EXPERIMENTAL MODIFICATION OF THE KNOWLEDGE OF LIMB LENGTH: A STUDY OF KINESTHESIS

FRANK T. KENNY

EXPERIMENTAL MODIFICATION OF THE
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A STUDY OF [illegible]

BY

© Frank T. Denny, B.Sc., M.Sc.

A Dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

Department of Psychology
Memorial University of Newfoundland

[illegible], 1978

St. John's Newfoundland

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ABSTRACT

This paper is composed of two parts, the first being a theoretical account of the topic at hand, the knowledge of limb-length, and the second being a description of a series of experiments designed to demonstrate that knowledge of limb-length constitutes a newly-discovered adaptive mechanism.

In Part I, it is suggested that in order to carry out a wide variety of kinesthetic and motor functions, the brain must have a knowledge of the lengths of all of the body segments, including the length of the limbs, which is of particular present concern. However, a search of the relevant literature in human experimental psychology, medicine, and general biological science has revealed that this is a topic which has, by and large, been completely overlooked and unexplored prior to the present investigation. Therefore, argument by example, by logical necessity, and by inference from a few medical and psychological phenomena (e.g. phantom limb), is given in support of the contention that knowledge of limb-length is a real, existing cerebral mechanism and that it constitutes an integral, essential, and prerequisite part of human kinesthetic and motor function.

Since such a system has never been considered before, a brief theoretical proposal is given concerning the underlying basis of such a mechanism with respect to other known kinesthetic and proprioceptive systems. It is proposed that knowledge of limb-length — termed 'registered limb-length'— along with knowledge of body volume, constitutes one part of a larger and superordinate system of body knowledge, termed the 'proprioceptive knowledge system'. The other sub-systems involved in this latter system are the joint-angle knowledge system and the system involving knowledge of cutaneous stimulation. It is further argued that all three sub-systems are cross-calibrated and that each is also calibrated against other spatial systems, particularly vision. Finally, it is suggested that registered limb-length might also be capable of recalibration in response to adaptive requirements.

In Part II, brief consideration is given to a set of experiments on perceptual adaptation to displacing prisms which led to the present proposal concerning knowledge of limb-length. This is followed by a description of six experiments which attempt to demonstrate that registered limb-length can be recalibrated in response to imposed perceptual discrepancies. It is concluded from analyses of subject performance in reaching tasks following exposure to both displacing prisms and kinesthetic discrepancies,

that a system involving registered limb-length does exist and that it is, in fact, capable of recalibrated change under certain circumstances. Some implications of this discovery are discussed.

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PART I

THE NATURE OF THE KNOWLEDGE OF LIMB-LENGTH

Introduction

It is clearly evident that human beings have a well-defined knowledge of the positions of their own limb segments. This knowledge directly implies that humans know the angles (at the joints) between the intervening limb segments, a topic which has received considerable attention in recent years (for a review see Skoglund, 1973). An additional implication of this assumed knowledge, which has received little to no consideration to date, is that humans, ipso facto, must also know the lengths of their limb segments.

The present study concerns itself with the nature of the knowledge of limb-length, how that knowledge is mediated, how it is acquired, and how it relates to other knowledge of the body. The initial task of this paper will be to demonstrate that this topic and its related questions are of substantial importance within the domain of kinesthesis and, also, within the realm of other, more encompassing, areas of perceptual research. It will be shown that knowledge of limb-length constitutes an integral, essential, and prerequisite part of both kinesthetic and motor function. In contrast, however, it will also be shown that despite its assumed importance, it is a topic of research which has been completely overlooked to date. It will be the ultimate aim of this dissertation to show that not only is such knowledge a major aspect of body function but that its components are to some extent flexible and plastic and, thus, able to serve an adaptive function in human motor behaviour.

Present interest in the process underlying knowledge of limb-length evolved from a series of studies that was concerned with certain aspects of adaptation to prismatic displacement of the visual field (see Craske, 1975; Kornheiser, 1976; and Welch, 1974, for recent reviews of this area of study). It developed as a consequence of a failure to demonstrate predicted adaptive changes at a specific joint location (c.f. Craske, 1976, and Part II of this paper). A subsequent search for a suitable explanation of the experimental results eventually led to a thorough consideration of the inherent knowledge of limb-length.

A detailed discussion of this experimentation and its theoretical rationale will not, however, be given until the introduction to Part II, even though it logically and chronologically preceded the epistomological inquiry into the knowledge of limb-length to be outlined in Part I. This reorganization permits the introduction of some background material which should facilitate understanding of the theoretical basis of the experiments which constitute the main body of Part II.

In addition to demonstrating the necessity of the knowledge of limb-length in kinesthetic and motor function, Part I also concerns itself with all previous literature on the topic. It will point out that little is known of the nature or properties of the knowledge of limb-length from past work, indeed that almost no consideration has been given to it in any field of inquiry to which it would appear to be germane. Following this, Part I will also present some tentative proposals concerning the underlying basis and function of the knowledge of limb-length. Specifically, it will be shown that such knowledge is not derived from any one specific sensory modality but that it results from a complex interaction of several sensory systems. Furthermore, it will be suggested that knowledge of limb-length is just one part of a larger system of proprioceptive knowlege.

Following Part I, Part II will, as mentioned, give an introduction to and description of several experiments on the knowledge of limb-length. These experiments will attempt to demonstrate that recalibrations of limb-length are possible and that these serve as potential sources of adaptive change.

Definitions of Terms — Domain of Inquiry

This section will present the definitions of only some of the terms used in this paper. Other terminology, being highly dependent on its theoretical context, will be defined as it enters into the discussion. The presently-given terms largely deliniate the domain of inquiry of the present study.

The present work on knowledge of limb-length falls primarily, but not exclusively, within the field of kinesthesis, according to the usage given by Howard and Templeton (1966). They define kinesthesis as "....the discrimination of the positions and movements of body parts based on information other than visual, auditory, or verbal (1966, p. 72)". By using this negatively-based functional definition, Howard and Templeton attempt to avoid an apparent pitfall in the use of the term 'proprioception', introduced by Sherrington in 1906, in which the latter term is seen to imply a specific set of sensory receptors, some of which are not necessarily involved in position sense and movement detection.

The relative use of the two terms, however, has been, and presently is, the subject of some controversy. Boring (1942) outlines the history of the debate over the use of the two terms, while Dickinson (1974), Hopkins (1972), and Smith (1969) give more recent treatments of the issue. It is clear from these discussions that there has yet to be any uniform agreement on the matter. For pragmatic reasons, therefore, this paper proceeds according to the functional definition of kinesthesis, given by Howard and Templeton, and reserves the term 'proprioception' to refer to the specific afferent activity of any of the proprioceptive receptor organs regardless of the function served. In making this distinction, however, it should be noted, as has been pointed out by Goodwin (1976), that many authors consider the two terms as being functionally synonymous in referring to kinesthetic function, as presently defined.

Howard and Templeton (1966) present a table which lists a number of different specific types of kinesthetic functions. This is reproduced below in Table 1 (their Table 4.3, page 82).

Detailed discussion of the evidence pertaining to each of these functions can be obtained from Howard and Templeton (1966) and Dickinson (1974).

The functions listed in Table 1 involve movements or positions of parts of the body. It will be the main argument of the next section of this paper, that in order to perform any of these functions, a person must have a knowledge of the lengths of the limbs which enter into those positions or movements. For present purposes, the list of kinesthetic functions given in Table 1 can be considered as at least a part of the domain of function in which knowledge of limb-length plays a role.

