh Handedness Inventory

Surname Given Names Date of Birth

Sex

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

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

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

	LEFT	RIGHT
1 Writing		
2 Drawing		
3 Throwing		
4 Scissors		
5 Toothbrush		
6 Knife (without fork)		
7 Spoon		
8 Broom (upper hand)		
9 Striking Match (match)		
10 Opening box (lid)		

A.3.1 Example of syllable sequence in the dicotic listening test

NUMBER	SIDE OF PRESENTATION		NUMBER	SIDE OF PRESENTATION	
	left	right		left	right
1	BO	DO	31	TO	DO
2	BO	PO	32	PO	DO
3	DO	PO	33	TO	BO
4	BO	PO	34	BO	DO
5	BO	PO	35	PO	TO
6	PO	DO	36	DO	PO
7	DO	TO	37	DO	BO
8	PO	BO	38	PO	BO
9	PO	BO	39	TO	PO
10	DO	TO	40	BO	DO
11	TO	PO	41	TO	DO
12	TO	DO	42	TO	PO
13	DO	BO	43	PO	DO
14	DO	BO	44	TO	BO
15	TO	DO	45	DO	PO
16	DO	TO	46	PO	BO
17	BO	TO	47	BO	PO
18	BO	TO	48	PO	BO
19	TO	BO	49	BO	TO
20	PO	TO	50	DO	PO
21	DO	BO	51	BO	PO
22	TO	BO	52	PO	DO
23	BO	DO	53	BO	DO
24	DO	PO	54	TO	PO
25	DO	BO	55	PO	TO
26	BO	TO	56	DO	TO
27	PO	TO	57	TO	PO
28	PO	TO	58	PO	DO
29	BO	TO	59	TO	BO
30	DO	TO	60	TO	DO

A.3.2 The Dicotic Listening Test Response Sheet

REPONSE SHEET 1   SYLLABLE SEQUENCE

NAME   DATE   SEX

Instructions: 1 Mark your responses in the left hand columns (1-30) first, then the right hand columns (31-60).

2 Circle the syllable you "hear".

1.	BO	DO	PO	TO	31.	BO	DO	PO	TO
2.	BO	DO	PO	TO	32.	BO	DO	PO	TO
3.	BO	DO	PO	TO	33.	BO	DO	PO	TO
4.	BO	DO	PO	TO	34.	BO	DO	PO	TO
5.	BO	DO	PO	TO	35.	BO	DO	PO	TO
6.	BO	DO	PO	TO	36.	BO	DO	PO	TO
7.	BO	DO	PO	TO	37.	BO	DO	PO	TO
8.	BO	DO	PO	TO	38.	BO	DO	PO	TO
9.	BO	DO	PO	TO	39.	BO	DO	PO	TO
10.	BO	DO	PO	TO	40.	BO	DO	PO	TO
11.	BO	DO	PO	TO	41.	BO	DO	PO	TO
12.	BO	DO	PO	TO	42.	BO	DO	PO	TO
13.	BO	DO	PO	TO	43.	BO	DO	PO	TO
14.	BO	DO	PO	TO	44.	BO	DO	PO	TO
15.	BO	DO	PO	TO	45.	BO	DO	PO	TO
16.	BO	DO	PO	TO	46.	BO	DO	PO	TO
17.	BO	DO	PO	TO	47.	BO	DO	PO	TO
18.	BO	DO	PO	TO	48.	BO	DO	PO	TO
19.	BO	DO	PO	TO	49.	BO	DO	PO	TO
20.	BO	DO	PO	TO	50.	BO	DO	PO	TO
21.	BO	DO	PO	TO	51.	BO	DO	PO	TO
22.	BO	DO	PO	TO	52.	BO	DO	PO	TO
23.	BO	DO	PO	TO	53.	BO	DO	PO	TO
24.	BO	DO	PO	TO	54.	BO	DO	PO	TO
25.	BO	DO	PO	TO	55.	BO	DO	PO	TO
26.	BO	DO	PO	TO	56.	BO	DO	PO	TO
27.	BO	DO	PO	TO	57.	BO	DO	PO	TO
28.	BO	DO	PO	TO	58.	BO	DO	PO	TO
29.	BO	DO	PO	TO	59.	BO	DO	PO	TO
30.	BO	DO	PO	TO	60.	BO	DO	PO	TO