TABLE 1

Howard and Templeton's (1966) Classification of Types of Kinesthetic Judgement

PASSIVE MOVEMENT	Threshold of Movement Judgement of Position (indication of when previous position is regained) Threshold of Detection of Movement Accuracy of Direction Judgements Judgement of Amplitude of Movement Judgement of Speed of Movement
ACTIVE MOVEMENT	Steadiness and Fineness of Movement Judgement of Position Accuracy of Direction of Movement Accuracy of Amplitude Accuracy of Pressure Production Accuracy of Speed of Movement

It would appear that knowledge of limb-length, however, might be utilized in more functions than those noted in Table 1. J.J. Gibson (1966) proposed the use of the term 'haptic perception', which he defined as "....the sensibility of the individual to the world adjacent to his body by the use of his body (1966, page 97)". The haptic system can be seen as a group of functions which are more encompassing, or more complex, than any of those generally subsumed under the title of kinesthesis in the sense that they require the integration of several simple kinesthetic functions and, hence, presumably require more extensive mediation. They may also make use of cutaneous information in reaching conclusions about objects in the proximal environment. An example of a typical haptic function, according to Gibson, is the human ability to accurately equate the distances between thumb and forefinger on each hand without the use of vision (Gibson, 1966). This task would appear to require kinesthetic knowledge of finger positions in both hands, plus a matching function. It is the necessary existence of this additional matching function which places the task in a higher-order relationship to the simpler kinesthetic functions (e.g. as outlined by Howard and Templeton — see above). Other examples would be the ability of a blindfolded subject to accurately point a rod or stick in the direction of an auditory stimulus, i.e. knowing that the rod is in the direct plane between hand and target, or the ability of a blindfolded subject to know that he has a small living worm in his hand. The latter task would require not only a determination of size and shape through various pieces of information about changes in position of the fingers, but also a determination of texture from cutaneous receptors, a determination of the extent of the skin surface on which the worm is situated, and a knowledge of movement on the skin from whence it is hypothesized that the animal is alive.

It might be argued that reference to these higher-order functions as 'haptic functions' is unnecessary, particularly as one could simply refer to kinesthetic or cutaneous components of a given task as required. Irrespective of this, it is important to point out that many of these more complex functions may require knowledge of limb length and, therefore, also constitute part of the domain of which knowledge of limb-length may be a salient feature. This is discussed further below.

The Nature of the Knowledge of Limb-length

As was noted in the Introduction, it is now clear that human beings have a well-defined knowledge of the positions of their limbs, which, in the case of stationary positions at least, implies that they have direct knowledge of the angles at the various joint sites on their body. This capacity is mainly attributed to the joint receptors (Skoglund, 1973), although it is now thought that receptors in the muscles, tendons, and skin also directly contribute to movement and position sense in some fashion (Goodwin, 1976; Matthews, 1977).[1]

On close examination, it would appear to be a logical necessity that in order to detect the position of, or to perceive the movement of a limb, there must be, in addition to any specific information arising from joint or other receptors, some minimal degree of knowledge of the structure of the limb itself. Without such knowledge, input from these receptors would have no referents and would hence be meaningless pieces of information (i.e. they would refer to no particular structures). At a bare minimum, knowledge of a joint angle arising from joint receptors can only be, in fact, knowledge of the angle between two known structures. Likewise, information from muscle, tendon, and skin receptors entering into position or movement detection must bear reference to a known structure, namely the limb to which they are affixed. At a maximum, it may be the case that information from proprioceptors underlying kinesthetic and haptic function are only meaningful when the structure of the entire body serves as a framework or ground against which changes in receptor activity may be judged.

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[1] Craske (1975); Konorski (1970); and Goodwin, McClosky, and Matthews (1972) all suggest that position sense, referring to perception of the position of a static limb, is the relatively-exclusive domain of joint receptors, while the other receptors play a role in detection of movement.

If knowledge of the structure of a limb is a necessary prerequisite to kinesthetic function, it must also be the case that this knowledge is of a three-dimensional entity. That is, the limb whose position or movement is perceived must be known to have volume. Therefore, the brain must have some value for both its length and its height and width (or circumference). It must be the case, then, that the brain has some value for, or knowledge of, the <u>length</u> of each of the limb segments in the human body.

The first piece of evidence which establishes the existence of the knowledge of limb-length is, thus, argument by logical necessity. But, although this confirms that the brain must have some value for limb-lengths, it does not imply that it must have accurate values for these lengths. Two examples, however, show that this is necessarily the case.

First, take the case of a person who, after closing his eyes, extends his arm into space, with extended forefinger, as if he were pointing at some object. On doing this, he is aware that the tip of his finger is at some specific distance from his body. The motor commands given to execute the movement, in themselves, provide no information of that distance; and yet the fingertip is clearly felt to be at a well-defined point in space with respect to the body. If this person subsequently looks in the direction of where he feels his fingertip to be (eye-in-head judgement) and then opens his eyes, he finds on the average that he is looking at his fingertip. Had he an incorrect value for his arm length, he would have the wrong value for the position of his fingertip and hence be surprised on opening his eyes at the discrepancy between the sighted and actual positions of the fingertip. The fact that little to no error is made in performing this task argues that an accurate value was held for the total length of the limb segments in question.

For a second example, consider a person reaching to scratch a spot on his leg in total darkness. Although he would be more accurate with visual guidance (Pillsbury, 1895, cited in Boring, 1942), he, nevertheless, brings his hand down opposite the itching spot quickly and accurately. However, if he did not have a knowledge of the length of the limb he was using to reach that spot, he would have no way of making an appropriate decision; he would either grossly overextend the arm or underextend it. Without knowledge of limb-length, finding stimulated spots on the body without visual guidance would require a trial-and-error method of successive approximations. The researches of Weber (1852), Pillsbury (1895), Parrish (1897) and others, discussed by Boring (1942), show clearly that this is not the case but rather that the spot is located directly with only minimal error. Thus, a second method of establishing the necessary existence of a knowledge of limb-length lies in this process of task analysis, as given in the above two examples. It also establishes knowledge of limb-length as an integral part of both kinesthetic and haptic function. A third piece of evidence for knowledge of limb-length will be given in Part II of this paper and will constitute an experimental demonstration of change in limb-length values.

It seems very likely, even without prevention of visual guidance, that there is a large class of automatic and semi-automatic movements which are dependent on accurate knowledge of limb-length. The racket player, for example, rarely has time to visually guide his arm and racket to the ball and, hence, must rely on proprioceptive cues and dead reckoning for the required outflow (see e.g. Gibbs and Logan, 1965). The accuracy with which ball contact is made suggests that not only does he have an accurate knowledge of his arm length but a knowledge of the additional racket length as well (a haptic function). Were the ball struck only with the arm and racket completely extended, it might be argued that this is solely an exercise in learning visual distances corresponding to the shoulder/racket head distances. The immense variety of positions taken by the striking arm in play suggests that this is probably not exclusively the case that the player operates with an internally-stored knowledge of the distance.

To refer to the knowledge of limb-length utilized in kinesthetic and haptic systems, the term 'registered limb-length' will be used in this paper. The adjective 'registered' is used so that the whole term refers to an internally-stored value which is in some fashion correctly aligned, in proper relative position to, or calibrated against spatial information about the limb derived from other sensory systems (particularly vision). There is an implication in the use of the term 'registered' that the value referred to will be variable according to the given state of its relationship to other sensory systems and may be capable of recalibration under appropriate circumstances.

Although it has never been previously stated that knowledge of limb-length is stored relative to other spatial knowledge, a similar proposal has been made for the closely-allied phenomenon of the knowledge of the registered position of the arm. Craske (1975) argues that the spatial senses (particularly visual direction, derived from eye-in-head position, and kinesthesis) must "....all map into the same space; each can substitute for the other to yield accurate directional information and accurate differences between directions (1975, page 125)". It has been proposed that recalibration of the registered or felt position of the arm can take place in response to discordance between two or more spatial senses (particularly visual displacement produced by wedge prisms) (Craske, 1966a, 1975).

Gibson (1966) provides a more global view of the relationships of the spatial senses in stating that there is a:

> "....hierarchy of bone directions, hinged together, relative to the vertebral long axis of the body (the dorsoventral and the right/left). But clearly, the three axes of this skeletal space must be anchored to environmental space if behaviour is to be adaptive and perception correct. This can only be accomplished if there is some sort of calibrating of the input from the articular system with other information (pages 121-122)."

This use of the term 'registered limb-length' is meant to place the function in the same category as knowledge of registered arm position or registered joint angle. Additionally, while both types of knowledge may be involved in systems of an even higher order than kinesthetic and haptic functions (see below), the terms are not meant to apply to the conscious knowledge of the lengths of the body as derived from visual comparison of those body parts and known external environmental referents. By this is meant the type of conscious worldly knowledge which would be obtained if subjects were asked to verbally indicate the lengths of their limbs, or if they were asked if the angle of their elbow was more or less than ninety degrees, or if their arm was shorter or longer than the width of the table and so on. In these cases the judgements involve considerably more intricate abstract analyses, probably involving several higher-order functions. In the present case, registered limb-length would be more linked to the notion of stimulus-bound discrimination functions rather than higher-order descriptive functions (Howard, 1974). More will be given later on the relative relationship between the level of body knowledge and the relevant assessment task.