A.4.1.1 Analysis of variance summary table (Chapter 3)

SOURCE	SS	d.f.	MS	F	P
P Position	0.82261	2	0.4113	16.42	0.0002*
Error	0.37575	15	0.02505		
I Intensity	10.82108	2	5.41054	261.18	0.0000*
I X P	1.31840	4	0.32960	15.91	0.0000*
Error	0.62148	30	0.02072		
M Method	0.00254	1	0.00254	0.42	0.5283
M X P	0.03386	2	0.01693	2.78	0.0943
Error	0.0915	15	0.00610		
I X M	0.00085	2	0.00042	0.08	0.9234
I X M X P	0.02433	4	0.00608	1.14	0.3462
Error	0.15946	30	0.00532		
O Order	0.12562	1	0.12562	6.87	0.0193*
O X P	0.00468	2	0.00234	0.13	0.8808
Error	0.27448	15	0.01830		
I X O	0.13435	2	0.06717	9.15	0.0008*
I X O X P	0.01066	4	0.00266	0.36	0.8331
Error	0.22031	30	0.00734		
M X O	0.03448	1	0.03448	2.67	0.1233
M X O X P	0.04010	2	0.02005	1.55	0.2443
Error	0.19395	15	0.01293		
I X M X O	0.01338	2	0.00669	0.77	0.4174
I X M X O X P	0.04105	4	0.01026	1.19	0.3365
Error	0.25932	30	0.00864		

* - denotes significant effect discussed in text.

A.4.1.2 Analysis of variance summary table (Chapter 3)

SOURCE	SS	d.f.	MS	F	P
P Position	0.77880	1	0.7880	17.88	0.0017*
Error	0.43547	10	0.04355		
I Intensity	7.03216	2	3.51608	92.40	0.0000*
I X P	0.86250	2	0.43125	11.33	0.0005*
Error	0.76102	20	0.03805		
M Method	0.02859	2	0.01429	1.98	0.1647
M X P	0.02687	2	0.01344	1.86	0.1819
Error	0.14463	20	0.00723		
I X M	0.00786	4	0.00196	0.37	0.8312
I X M X P	0.01268	4	0.00317	0.59	0.6713
Error	0.21457	40	0.00536		
O Order	0.17013	1	0.17013	4.59	0.05
O X P	0.00099	1	0.00099	0.03	0.8774
Error	0.37072	10	0.03707		
I X O	0.18318	2	0.09159	6.15	0.0083
I X O X P	0.00896	2	0.00448	0.03	0.7435
Error	0.29794	20	0.01490		
M X O	0.04446	2	0.02223	2.02	0.1594
M X O X P	0.03878	2	0.01939	1.76	0.1980
Error	0.22062	20	0.01103		
I X M X O	0.01267	4	0.00317	0.44	0.7805
I X M X O X P	0.04285	4	0.01071	1.48	0.2262
Error	0.28941	40	0.00724		

* denotes significant effect discussed in text.

A.4.1.3 Analysis of variance summary table (Chapter 3)

SOURCE	SS	d.f.	MS	F	P
I Intensity	1.48604	2	0.74302	38.45	0.0000*
Error	0.19322	10	0.01932		
M Method	0.01015	2	0.00508	0.87	0.4484
Error	0.05836	10	0.00584		
I X M	0.00392	4	0.00098	0.22	0.9256
Error	0.09019	20	0.00451		
O Order	0.07259	1	0.07259	1.79	0.2382
Error	0.20246	5	0.04049		
I X O	0.11647	2	0.05823	3.04	0.0929
Error	0.19139	10	0.01914		
M X O	0.00344	2	0.00172	0.28	0.7647
Error	0.06246	10	0.00625		
I X M X O	0.00521	4	0.00130	0.42	0.7894
Error	0.06147	20	0.00307		

* denotes significant effect discussed in text.