In summary then, logical and task analysis suggests that knowledge of limb-length is an integral part of both kinesthetic and haptic systems. The term 'registered limb-length' will be used to refer to this knowledge. Some reservations must be entertained in applying the term to certain higher-order perceptual systems.

Previous Studies Bearing on Knowledge of Limb-Length

A survey of the literature in kinesthesis, proprioception, motor function, and haptic function has failed to reveal any experimental or theoretical consideration of the necessary existence of registered limb-length. Gibson's (1966) theoretical analysis of the haptic system and Craske's (1975) analysis of the spatial senses would appear to have come closest to this realization but both fell somewhat short, possibly because the systems were not extensively elaborated. There has also been a considerable amount of work on aspects of 'the body image' and other similar types of higher-order perceptual research. These involve some experimental measures of body dimensions (Shontz, 1969, provides an overview), but this research is basically concerned with conscious subjective impressions of body shape obtained primarily by visual estimates and is consequently not of particular concern to present interests. Only brief mention of it will be made below. Some aspects of research on kinesthesis and related areas have, however, yielded important information which indirectly bears on knowledge of limb-length; and a review of this work will constitute the bulk of the present section.

ANATOMY AND PHYSIOLOGY

Knowledge of the physical anatomy of the human body with respect to the proprioceptive receptor organs, their functions, and their peripheral and central nervous system connections is now extensive. Taken together with the vast literature presently available on motor function, it would seem reasonable to expect that fairly-extensive consideration would have already been given to which of these processes (and their combinations) might enter into any given class of kinesthetic function and what additional factors might have to be considered in providing a complete explanation of those functions (kinesthesis). Judging from recent reviews and papers which deal extensively with kinesthesis, however, (e.g. Mountcastle and Powell, 1959a; Rose and Mountcastle, 1960; Skoglund, 1973; Goodwin, 1976; Matthews, 1977), attention has focused primarily on the function of the known sensory receptors, their peripheral correlates, and their topographical representation in the post-central parietal cortex. This has occurred largely to the exclusion of kinesthetic factors and/or functions not directly implied by these receptors.

The usual methodology employed in anatomical and physiological studies is to make (or have the subject or animal make) finely-controlled movements of (usually) single limbs or at single-joint sites and subsequently obtain verbal reports about change or awareness of position (e.g. Horch, Clark, and Burgess, 1975), or record from single cells in the somatosensory and/or associational cortex of the brain (e.g. Mountcastle, 1957; Mountcastle, Davies and Berman, 1957; Mountcastle and Powell, 1959b). With this standard approach, in which little consideration is given to the complete specification of kinesthetic function per se, it is understandable why attention might have remained focused only on the relative function of the receptor organs and why it is only recently that aspects of sensory/motor relationships not directly implied by a given receptor organ are being approached (Mountcastle et al, 1975; Lynch et al, 1977).

The question of how the brain knows the lengths of the limbs and other body segments has thus not been broached to date in neurophysiology and related areas. A related topic, the localization of tactile stimulation (in the absence of visual information) has, however, been given some consideration and will be mentioned here, as both this function and those involving knowledge of limb-length involve the spatial location of parts of the body. In this respect it might be conceived that they have similar solutions.

The topic of tactile localizations falls into the general area of somesthetic or somatosensory functions; and various recent reviews and important papers on the latter subject have been given by Boring (1942), Melzack and Wall (1962), Perl (1963), Werner and Whitsel (1973), and Lynn (1975). Specific consideration of various aspects of tactile localization per se have been provided by Boring (1942), Halnan and Wright (1960, 1961) and Sinclair (1967).

The main question involved in tactile localization is how the brain knows, in the absence of visual information, where on the body a touch has been received. Since this function can be performed simply with light touch to the skin (Weber, 1852); that is, without deep pressure or displacement of the limb, the most obvious source of information is the mosaic of receptors in the glabrous and hairy skin. The crux of the problem would be, therefore, to explain how such receptors could provide information about spatial location.

One of the earliest solutions, attributed to Lotze (1852), was that skin receptors provide a 'local sign' for tactile localization. Both the nature of the local sign and how it was used remained unspecified, however, and the theory was eventually abandoned (Boring, 1942). Its replacement appeared to be the notion that the topographical organization of the somatosensory cortex provides the required information as it functions essentially as a map in the cortex. This notion that the brain has a map of the body from which would be read off relative locations was also the central aspect of the 'body schema' proposed by Head and Holmes (1911) (see also Oldfield and Zangwill, 1942, and see below). It is difficult, however, to see the essential difference between this notion of topological mapping and that of local sign.

Despite the extensive knowledge of the functional organization of the sensory cortex (Werner and Whitsel, 1973), this notion of a topological map, as it stands, would appear to be erroneous. Two major objections have been cited in this regard. The first is a logical fallacy, termed 'naive realism' (Ryle, 1949; Smythies, 1953), which has resulted from a failure to identify 'the outside world' as a train of events in the brain, rather than as an objective reality. In fact, the communication of receptor to cortex is preperceptual, being essentially the manner in which information gets from one place to the other. While some modification of afferent stimulation can take place peripherally, it is only after this information has reached the cortex that the perceptual processes which underly identification of tactually-stimulated locations may begin. This remains true even though there may be a hierarchial organization of cells in the sensory cortex and association cortex in which there is increasing complexity of cellular function in terms of the receptive fields or joint sites served (c.f. Mountcastle, et al, 1975). In essence, this topographical organization only begs the question of how these maps (or organizations) are read or interpreted, a matter which is, in fact, more or less a repostulation of the original question.[2]

The second objection to this line of explanation comes from the observation that some parts of the body are more easily localized than others (Weber, 1852; Halnan and Wright, 1960, 1961). Even if more area of the cortex is involved in

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[2] This, however, does not mean that the neural mechanisms which do underly such spatial functions do not have some of the 'properties' of topological maps (c.f. below, and Craske, 1975).

the sensory/motor functions of some parts of the body than others (Penfield and Boldrey, 1937), there is still no inherent explanation in the notion of topographical organization (i.e. distances between body-part representations in the cortex) why there should be a difference in locating different body parts (e.g. in the same fashion that a cartographer would find no difference in the difficulty of plotting the distance and direction to Iceland and to Great Britain just because Iceland occupies less space on the map). To account for this phenomenon, the notion of topological location in the cortex must be modified somewhat (e.g. by proposing that there are more or less differentiated receptive fields in addition to relative distances in location). Such a step might provide the beginnings of an adequate theory of tactile location, bearing in mind the earlier cited point that the major task is to discover how somatosensory information in the sensory cortex is to be used in performing this function.

Thus, it would appear that additional and more complex mechanisms are required to adequately explain tactile localization. Halnan and Wright (1960) cite five processes which might be operative during the identification of the location of a tactually perceived stimulus (e.g. a pin prick) when there is no direct visual knowledge of the event. These include: " (i) such sensations and perceptions as are available

(ii) any prior sensations and perceptions that can be obtained — as by 'cheating'; (iii) tactile memory images; (iv) visual images of the digits; and (v) abstract ideas such as the knowledge that (the subject) has five digits in each limb (1960, page 691)." Halnan and Wright imply, in addition, as have others (Head and Holmes, 1911; Schilder, 1935), that accurate tactile localization may, in fact, rely on a knowledge of the whole body (presumably the spatial relations among the various parts). However, no author, to date, has made any definite proposals as to how all of these functions may be carried out or how they interact, and the question of how tactile localization is achieved seems as unanswered presently as it has ever been.

It seems evident that any attempt to explain knowledge of limb-length on similar grounds (skin maps in the cortex) will encounter similar objections. To this may be added the following additional drawback: If the brain is dependent on skin receptors for information concerning limb-length, then it must by necessity be dependent on irregular skin stimulation for obtaining accurate length values, a dependence which seems unlikely for such an important function.

In conclusion, then, studies emanating from the fields of anatomy and physiology appear to have overlooked (rather than having failed to devise an explanation) the function of knowledge of limb-length in both kinesthetic function, and as it occurs analogously, in the function of tactile localization. It also appears that any theories based on sensory mapping of the skin would fall far short of the specifications required for an adequate explanation of kinesthesis and tactile localizations, although it is possible, and indeed likely, that they are involved in some fashion. This latter possibility will be dealt with in a future section.