A.4.1.4 Analysis of variance summary table (Chapter 3)

SOURCE	SS	d.f.	MS	F	P
I Intensity	0.03906	1	0.03906	18.52	0.0077*
Error	0.01054	5	0.00211		
M Method	0.00481	2	0.00240	4.02	0.05*
Error	0.00598	10	0.00060		
I X M	0.00279	2	0.00139	3.11	0.0893
Error	0.00449	10	0.00045		
O Order	0.00054	1	0.00054	0.12	0.7413
Error	0.02212	5	0.00442		
I X O	0.00031	1	0.00031	0.11	0.7576
Error	0.01450	5	0.00290		
M X O	0.00551	2	0.00276	1.38	0.2959
Error	0.01999	10	0.00020		
I X M X O	0.00034	2	0.00017	0.14	0.8678
Error	0.01190	10	0.00119		

* denotes significant effect discussed in text.

A.4.1.5 Analysis of variance summary table (Chapter 3)

SOURCE	SS	d.f.	MS	F	P
I Intensity	6.40862	2	3.20431	56.43	0.0000*
Error	0.56780	10	0.05678		
M Method	0.04531	2	0.02265	2.63	0.1212
Error	0.08627	10	0.00863		
I X M	0.01661	4	0.00415	0.67	0.6218
Error	0.12438	20	0.00622		
O Order	0.09852	1	0.09852	2.93	0.1477
Error	0.16825	5	0.03365		
I X O	0.07568	2	0.03784	3.55	0.0683
Error	0.10655	10	0.01066		
M X O	0.07980	2	0.03990	2.52	0.1297
Error	0.15816	10	0.01582		
I X M X O	0.05031	4	0.01258	1.10	0.3822
Error	0.22794	20	0.01140		

* denotes significant effect discussed in text.

A.4.1.6 Analysis of variance summary table (Chapter 3)

SOURCE	SS	d.f.	MS	F	P
I Intensity	0.11648	1	0.11648	161.48	0.0001*
Error	0.00361	5	0.00072		
M Method	0.01031	2	0.00515	9.54	0.0048*
Error	0.00540	10	0.00054		
I X M	0.00071	2	0.00036	0.96	0.4162
Error	0.00372	10	0.00037		
O Order	0.01125	1	0.01125	1.70	0.2488
Error	0.03304	5	0.00661		
I X O	0.00798	1	0.00798	12.78	0.0160*
Error	0.00312	5	0.00062		
M X O	0.01029	2	0.00515	2.21	0.1601
Error	0.02326	10	0.00233		
I X M X O	0.00007	2	0.00004	0.01	0.9893
Error	0.03282	10	0.00328		

* denotes significant effect discussed in text.

A.4.1.7 Analysis of variance summary table (Chapter 3)

SOURCE	SS	d.f.	MS	F	P
I Intensity	6.66797	2	3.33399	784.43	0.0000*
Error	0.04250	10	0.00425		
M Method	0.00168	1	0.00168	0.30	0.6076
Error	0.02806	5	0.00561		
I X M	0.01349	2	0.00674	1.23	0.3318
Error	0.05463	10	0.00546		
O Order	0.02369	1	0.02369	3.53	0.1191
Error	0.03357	5	0.00671		
I X O	0.03282	2	0.01641	4.32	0.0443*
Error	0.03795	10	0.00379		
M X O	0.00061	1	0.00061	0.13	0.7345
Error	0.02382	5	0.00476		
I X M X O	0.00433	2	0.00216	0.33	0.7232
Error	0.06461	10	0.00646		

* denotes significant effect discussed in text.