STUDIES IN NEUROLOGY

The standard means of investigation in neurology is the case-study method. It begins with complete descriptions of the behaviours of concern (symptoms) exhibited by patients with known or unknown lesions. With unknown lesions, subsequent physical verification is usually attempted. Once cases are completed, they are usually worked into some form of classificatory system. This is usually the last stage for clinicians prior to treatment. However, an additional stage is often enacted with one or more cases, where anatomical, physiological, symptomatic, philosophical, and psychological considerations are brought together in an attempt to devise suitable central explanations. For a further discussion of the merits and pitfalls of this approach, see Shontz (1969). The study of clinical neurology has dealt with two topics of interest to this paper: 1) neurological case studies of patients with disturbances of body perception; and 2) the closely-allied clinical phenomenon of phantom limb.

In disorders of perception of the body arising from cerebral lesions, there is sometimes a discordance between the physical body which is intact (but dysfunctional) and the perception of the body which is impaired. A common example of this is a phenomenon known as anosognosia (Critchley, 1965, 1971) in which patients, among other things, are apparently unaware of, or deny, a hemiplegia (usually on the left body side). A patient with this disorder will often behave as if the affected body side were not paralysed, express surprise at any suggestion that there is something wrong with it, and sometimes fall as a result of an attempt to walk on it. The disturbance in perception and the paralysis usually have a common source in the cerebral lesion. The patient apparently sees his affected body side as normal which it is, but also functional which it is not.

Critchley outlines a number of these dysfunctions under the titles of disturbances of the body image (1950, 1971) or disorders of corporeal awareness (1965). His excellent descriptions and discussions of patients (usually with lesions of the parietal lobes) make it apparent that the nature of each of these symptoms is very complex indeed and each can be (and has been) interpreted in several ways.[3]

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[3] And misinterpreted, as in the examples given by Smythies (1953), in an otherwise excellent discussion of perceptual aspects of cerebral disorder.

It is unfortunate that Critchley chooses to employ the term 'body image' for his classificatory system, as this is based on notions of body image and body schema which, as argued by Poeck and Orgass (1971) are far from being established entities and, thus, should not serve as a basis for classification. Corporeal awareness, or perhaps simply body perception, would be better terms.

The cases described by Critchley usually involve gross disturbances of the parietal cortex and probably involve other regions of the cerebral cortex. It is likely that the disorders affect many central processes simultaneously. It is, therefore, difficult to place much credence on theory based on these symptomatic descriptions (c.f. Poeck and Orgass, 1971).

A second type of case of interest involves patients who have discrete disturbances of sensory systems (in the present case proprioceptive systems). According to the description of Head and Holmes (1911) there are cases in which there is a loss in the sense of position of a limb but no apparent loss in the ability of tactile localization. That is, these patients can identify or point to (with an intact hand) a spot on the affected limb stimulated by a probe (while blindfolded) but will point to the same location in space if the affected limb is passively rotated out of position prior to pointing (i.e. as if the arm was still there).[4]

Head and Holmes argue that these cases demonstrate that the two functions (position sense and tactile localization) are independent. This, however, is not entirely true since the latter function is no longer completely intact (i.e. it is not accurate when the affected limb is rotated). What seems to be the case, in the light of the discussion of the previous section, is that there is loss of afferent information from joint muscle receptors of the affected limb but no loss of information from skin receptors from that limb nor impairment of any previously-established central processes involved in tactile localization; hence, a rudimentary tactile localization function is maintained.[5]

From the descriptions provided by Head and Holmes (1911), it is apparent that either the lesions suffered by their patients were in different parietal regions than those of Critchley (1965) or involved considerably less cortical

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[4] The patient presumably obtained information about the original position of the arm from vision.

[5] However, this is not really the same as tactile localization as discussed above since the fully-intact function also requires knowledge of position sense. That is, tactile localization, as referred to in an intact human being, is really a higher-order (haptic) function than position sense since the former requires the latter. Position sense and cutaneous knowledge could be seen as independent functions, but not position sense and tactile localization.

area, or both. Mountcastle et al (1975) argue that the symptoms described by Critchley were largely due to effects of lesions in the superior and inferior parietal lobules. They argue that this region contains specialized cells, the disturbance of which could produce symptoms similar to those described by Critchley, whereas lesions of the post-central lobules should not. Selective lesions of the latter area could conceivably produce the phenomena described by Head and Holmes. In any event, it is difficult, as mentioned, to place much confidence in processes derived from lesion studies due to the great variation in the nature of the lesions themselves. The material from both types of study, therefore, provides little which can be of direct use in kinesthetic study.[6]

A second area of neurological inquiry, distinct from that described above but with similar ramifications, concerns the phenomenon of the phantom limb (see Henderson and Smith, 1948, for an extensive review). When patients

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[6] The clinical phenomenon of allesthesia (also called allochiria and alloesthesia) in which the sensation of a tactile stimulus in one limb is referred to the other, is also of some interest to the present thesis, particularly as the stimulus in question is often referred to the same locus on the opposite limb, thereby implying that a congruent relationship may be maintained between corresponding regions of the two body sides. Unfortunately, other than receiving notable mention in some discussions (e.g. Melzack, 1973) this phenomenon and its implications have not been explored in any depth.

incur sudden loss of a limb or limb segment, it is usually followed by a strong perceptual experience that the affected limb or segment is still present. The limb often feels warm and moist, sometimes has a tingling sensation and patients often report that they can move parts of it. It is usually inferred that there are strong signals emanating from some central-knowledge system of the body which are the same, or highly similar to, those which would be present if the missing limb were, in fact, intact, and that this information is at odds with visual input, the patients knowledge that the limb is missing (e.g. memory of the operation) and from information derived from haptic exploration of both the space previously occupied by the limb and the stump. The latter processes appear to determine objective reality for the patient but do not prevent the experience of the missing limb provided by the former process.

There is a normal course of phantom experience which has received extensive documentation (Henderson and Smith, 1948; Cronholm, 1951; Melzack, 1973). To use an arm amputated at the elbow as a typical example, the phantom limb is observed to selectively disappear over a number of days or weeks following its appearance. The wrist to elbow segment will disappear first leaving the hand 'suspended in space' (in general, the areas of least sensory innervation go first).

Subsequently, the hand begins to telescope toward the stump, coming closer and closer until eventually it seems to be attached to the stump. Gradually, the impression of that hand breaks up, dissolves into the stump or just disappears, although on occasion it is reported as being experienced inside the stump.

Phantom limb usually occurs vividly only in cases of sudden loss of limb. In conditions where slow degeneration of a limb takes place, the phantom is much rarer. In a small percentage of cases of phantom limb, it is accompanied by intense prolonged pain along with the experience that the pain is related to a deformed, cramped, or distorted position of the limb. Often, neurosurgical intervention is required to relieve this pain and some patients become total invalids as a result of long-term intractable pain. There is little doubt about the reality of the experience. There is an additional host of findings from phantom limb investigation, but they are not of particular concern for present purposes (Riddoch, 1941; Weinstein and Sersen, 1961; Weinstein, Sersen, and Vetter, 1964; Prevoznik and Eckenhoff, 1964; Fisher, 1968, Sunderland, 1968; Weinstein et al, 1970; Melzack, 1971, 1973; Conomy, 1973; and Price, 1976).

The two aspects of phantom limb which are of particular interest presently are: 1) the processes which underlie its appearance; and 2) those which underlie its disappearance.

Superficially, at least, these two facets of the experience seem easily explainable. As noted above, it is generally inferred by almost all authors on the subject that somewhere in the brain there exists some form of 'knowledge system' of the body which immediately, and for some time after loss of limb, still includes representation of the missing limb. The term 'proprioceptive knowledge system' is preferred here as it does not carry the implications of other terms (e.g. body image, body schema) used elsewhere (see below). It is thought that the proprioceptive knowledge system continues to report information concerning the missing limb even though it can no longer be receiving incoming proprioceptive signals. The activity of this system is responsible for the strong impression that the limb is present, particularly if not attended to visually.

If this system is to be inferred, then several other assumptions are also necessarily required. First, it must be the case that the proprioceptive information from the intact body must pass into this knowledge system and in some way interface with it; otherwise, we would have information about two bodies or some kind of combination body. Second, it must be the case that this knowledge system is not totally dependent on continuous input for its moment-to-moment existence, as it is not immediately modified by loss of proprioceptive afferentation. In this sense the proprioceptive knowledge system must be subject to modification in a different fashion to that of the visual knowledge system which immediately signals loss of external stimulation. Finally, the proprioceptive knowledge system must be preconscious since we have no awareness of it. This postulation and its corollaries seem at present to be the only reasonable explanations for the existence of phantom limb.

Shortly after loss of limb there is a large discrepancy between visual and proprioceptive perception. Gradually, the representation of the arm in the proprioceptive knowledge system breaks up and presumably eventually ceases to report altogether. How this takes place is unknown. The course of disappearance suggests that it could be a physiological (synaptic?) change resulting from disuse which proceeds along a continuum of loss of representation from the least to the most sensorially-innervated regions of the affected limb. Against this hypothesis are rare instances of return of phantom limb after prolonged absence (Melzack, 1973), but conclusions drawn from rare and unusual cases of phantom limb, which may have complicating factors, should probably not be held in great stead. The normal course of phantom limb may be disrupted by other abnormal or unusual physical, physiological, or psychological events and produce complications such as severe phantom pain (Melzack, 1971). It is possible that the loss of the phantom has not proceeded, or has been prevented from proceeding, in the normal fashion. These cases are also not of high incidence, and it is the normal phantom process which should be viewed as giving the critical information regarding required neural mechanisms.

An alternative explanation is that disappearance of phantom limb results from a true adaptive change of the type that is known to result when two sensory systems produce discrepant information (e.g. visual-kinesthetic discrepancies resulting from prismatic displacement of the visual field) (Howard, 1974; Craske, 1975). This appears less likely, as sensory adaptation takes place relatively quickly, whereas the present changes are very slow in comparison.

In summary, the study of clinical neurology has provided two points of theoretical interest. First, it has been suggested that position-sense and tactile-localization functions in the same limb are independent. This, however, has been reinterpreted to mean that position sense (joint-angle knowledge) can be impaired by lesions at the same time that proprioceptive information from skin receptors and central factors in tactile localization remain unaffected. Second, it has been suggested that there is a need to postulate a proprioceptive knowledge system in the brain which must be integrally linked to the proprioceptive receptor organs and which must have certain characteristics.

The need to postulate some forms of mechanisms such as those discussed above has been apparent since the turn of the century (Head and Holmes, 1911; Boring, 1942; Poeck and Orgass, 1971). The resultant debate, rather than being about the nature of the systems involved in these clinical phenomena, appears to have been concerned with what to call them (presumably because of the underlying implications of the terminology). The consensus of opinion appears to have favoured the ideas of Head and Holmes (1911) (over those of Munk, 1890; Wernicke, 1900; and others, c.f. Poeck and Orgass, 1971) who inferred the presence of two or more systems of the brain which they called 'schemata' or 'body schema'. These schemata are responsible for functions which subserve both sense of position and sense of tactile location, as well as presumably some overall knowledge of the body. Head and Holmes also provide the only operative principle concerning these functions (with respect to the schema for position sense).

> "....in addition to its function as an organ for local attention, the sensory cortex is also the storehouse for past impressions. These may rise into consciousness as images, but more often, as in the case of spacial impressions, remain outside central consciousness. Here they form organized models of ourselves which may be termed 'schemata'. Such schemata modify the impressions produced by incoming sensory impulses in such a way that the final sensations of position, or of locality, rise into consciousness changed with a relation to something that has happened before (page 189)."

Thus, a schema exists for each function and presumably these are mechanisms which would also produce phantom limb phenomena under appropriate circumstances. The operative principle here is that incoming signals are 'charged with a relation to something that has happened before'. They also assume that the schema itself is modified as a result of change in proprioception input.

Head and Holmes (1911) are far from explicit on this matter and provide no indication as to how or in what form all of this activity might take place. Oldfield and Zangwill (1942) liken the moment-to-moment function of a schema to making and reading a map where every place encountered is charted with respect to its previous place(s). It is not clear if Head and Holmes (1911) had this in mind, although as Poeck and Orgass (1971) note, "it is difficult to see the difference between the superficial schema as an organized model and the 'homunculus' of the cortical sensorimotor representation (page 258)."

In addition to the vagueness of the original notions of the body schema, there has been no expansion or modification of it. The concept has been so thoroughly accepted by most writers since Head and Holmes that some writers have even based a system of symptom classification on it (Critchley, 1965). As Poeck and Orgass (1971) point out, however, the existence of a body schema is far from established fact. Indeed, it amounts to little more than a proposal and is even less developed than Gibson's (1966) speculations concerning haptic function. In the long run, therefore, while clinical neurology has contributed some valuable descriptive information concerning kinesthetic and proprioceptive function, it has provided little in the way of theoretical proposals, the latter possibly even being counterproductive.

One facet of the above-described neurological study which is of particular interest presently, as it concerns limb-lengths, is the phantom limb phenomenon in which a gradual telescoping of phantom arms takes place. The movement of the distal portions of the limb towards the stump suggests that the proprioceptive knowledge system is changing differentially, as if the arm were shrinking. This cannot entirely be the case, as the impression of the hand eventually breaks up and disappears as well, and the forearm segment can actually be perceived as missing. However, the hand and wrist do move (shrink) towards the stump giving the impression that the arm is being perceived as shorter. Regardless of whether this is a result of a synaptic or an adaptive change, this phenomenon suggests that the proprioceptive knowledge system may incorporate a mechanism which registers arm length in some fashion and which is also capable of recalibration under appropriate circumstances (in the present circumstances, a perceived shortening results). That is, the mechanism(s) for knowledge of limb-length discussed earlier may be one part of this larger and more complex proprioceptive knowledge system. Some additional discussion of this possibility will be given in a following section.

CLINICALLY-RELATED STUDIES

There are a number of studies present in the literature which are not strictly speaking neurological studies since they do not involve clinical cases but which are also not psychological studies in that they are usually not experimentally rigorous nor directly concerned with 'psychological' problems in the classic sense. These studies are usually observational or actuarial examinations, or pseudo-experimental investigations of normal individuals in relation to clinical topics. Like the clinical work outlined above, these studies do on occasion describe interesting phenomena.

One such type of clinically-related study, which is an offshoot of notions of the body schema, deals with the examination of the concept of 'body image'. These are phenomenological studies of the conscious experience of the body. It seeks to answer questions such as 'how long do people's arms feel in relation to the rest of their body?' or 'how aware are people of their back?' (c.f. Shontz, 1969).

These questions and their related theory can be traced back primarily to Schilder (1935) and Fisher and Cleveland (1958). This material is highly clinically related and often psychoanalytically oriented. Most authors in the field postulate the existence of a 'body image' which is usually some form of construct or idea that each person has about his own body — it is essentially a notion about what shape each person perceives himself to be. It is clear that there is no intention to equate this concept with that of a body schema although much of the work is vague in respect to delineation of concepts (Shontz, 1969; Dickinson, 1974). The study of the body image contains nothing of particular relevance to kinesthetic function since the former is concerned with the activity of far more complex, higher-order cognitive systems than the latter. A more detailed discussion of this argument is given in the next section and will not be discussed further here. It is important that these studies and concepts are not confused with those of body schema which do directly deal with kinesthesis and proprioception.

As noted earlier, the very existence of phantom limb phenomena argues that there must be a proprioceptive knowledge system of some sort but yields little additional information as to what its composition might be. Recently, however, Melzack and his co-workers (Melzack and Bromage, 1973; Bromage and Melzack, 1974; Gross, Webb, and Melzack, 1974) have argued that certain evidence from phantom limb studies does yield information about 'the body schema' and that it strongly suggests that such a schema is innately determined. Bromage and Melzack (1974) state, "....We conclude that the nature of the schema is fixed, archetypal and possibly inherited, rather than plastic and acquired." Melzack and Bromage (1973) and Bromage and Melzack (1974) studied phantom limbs which appeared in normal (non-amputated) subjects ten to twenty minutes after anesthetic block of the brachial plexus (they also studied some subjects with experimentally-induced phantom leg). Their chief finding in this uncontrolled study was a consistency in the apparent position of the phantom arm, according to subjects descriptions. Bromage and Melzack (1974) note:

> "Both upper and lower limb phantoms assumed attitudes of partial flexion and rose in the air above the supine body. These attitudes were not modified by passive alteration of limb. The phantom arms were partially flexed, abducted and internally rotated at the shoulder, and partially bent at the elbow with the forearm midway between pronation and supination. Wrists were in the neutral position, with the fingers and thumb semi-flexed. The phantom legs were semi-flexed at the hips and knees with the foot plantargrade. The hips were slightly abducted with the knees 24 to 40 cms apart (pages 269-270)."