A.4.1.8 Analysis of variance summary table (Chapter 3)

SOURCE	SS	d.f.	MS	F	P
I Intensity	0.08020	1	0.08020	71.39	0.0004*
Error	0.00562	5	0.00112		
M Method	0.00112	1	0.00112	3.98	0.1025
Error	0.00141	5	0.00028		
I X M	0.00003	1	0.00003	0.08	0.7822
Error	0.00187	5	0.00037		
O Order	0.00044	1	0.00044	0.10	0.7634
Error	0.02197	5	0.00439		
I X O	0.00000	1	0.00000	0.00	0.9914
Error	0.01288	5	0.02589		
M X O	0.00007	1	0.00007	0.06	0.8215
Error	0.00620	5	0.00124		
I X M X O	0.00188	1	0.00188	1.42	0.2870
Error	0.00661	5	0.00132		

* denotes significant effect discussed in text.

A.4.1.8 Analysis of variance summary table (Chapter 3)

SOURCE	SS	d.f.	MS	F	P
I Intensity	0.08020	1	0.08020	71.39	0.0004*
Error	0.00562	5	0.00112		
M Method	0.00112	1	0.00112	3.98	0.1025
Error	0.00141	5	0.00028		
I X M	0.00003	1	0.00003	0.08	0.7822
Error	0.00187	5	0.00037		
O Order	0.00044	1	0.00044	0.10	0.7634
Error	0.02197	5	0.00439		
I X O	0.00000	1	0.00000	0.00	0.9914
Error	0.01288	5	0.02589		
M X O	0.00007	1	0.00007	0.06	0.8215
Error	0.00620	5	0.00124		
I X M X O	0.00188	1	0.00188	1.42	0.2870
Error	0.00661	5	0.00132		

* denotes significant effect discussed in text.

A.4.2 Analysis of variance summary table (Chapter 4)

SOURCE	SS	d.f.	MS	F	P
A Sex	0.38295	1	0.38295	0.13	0.7165
B Hand Preference	0.10325	1	0.10325	0.04	0.8504
A X B	1.58253	1	2.87488	0.55	0.4612
Error	160.993	56	2.87488		
P position	23.6800	1	23.6800	1.41	0.2405
P X A	73.7625	1	73.7625	4.38	0.0408*
P X B	28.3615	1	28.3615	1.69	0.1995
P X A X B	5.48294	1	5.48294	0.33	0.5704
Error	942.165	56	16.8244		

* denotes significant effect discussed in text.

A.4.3.1 Analysis of variance summary table (Chapter 5)

SOURCE	SS	d.f.	MS	F	P
S Sex	0.90433	1	0.90433	0.34	0.5620
E Hand preference	13.0469	1	13.0469	4.90	0.0305*
S X E	1.18663	1	1.18663	0.45	0.5067
Error	164.942	62	2.66035		
H Hand	0.61300	1	0.61300	0.40	0.5272
H X S	7.12253	1	7.12253	4.7	0.0341*
H X E	1.11377	1	1.11377	0.73	0.3947
H X S X E	0.15604	1	0.15604	0.10	0.7494
Error	94.0144	62	1.51636		
O Order	181.742	1	181.742	67.32	0.0000*
O X S	1.60743	1	1.60743	0.60	0.4443
O X E	0.03176	1	0.03176	0.01	0.9140
O X S X E	8.00556	1	8.00556	2.97	0.0901
Error	167.380	62	2.69968		
H X O	21.4944	1	21.4944	11.18	0.0014*
H X O X S	4.31411	1	4.31411	2.24	0.1392
H X O X E	9.45341	1	9.45341	4.92	0.0303*
H X O X S X E	0.09905	1	0.09905	0.05	0.8212
Error	119.198	62	1.92254		

* denotes significant effect discussed in text.