Bromage and Melzack (1974) recognized that the phantom positions probably reflected physiological properties of the joint and muscle system. "....acute phantom of the upper and lower limbs tend to adopt a position of orthopedic rest. The ghostly, deafferented joints were clustered around the null position in the mid-range of joint movement, and none of them fell at the extremes of flexion or extension (p. 271)." Rather than be content with this description, however, the authors make the astonishing leap to the position that this provides evidence of a fixed, inherited body schema. This jump would once again appear to be the result of a conceptualization of body knowledge system as some type of topographical map.

The fact that the position sense of a limb 'returns' to a null position under conditions of anesthetic block should be of interest both to the physiology of joint and muscle action (see Matthews, 1977) and to the study of kinesthesis. It may be an important clue as to how the brain calculates and keeps track of the various parts of the body. What the study does not do is provide any further evidence for the existence of a schema than has any other consideration of phantom limb; and it certainly provides no evidence for an inherited mechanism.

Gross, Webb, and Melzack (1974) provide 'evidence' that the arm tends to seek a null position when concealed from vision. In a rather confusing and badly-executed study, Gross et al (1974) had subjects rest their right arm on a table in front of them and leave it there for up to 12 minutes. The requested arm position was initially somewhat bent inward at the elbow so that the hand fell opposite the midline of the body. The arm was obscured from view and subjects were required to indicate with their left hand where certain landmarks of the hidden arm were (wrist, elbow, finger, knuckles, etc) at certain specified times (3, 9, 12, minutes).

Gross et al found that when the arm is restricted from vision for at least three minutes (time being a non-significant factor), there is a discrepancy between the real and perceived locations of the landmark positions. The perceived locations were "....closer to the midline of the body on the right-left dimension, and closer to the body on the near-far dimension than it really is (page 346)." This difference occurred whether it was vibrated during the 12-minute interval (Experiment 2), whether subjects moved the arm around during the interval without seeing it (Experiment 3), whether they verbally described its position (Experiment 4), or whether they moved their hand to a prespecified location (Experiment 4). The authors interpret their findings as being supportive of Melzack and Bromage's contention that there is a body schema and that it tends to assume common positions thereby suggesting an innate basis.

The study by Gross et al (1974) is fraught with difficulties. Apart from being confusing with respect to analysis, the authors fail to include a pre-test so that one doesn't know if the difference between real and perceived locations is simply a constant error of the system. The four experiments are inadequately controlled, the first experiment having no control groups and the last three using the first as a control. The data are combined in an unknown fashion with no explanation. Only one position of the arm is utilized and in a position rather suspiciously close to the null position. Only the right arm was tested. Overall the study would be of little interest, except for the appearance of one phenomenon apparently overlooked by authors.

A re-examination of Figure 2 (Experiment 1, page 352) suggests that in addition to a movement of the arm toward the body, the forearm 'shrinks' (decreases in distance between the tip of the fingers and the elbow). It is difficult to ascertain this finding due to the confusion surrounding the analysis and the lack of a pre-test or control, but

Figure 2 appears to show that while the elbow is accurately located, the perceived position of the landmarks distal to the elbow are considerably shorter than their actual positions.

If this observation could be verified, it would be the second indication that the kinesthetic system is capable of a shortening of registered limb-length (the first indication being noted above as possibly occurring during phantom limb change). On the surface of it, neither the changes noted by Gross et al nor those suggested above are very likely, as there is no obvious reason why a restriction of vision should result in a dysfunction in the kinesthetic system, whereas it is quite reasonable after anesthetic block. Most likely, therefore, a proper study would show the differences as systematic error reflecting tendencies of the calibrating systems for both registered joint angle and possibly registered limb-length.

PSYCHOLOGICAL STUDIES

In previous sections, it was intimated that the perceptual or cognitive structure that was being tapped in any given experiment was highly dependent on the task being undertaken. Most of the studies mentioned above have used relatively uncontaminated kinesthetic measures in which vision was restricted and in which subjects were required to make certain judgements of position or movement with their bodies or perform or assume certain positions or movements. The tasks employed by Gross et al (1974) permitted subjects to have their eyes open but kept the target arm from view with a screen while subjects pointed to landmark places on the target arm. Many of the studies of prism adaptation utilized similar tasks. Pillsbury (1895) showed that location of stimulated sites was best when subjects were allowed to look at their arm while making the localization (after stimulation) and poorest when vision is not permitted and visual imagery is inhibited. Vision is, thus, a contaminating factor in these studies to some degree.

There is, however, a large number of psychological studies concerned with 'perception of the body' which according to the present view fall well outside the conceivable or acceptable level of kinesthetic measures. A review of this general area of research is given by Shontz (1969). These works employ the following types of dependent measures: 1) adjustment of a visual scaling device (usually two blocks on a rod) until the scaled distance is equal to the distance between either stimulated or verbally-indicated body landmarks (the body being usually concealed from view) or until it is equal to the distance stimulated by the two ends of a set of calipers (e.g. Shontz, 1956). This is called the linear method according to the terminology of Shontz (1969);

2) adjustment of a picture or model of the body until it is judged that the model accurately represents the real body (configurational method) (e.g. Traub and Orback, 1964); 3) the drawing of pictures of the body or lines of distance indicating perceived body sizes (pictorial method) (e.g. Nash, 1965); or 4) asking subjects for a verbal estimate of the distances on the body (i.e in inches) (e.g. Fisher, 1964).

These studies all have two facets in common which makes them distinct from most of the studies of kinesthesis, haptic function, and tactile localization, as discussed thus far. First, the above-noted dependent measures appear to require judgements which involve some form of abstraction as opposed to methods of direct comparison which are characteristic of kinesthetic studies. For example, in the study of body dimensions described by Shontz (1969, Ch. VI), subjects' bodies were hidden from view and distances on them indicated either by stimulating two points on the body with calipers or by verbally indicating a body segment (i.e. elbow to wrist). The required judgement for each subject was to subsequently adjust two blocks on a horizontally-aligned rod placed in front of them until the distance between the two blocks was felt to be equal to the body segment distance.

Such a task appears prone to error and variability for two main reasons. First, the kinesthetic stimulus must be estimated and subsequently retained for some period of time while the visual scaling device is being operated. Second, since the two stimuli are not aligned in the same space, they cannot be directly compared. Rather two separate estimates must be made and subsequently compared in some abstract fashion. Possibly, each is compared to a third higher-order standard (e.g. an idea of distance in feet), or perhaps some form of mental rotation of imagery to align the two systems is performed. Thus, at the very least, the necessity of these additional operations should result in increased complexity and error. There is even some possibility that there is a complex abstract system of bodily perception which is invoked in such comparative judgements and which is of a much higher order than simpler kinesthetic judgements (see below).

The predicted error and variability of these tasks appears to have emerged in these types of study. Most of the studies reviewed by Shontz (1969) found considerable amounts of under- and over-estimates depending on the body site stimulated. Furher and Cowan (1967), Boraks (1962), Shontz (1963), and Dillon (1962) all found similar types of variability. As a generalization, it appeared that the less visual experience there was of a body area, the more inaccurately it was estimated. So extensive was the variability and error that in reviewing this work Shontz (1969) was forced to conclude "....It does appear that body-part size judgement is patterned and that the pattern cannot be accounted for by stimulus lengths alone.... The outcomes of these investigations establish that the judgement of distance on the personal body is not equivalent to the judgement of pure length in the extrasomatic environment (pages 74-75)." The implication of such a conclusion is that some type of more complicated abstract analysis is being undertaken by subjects in these tasks.

As noted, these tasks are very different from the traditional kinesthetic studies which compare vision and kinesthesis when they are aligned in the same space. For example, in the study by Craske (1966a), subjects were required to indicate with the finger of one hand, the location in space of a part of the other arm (elbow, wrist, or shoulder) which was hidden by a screen. In this type of task both the visual and kinesthetic components are aligned in the same space and can be directly compared. Little error would be expected from such a judgement and available studies suggest that such tasks are performed with considerable accuracy.

The two methodologies are thus considerably different, and it seems reasonable to infer that the central processes being measured in each type of study are substantially different. Specifically, studies of the perception of the body as discussed by Wagner (1964), Witkin (1965), and Shontz (1969) are likely to be measuring some higher-order system of bodily perception. This, at the very least, would appear to combine in some fashion both proprioceptive and visual knowledge of the body to produce a perception of more depth and complexity than either system alone would be capable of producing.

The second aspect of similarity of these perceptual studies is that they purport to be investigations of the body schema or body image, which as noted by Shontz (1969), is an assumed construct without systematic confirmation or validation. The term body schema or body image in this instance is argued by Shontz (1969) to be similar to that of Head and Holmes (1911) but, in fact, appears to be a more extensive and elaborate construct which has never been adequately defined and which appears to mean different things depending on the study in question. In contrast no such framework has been imposed in kinesthetic studies. It is not clear whether this practice of assuming a body schema has any repercussions (i.e. for research) other than the imposed theoretical bias suggested above. However, the design of many experiments has clearly been made on the basis of the assumption that there is a body schema and possibly more importantly, sometimes data appear to be transformed or interpreted in terms of a body image. For example, Boraks (1962) uses a sensitivity ratio which combines logarithmically-transformed scores of real and perceived body distances which he uses for comparison of presumed differences in perception of the lengths of various body segments. This appears to have been done with the implicit assumption that the ratio has a common meaning with respect to all these segments because they are all part of a body image. Consequently, Boraks uses his results to support a notion that the body image is organized with respect to a cephalo-caudal dimension because the sensitivity index is greater for the lower part of the body and the extremities than the upper trunk and head. His assumption of a body image would, thus, appear to have caused him to overlook or ignore the simpler explanation that the experimental results are due to a greater visual experience with the lower trunk and the extremities.

It is of interest to note that Shontz (1969) discusses those studies on visual estimations of body size (including many of his own) separately from those concerned with sensory/tonic theory (Wapner and Werner, 1965). The latter, in

Shontz' terms, "....propose to explain perception in terms of relations between the organism and its environment (page 79)". Their methods are either to produce a change in the external environment or the bodily state and show how this influences various types of bodily-oriented judgements, for example, judgement of verticality, (e.g. Bauermeister, Wapner, and Werner, 1963) and judgement of the apparent horizon or the median plane of the body (e.g. Comalli, Werner, and Wapner, 1957). One study with direct relevance to perception of the body per se is that of Wapner, McFarland, and Werner (1963) in which subjects viewed their two arms with respect to different backgrounds and then reported which felt longer. Since more subjects reported that arms viewed against a distant background 'felt longer' than those viewed against a near background, the authors concluded that expansion of the perception of the body occurs in an open-extended space, while shrinkage occurs in a closely-confined space.

It is not clear whether Shontz (1969) wished to divorce these studies from his own. However, those studies of sensory/tonic theory which are relevant to body perception can reasonably be grouped with those discussed initially (particularly with the fourth type of method involving verbal estimates).

A third area of research, which definitely is distinct from the two sets of studies discussed above, is that involving the study of the 'body image' as a personality construct. Although no clear differentiation between these and other notions of body image have been made, it is generally acknowledged that the methodology is concerned with very different processes than those discussed thus far. Schilder (1935); Fisher and Cleveland (1958, 1968); and Shontz (1969) provide reviews of this field of inquiry. Although the methods and theories in these studies are heterogeneous, typical dependent variables are scores on the draw-a-person test (Swensen, 1968); inkblot responses (Fisher, 1963); and scores on various questionnaires related to subjective impressions of the body (e.g. Fisher, 1965). The scores are usually related to other measures of personality or to sex, age, and other similar variables in terms of a 'body image' whatever that is construed to be in any given study. Since clearly-established principles within this area of research have clearly not been forthcoming, it is difficult to relate it to any other field of investigation. It would seem reasonably clear, however, that whatever processes are being measured they are of even greater complexity and involve many more variables than any of those discussed earlier in this section.

It is the opinion of the present author that the entire range of studies mentioned in this section falls well outside the body of research which is of direct relevance to the knowledge of limb-length as it is presently viewed in terms of kinesthetic and proprioceptive function. The reason for this is simply due to the complexity and higher-order nature of these processes, as noted above. It would seem reasonable to expect that there will eventually be a bridging of the gap between the two areas of research, but at present, they would appear to be nearly completely independent. Accordingly, the area of research referred to in this section will not be reviewed in any more depth. However, one or two facets of particular interest are noted below.

Fink and Shontz (1960), Guess (1963), Shontz (1963), Arnhoff and Mehl (1963), Lebovitz and Lakin (1957), and Wight and Moed (1963) have all studied the perception of the body in patients with various organic diseases or disabilities. One finding which has emerged with some consistency from this work is that severe organic brain disease and/or prolonged disuse of the body and its parts can lead to 'constriction' of visual estimates of body size, in which the body is perceived as smaller in general, and in which limbs are sometimes perceived as shorter. This work is of interest because of the previously-noted indications from kinesthetic studies that changes in perceived length of limbs can take place (specifically perceived shortening of phantom limbs and perceived shortening of the limb when at rest — see previous section).

While not of direct applicability to knowledge of limb-length as discussed presently, the findings do add credence to the notion that the brain does have, in fact, one or more mechanisms which do monitor perceived limb-length and which can result in perceived changes in those lengths under certain circumstances.

Mechanisms of Limb-Length Knowledge

Thus far, several areas of research have been reviewed. The observation has been that while there have been some indirect findings which suggest that perceived changes in registered limb-length can take place, no direct consideration has been given to the question of how the brain knows the lengths of the body segments. This paper has taken the position that knowledge of limb-length, as discussed, is primarily involved with kinesthetic, proprioceptive, and haptic functions. It was suggested that there might be other higher-order systems of body knowledge but that these were necessarily more complex and quite different from that referred to presently.

With reference to specific characteristics of knowledge of limb-length, it has been argued that the brain does have reasonably accurate values for these segment lengths and that these values enter into a wide variety of motor functions, even when visual information is available. Further, it has been suggested that knowledge of limb-length bears some relationship to a system which is concerned with a three-dimensional knowledge of limbs and that, in turn, both limb-length and any other facets of this tri-dimensional knowledge are part of a system of proprioceptive knowledge of the body (suggested by studies of phantom limb). Finally, knowledge of limb-length has been referred to as 'registered limb-length', implying that it refers to an internally-stored value which bears some relation to (is calibrated against) other systems which provide spatial information. In this respect it is seen as similar to the system which monitors registered limb position via knowledge of joint angle.

This section attempts to provide a more complete proposal for possible mechanisms underlying the knowledge of limb-length, keeping in mind that there is little experimental evidence which can be brought to bear on the question.

In a previous section it was argued that simple explanations of processes involved in tactile localization, in terms of local signs or topological organization of the cortex, were inadequate, even though no good alternative theory was available. It was subsequently argued that any attempt to provide the same solution for knowledge of limb-length would meet similar objections. The abandonment of this potential theory means that it has to be recognized that knowledge of limb-length cannot be viewed as the function of a single sensory system. Neither joint receptors nor muscle afferents could provide the type of information which is adequate to perform this function (c.f. Skoglund, 1973; Matthews, 1977).

Halnan and Wright (1960, 1961) have suggested that to carry out accurate tactile localizations, there must be activation of several central processes. Although giving some examples of the latter, they do not provide any specifications as to how the entire system might operate. Nor have there been any other proposals forthcoming since that time. Gibson (1966) considered the matter of tactile localization, and although he, as well, did not provide any specific proposals for its nature, the following theoretical statement is highly revealing:

> "The layout of physical surfaces, according to this (Gibson's) theory, is perceived by way of the disposition of body members when touch and posture are covariant. It is not that sensations from the skin and the joints are blended or fused when they occur together .... but that the <u>receptors combine in one system to register one</u>

> kind of invariant stimulus information. In this theory, the sensitivity of the skin should not be conceived as that of a mosaic of receptors, each with its own absolute local quality but simply as being differentiated. A locus on the skin consists of the set of differences between it and other possible loci. The discriminations are crude in the embryo and the infant, but they get better. Right and left, head and foot, belly and back are distinguished first. Then the large divisions get subdivided into smaller divisions. Finally, the exploratory members of the body (fingers, toes, lips, tongue) develop the highest degree of autonomous differentiation. It is not that the location of each spot on the skin has to be learned but that parts of the skin have to be separated from one another by a joint process of maturation and learning. The input of the joints and that of the eyes also differentiate at the same time. The cutaneous, articular, and visual systems are covariant during the exploratory activity of the developing individual. The 'images' of the body — cutaneous, skeletal, and visual — thus come to coincide (1966, page 114)."

Taking Gibson's notions as a whole, it is apparent that he believes there are two central proprioceptive systems, one serving knowledge of the skin and the other serving knowledge of the joints and that those combine in one system to produce a single piece of information about the body for other purposes (e.g. motor function). This latter system appears to be essentially the same as the 'proprioceptive knowledge system' suggested earlier.