A.4.3.2 Analysis of variance summary table (Chapter 5)

SOURCE	SS	d.f.	MS	F	P
S Sex	1.46942	1	1.46942	0.75	0.3897
E Hand Preference	5.12368	1	5.12368	2.62	0.1109
S X E	0.00789	1	0.00789	0.00	0.9496
Error	121.428	62	1.95852		
H Hand	2.64459	2	1.3223	1.12	0.3280
H X S	3.86335	2	1.93167	1.64	0.1975
H X E	2.05195	2	1.02592	0.87	0.4203
H X S X E	2.20884	2	1.10442	0.94	0.3936
Error	145.759	124	1.17548		

* denotes significant effect discussed in text.

A.4.3.3 Analysis of variance summary table (Chapter 5)

SOURCE	SS	d.f.	MS	F	P
S Sex	2.63869	1	2.63869	0.59	0.4438
E Hand Preference	0.19040	1	0.19040	0.04	0.8367
S X E	3.09078	1	3.09078	0.07	0.4074
Error	275.420	62	4.44226		
P Position	2.24060	1	2.24060	0.12	0.7308
P X S	97.0730	1	97.07370	5.17	0.0264*
P X E	5.58587	1	5.58587	0.30	0.5873
P X S X E	38.0100	1	38.0100	2.03	0.1596
Error	1163.15	62	18.7605		

* denotes significant effect discussed in text.

A.4.4 Analysis of variance summary table (Chapter 6)

SOURCE	SS	d.f.	MS	F	P
S Sex	1.19019	1	1.19019	0.28	0.5987
E Hand Preference	1.30154	1	1.30154	0.31	0.5822
S X E	5.32668	1	5.32668	1.25	0.2677
Error	229.352	54	4.24727		
O Order	19.29528	2	9.64764	3.11	0.0485*
O X S	3.78526	2	1.89263	0.61	0.5449
O X E	1.12304	2	0.56152	0.18	0.8346
O X S X E	7.17487	2	3.58743	1.16	0.3182
Error	334.793	108	3.09994		
P Position	27.5918	1	27.59178	0.99	0.3253
P X S	0.60182	1	0.60182	0.002	0.8840
P X E	0.04082	1	0.04082	0.00	0.9607
P X S X E	6.39514	1	6.39514	0.23	0.6347
Error	1512.34	54	28.00639		
O X P	766.162	2	383.081	50.19	0.0000*
O X P X S	41.0465	2	20.52328	2.69	0.0727
O X P X E	1.09669	2	1.09669	0.07	0.9307
O X P X S X E	62.7364	2	31.3682	4.11	0.0190*
Error	824.354	108	7.63291		

* denotes significant effect discussed in text.

A.4.5 Analysis of variance summary table (Chapter 7)

SOURCE	SS	d.f.	MS	F	P
G Sex	15.5284	1	15.5294	2.14	0.1499
H Hand preference	40.1713	1	40.1713	5.52	0.0226*
I Ear preference	2.45208	1	2.45208	0.34	0.5639
G X H	41.7259	1	41.7259	5.74	0.0202*
G X I	0.15652	1	0.15652	0.02	0.8839
H X I	3.07586	1	3.07586	0.42	0.5183
G X H X I	36.7535	1	36.7535	5.05	0.0288*
Error	378.099	52	7.27115		
R Hemispace	0.06218	1	0.06218	0.02	0.8769
R X G	1.28240	1	1.28240	0.50	0.4827
R X H	7.22838	1	7.22838	2.82	0.0993
R X I	85.8899	1	85.8899	33.48	0.0000*
R X G X H	3.33988	1	3.33988	1.30	0.2591
R X G X I	16.7591	1	16.7591	6.53	0.0136*
R X H X I	1.76699	1	1.76699	0.69	0.4104
R X G X H X I	0.24541	1	0.24542	0.10	0.7583
Error	133.417	52	2.25657		
S Hand	7.68465	1	7.68465	2.82	0.0988
S X G	0.29121	1	0.29121	0.11	0.7449
S X H	4.86153	1	4.86153	1.79	0.1871
S X I	3.85787	1	3.85787	1.42	0.2392
S X G X H	8.27065	1	8.27065	3.04	0.0872
S X G X I	0.99913	1	0.99913	0.37	0.5472
S X H X I	4.50140	1	4.50140	1.65	0.2041
S X G X H X I	0.06278	1	0.06278	0.02	0.8799
Error	141.488	52	2.72092		

A.4.5 Analysis of variance summary table (Chapter 7)

R X S	11.0119	1	11.0119	2.56	0.1158
R X S X G	3.57720	1	3.57720	0.83	0.3662
R X S X H	0.27044	1	0.27044	0.06	0.8031
R X S X I	0.36459	1	0.36459	0.08	0.7722
R X S X G X H	1.68292	1	1.68292	0.39	0.5346
R X S X G X I	0.49916	1	0.49916	1.12	0.7349
R X S X H X I	0.82612	1	0.82612	0.19	0.6632
R X S X G X H X I	4.87950	1	4.87950	1.13	0.2920
Error	223.888	52	4.30554		
T Presentation	1157.85	1	1157.85	98.78	0.0000*
T X G	0.81284	1	0.81284	0.07	0.7933
T X H	12.8671	1	12.8671	1.10	0.2996
T X I	0.28353	1	0.28353	0.02	0.8770
T X G X H	27.0491	1	27.0491	2.31	0.1348
T X G X I	69.9997	1	69.9997	5.97	0.0180*
T X H X I	3.53921	1	3.53921	0.30	0.5850
T X G X H X I	36.7139	1	36.7139	3.13	0.0826
Error	609.513	52	11.7214		
R X T	16.7261	1	16.7261	2.94	0.0922
R X T X G	7.89586	1	7.89586	1.39	0.2440
R X T X H	0.27700	1	0.27700	0.05	0.8262
R X T X I	4.28994	1	4.28994	0.75	0.3890
R X T X G X H	3.79974	1	3.79974	0.67	0.4173
R X T X G X I	0.84811	1	0.84811	0.15	0.7009
R X T X H X I	0.0603	1	0.00603	0.00	0.9741
R X T X G X H X I	13.7376	1	13.73762	2.42	0.1261
Error	295.617	52	5.68495		

A.4.5 Analysis of variance summary table cont'd (Chapter 7)

S X T	82.0784	1	82.0784	18.19	0.0001*
S X T X G	0.60829	1	0.60829	0.13	0.7150
S X T X H	3.39328	1	3.39328	0.75	0.3899
S X T X I	0.15146	1	0.15146	0.03	0.8554
S X T X G X H	4.80951	1	4.80951	1.07	0.3067
S X T X G X I	1.11549	1	1.11549	0.25	0.6212
S X T X H X I	0.69639	1	0.69639	0.15	0.6961
S X T X G X H X I	0.74930	1	0.74930	0.17	0.6853
Error	234.690	52	4.51327		
R X S X T	2.30540	1	2.30540	0.69	0.4114
R X S X T X G	5.12659	1	5.12659	1.52	0.2224
R X S X T X H	0.31413	1	0.31413	0.09	0.7611
R X S X T X I	0.57311	1	0.57311	0.17	0.6814
R X S X T X G X H	0.78634	1	0.78634	0.23	0.6307
R X S X T X G X I	8.35139		8.35139	2.48	0.1211
R X S X T X H X I	10.7014	1	10.7014	3.18	0.0802
R X S X T X G X H X I	1.95	1	1.95	0.58	0.4500
Error	174.817	52	3.36188		

* denotes significant effect discussed in text.

A.4.5.1 Analysis of variance summary table (Chapter 7)

SOURCE	SS	d.f.	MS	F	P
E Hand preference	39.9088	1	39.9088	16.33	0.0005*
D Ear preference	0.33373	1	0.33373	0.14	0.7149
E X D	14.8870	1	14.8870	6.09	0.0211*
Error	58.6405	24	2.44335		
S Hemispace	0.19002	1	0.19002	0.12	0.7324
S X E	4.96975	1	4.96975	3.13	0.0896
S X D	43.5027	1	43.5027	27.39	0.0000*
S X E X D	0.16944	1	0.16944	0.11	0.7468
Error	38.1145	24	1.58810		
H Hand	1.21446	1	1.21446	0.98	0.3330
H X E	6.29021	1	6.29021	5.06	0.0340*
H X D	0.22672	1	0.22672	0.18	0.6732
H X E X D	1.37123	1	1.37123	1.10	0.3042
Error	29.8533	24	1.24389		
S X H	0.49625	1	0.49625	0.31	0.5805
S X H X E	0.14720	1	0.14720	0.09	0.7629
S X H X D	0.41838	1	0.41838	0.26	0.6116
S X H X E X D	0.41184	1	0.41184	0.26	0.6144
ERROR	37.9395	24	1.58081		

* denotes significant effect discussed in text.

A.4.5.2 Analysis of variance summary table (Chapter 7)

SOURCE	SS	d.f.	MS	F	P
E Hand preference	0.00379	1	0.00379	0.00	0.9775
D Ear preference	0.98755	1	0.98755	0.21	0.6487
E X D	4.76483	1	4.76483	1.02	0.3205
Error	130.409	28	4.65748		
S Hemispace	0.49006	1	0.49006	0.48	0.4942
S X E	0.19028	1	0.19028	0.19	0.6603
S X D	6.87066	1	6.87066	6.73	0.0149*
S X E X D	0.85445	1	0.85445	0.84	0.3681
Error	28.5942	28	1.02122		
H Hand	2.81503	1	2.81503	1.93	0.1760
H X E	0.11556	1	0.11556	0.08	0.7806
H X D	2.25443	1	2.25443	1.54	0.2244
H X E X D	0.89858	1	0.89858	0.62	0.4394
Error	40.8905	28	1.46038		
S X H	6.96631	1	6.96631	2.64	0.1157
S X H X E	0.84776	1	0.84776	0.32	0.5757
S X H X D	0.00271	1	0.00271	0.00	0.9747
S X H X E X D	2.49506	1	2.49506	0.94	0.2296
ERROR	74.0046	28	2.64302		

* denotes significant effect discussed in text.

Jiggling a lifted weight does aid discrimination

It has been shown that our ability to discriminate between weights is affected by the manner of obtaining the stimuli. Active lifting gives better discrimination than passive pressure (Weber, 1834/1978, pp. 54-56). Discrimination improves with the frequency of lift (Holway, Smith & Zigler, 1937b), and the stimulus intensity and the number of limb joints subserving the lift (Oberlin, 1936; Holway & Hurvich, 1937; Holway, Smith, & Zigler, 1937a). It therefore seems probable that the common procedure of "jiggling" objects when estimating their weight should aid discrimination. Surprisingly, it has been claimed that this is not the case (Sekuler, Hartings & Bauer, 1974). The failure of these authors to find an improvement may lie in the fact that they did not study normal jiggling or normal weight perception, but rather the repeated rapid lifting of a lever. Such an experiment may investigate the sense of force rather than the perception of weight.

We decided to re-open the question of the beneficial effects of jiggling, using a normal weight lifting procedure, and a larger number of subjects than Sekuler et al (who used only 10). Differential thresholds (DLs) were calculated from 30 undergraduate psychology students (17 male and 13 female). They volunteered for this experiment as part of course requirements and had no prior knowledge its precise purpose. The weights consisted of 7 standard cylinders of 50 g and 7 comparison cylinders ranging from 52 g to 64 g in 2 g intervals. The cylinders were constructed out of aluminium and were all of the same dimensions (4.5 cm X 2.5 cm). A bar, located 20 cm above the bench surface, was used to limit the height of the lift. The lift was timed by a stop clock. An APPLE microcomputer was programmed to generate two randomly interspersed Up-Down Transformed Response Rules at the 70.7% correct level. It also calculated the DL from 16 reversals (or 40 trials, if earlier) and then stopped the test sequence (Wetherill & Levitt, 1965).

A standard set of instructions was given to subjects, followed by a practice session of three trials for each condition. Subjects were blindfolded and tested by a one-handed (consecutive) forced-choice discrimination task for two lifting conditions, "holding" and "jiggling". In the holding condition subjects had to lift the weight to the bar, by grasping it between thumb and forefinger, hold it there for 3 sec, and then lower it. In the jiggling condition subjects had to lift the weight to the bar, jiggle it for 3 sec and then lower it. Jiggling was described as being repeated vertical movements. In both conditions the subjects used the shoulder as fulcrum for lifting. The experimenter presented pairs of weights to the subjects and recorded their responses on the computer.

The subjects had to decide whether the first or second weight was heavier. The order of presentation of the standard (lighter) and comparison (heavier) weights, and of the two lifting conditions, was counterbalanced. Testing lasted for approximately 35 min, including a five minute rest period between the two conditions.

The mean DL for the holding condition was 4.25 g (S.D.=1.33 g) and for the jiggling condition 3.16 g (S.D.=1.08 g). Statistical analysis (ANOVA) revealed a significant difference between the DLs for the two conditions, $F(1,29)=14.20$, $p<0.001$, and between the two presentation orders of the standard and comparison weights, $F(1,29)=34.34$, $p<0.001$. The latter effect merely reflects the normal time-order bias towards judging the second weight as heavier, thus producing a lower threshold when the comparison was second (2.78 g) than when it was first (4.64 g).

Weber fractions were calculated according to the formula $2\Delta W/(W1 + W2)$ where ΔW is the DL, W1 is the standard weight and $W2 = W1 + \Delta W$. The fraction for the jiggling condition (0.061) was naturally lower than that for the holding condition (0.082). If other literature is considered (e.g. Woodworth and Schlosberg, 1961, p. 224; Ross & Reschke, 1982) values of 0.06 and 0.08 are well within the normal range: in fact 0.06 lies towards the bottom of the range for a 50 g stimulus, and this low value probably reflects the benefit of jiggling. There are several possible explanations of why jiggling aids the judgement of weight.

1) Jiggling could provide a statistical sampling system that uses each oscillatory movement as a sample unit, or "trial". Accuracy of the mean would initially increase with the number of trials but eventually level off. This argument should apply to any sense modality or manner of jiggling in which repeated trials occur. It is surprising that Sekuler et al (1974) found no beneficial effect.

2) Jiggling could also provide inertial cues to mass. It is possible to perceive and discriminate the mass of objects by accelerating them in a weightless environment (Ross, Brodie & Benson, 1984). The additional force required to jiggle an object, over and above that required merely to counteract gravity, may thus provide another sensory cue.

3) Jiggling could improve discrimination by varying the contact pressure of the lifted object upon the skin. However, it has been found that tactile sensitivity decreases during movement, perhaps to allow the transmission of afferent signals from those receptors actively involved in movement and its control (Dyhre-Poulson, 1978, pp. 171-176). It is therefore not clear whether the increased pressure differences would be readily detectable.

4) Jiggling could enable the muscle, tendon and joint receptors subserving weight perception to operate optimally. For example, in the holding condition the

muscle spindles in the upper arm may be used primarily to keep the arm in a stationary position by use of local reflex feedback. In the jiggling condition they may interact, perhaps through the gamma efferent system, with higher areas in the nervous system. A complex interaction between efferent and afferent signals may contribute to sensitivity (for reviews see Ross & Bischof, 1981; Hershberger & Misceo, 1983).

5) Jiggling may enable objects to be manipulated at an optimum velocity for the use of feedback. Sekuler et al (1974) used very fast jiggling and may have restricted the movements involved to ones of an "open-loop", "feedforward", or "ballistic" nature. It is less likely that such movement could be modified by feedback in the course of a jiggle. Thus the feedback system involved in weight perception may not have been brought into play.

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