Gibson also states that the cutaneous, articular, and visual systems are covariant. This notion of covariance appears similar to Craske's (1975) proposal that the spatial senses all map into the same space, a combination which provides the brain with information about the position of the body parts in space.

It is the present proposal that the proprioceptive knowledge system of the body contains a third major element in addition to knowledge of the skin and joint angles. This third factor would be a system of three-dimensional knowledge of the body including values for length and volume. It is suggested that the system of three-dimensional knowledge is covariant with (interfaces with) the articular and cutaneous systems and that all three elements of the proprioceptive knowledge system produce a single piece of information which is a combination of values of the form, length, and position of the various body segments. It is proposed that this information is essential in its entirety for any given motor function. Since it is also the action of this proprioceptive system which produces the phenomenon of phantom limb (as argued earlier), the proprioceptive knowledge system must monitor information from the entire body in a holistic fashion.

It is also proposed that the system of three-dimensional knowledge, along with the articular and cutaneous systems, interfaces with the visual system and is an integral part of the entire system which provides information about spatial location of parts of the body. It is further proposed that knowledge of limb-length (registered limb-length) is an acquired value obtained through the interactions of the various spatial systems in the manner similar to that described for cutaneous knowledge by Gibson (loc. cit.). Finally, it is proposed that registered limb-length is acquired in a fashion whereby it is cross-calibrated with the other spatial systems and is, hence, subject to recalibration if the need arises.

The proposition that there is knowledge of a three-dimensional system of the body (particularly registered limb-length), which forms an integral part of motor function, has been given in an earlier section through argument by logical necessity and argument by example. This system will, hereafter, be termed the 'body-space' system. Due to the generally-cylindrical shape of the body parts, body space is probably a two-part system involving distance (registered limb-length) and either volume (the space inside the skin) or circumferential distances and relationships (or possibly both). It seems that the only additional evidence which could be obtained for the existence of such a body-space system, is to demonstrate that its inferred values can be changed. Such a demonstration in the case of limb-length will be given in Part II of this dissertation.

The step from this proposal to the notion that the system of knowledge of body space constitutes a third major element of a system of proprioceptive knowledge of the body requires essentially the same assumptions. The suggestion that a proprioceptive knowledge system exists at all is given because of its necessity in explaining certain phenomena, such as the phantom limb (as argued earlier). For the proprioceptive knowledge system to be the source of phantom limb (that is, for it to be capable of producing a unitary piece of information concerning the proprioceptive state of the body) it would appear to require a knowledge of body space in addition to cutaneous and articular knowledge. If this were not the case, then the latter two systems would have no referents. They could refer to each other, but then the skin would be as easily interpreted as a flat sheet than as a structure wrapped around a bone. Without knowledge of a body space there could be no above and below, or left and right on the skin surface with respect to underlying bone. Loci on the skin could be differentiated from each other, but they could not be differentiated with respect to the relative length of the whole segment. It is, thus, this third element of body space which completes the proprioceptive knowledge system. However, it should be stated that it is not necessary to accept the role of knowledge of body space in the proprioceptive knowledge system, or to accept the latter at all, in order to acknowledge the necessary existence of a system of knowledge of limb-length.

The argument that the proprioceptive knowledge system must act in a holistic fashion (that is, that it produces a unitary perception of the body beyond that specifiable from receptor information alone) is again made by inference. It appears that proprioceptive events do not take place with respect to an isolated body segment but with respect to the whole body. The phantom limb has a specific location and position in space with respect to the whole body. Therefore, in the fashion that it was argued that proprioceptive activity must refer to the entire knowledge of the segment in question, so, also, would it seem to be required to refer to the entire structure of the body. Thus, the proprioceptive knowledge system monitors proprioceptive information from the entire body, and although it would appear to bear an integral relationship to its constitutional parts, the appearance of phantom limb suggests that it also operates in a holistic fashion to some extent.

The manner in which the spatial senses interact and in which registered arm length becomes acquired and calibrated with respect to them is a more complex affair. It is further complicated by the fact that registered limb-length does not appear to bear a direct relationship to any individual receptor system. This latter fact would imply that the system for knowledge of limb-length will be considerably different from those of the cutaneous and articular systems, possibly in the sense that the latter have a specific and constant set of sensory inputs which can modify or modulate previously-stored information on a regular basis, while the former is more of a tabula rasa on which successive, but irregular, estimates of limb-length are stored and averaged.

It would appear to be the case that knowledge of limb-length should be most closely aligned with cutaneous knowledge and vision, as the latter two systems are those which could provide direct information about distance. The cutaneous system could be envisaged to provide relative distance information (e.g. such that its receptive fields bear certain relationships to each other in terms of nominal position or order), while vision would provide a more direct and continuous flow of information concerning spatial relationships. With experience, the two become calibrated with respect to each other, such that a touch felt at a specific location should correspond (feel right) to the view of the object which is creating the touch. As mentioned, intermediary to those two mechanisms would have to be the system for body space. It would have to be cross-calibrated with both of the latter systems but totally dependent on neither. Hence, changes in either cutaneous or visual relations might be adequate for initiating a recalibration of the former. Whether knowledge of limb-length could, in turn, force a recalibration of cutaneous knowledge or vision is difficult to determine.

The articular system initally would seem to bear a less direct relationship, as it provides information primarily concerning position in space and detection of movement but not relative distance in space. However, the nominal order of the joint receptor sites could be spatially aligned with the other three systems and cross-calibrated in a fashion similar to the cutaneous system. Furthermore, it was argued previously that the articular system, along with cutaneous and body-space systems, constitute a proprioceptive knowledge system which has some independence from visual knowledge (viz. the phantom limb). Considering these aspects, it is difficult to make any definite statements concerning the relative role of the articular system to the other three systems.

The simplest overall solution would be to assume the following: The three proprioceptive systems are spatially aligned with each other (map onto the same space in the terminology of Craske, 1975) and cross-calibrated with each other, thereby forming the core of the proprioceptive knowledge system. At the same time, however, each is cross-calibrated with vision, a system of auditory localization and even possibly with a system of olfactory localization. As noted, this arrangement or alignment of the systems would be the simplest proposal for the interactive relationships among them. However, there is a possibility that some form of hierarchial relationship exists. Vision, for example, is known to exert a very powerful influence on at least one of the proprioceptive sub-systems. It has been well established from the prism adaptation literature (c.f. Welch, 1974; Crawshaw, 1974; Craske, 1975; and Kornheiser, 1976 for reviews) that a change in visual spatial information (i.e. via displacing prisms) resulting in a discrepancy between the spatial position of an object, as determined by vision and by kinesthesis, can result in a change in perceived position of a limb (registered joint angle). It seems very likely that a similar discrepancy could result in recalibrations of either of the other two proprioceptive systems. Similarly, since changes in registered arm position have been known to result from discrepant auditory information (Craske, 1966b), it is likely that spatial information from the auditory system could also result in recalibration of the other two proprioceptive systems. It is not yet known whether this relationship is reciprocal; and thus, the possibility that there are hierarchial relationships among these systems cannot be abandoned.

Finally, although the system of registered limb-length is likely to have flexible values, it is also probably the case that changes in these values are available only on a short-term basis and that a return to values established over a lifetime of experience is probably rapid. Changes in registered arm position resulting from prismatic displacement of the visual field do, in fact, rapidly return to normal values following prism removal (Harris, 1963). In fact, changes in registered postion of the eyes in the head appear to supercede those of registered arm position during prolonged exposure (Pick and Hay, 1964; Hay and Pick, 1966); and those also quickly revert to normal, indicating that these recalibrations are indicative of short-term adaptive mechanisms. The slow shrinkage of phantom limb, however, argues strongly that long-term changes in the values of registered limb-length are difficult to obtain and occur more slowly. It is, therefore, clear that knowledge of limb-length is not a temporary transient system but a thoroughly-established part of the proprioceptive system.

Summary of Part I

The topic of the possible existence of a system of knowledge of limb-length has been introduced and discussed as constituting a central component of kinesthetic, proprioceptive, haptic, and motor function. Its set of values has been termed 'registered limb-length', and it has been argued to be a system of considerable plasticity which may be capable of short-term adaptive recalibrations. A review of the literature in anatomy, physiology, neurology, and experimental and clinical psychology has failed to reveal any consideration of the subject, although some incidental findings and indirectly-related topics have been noted. Knowledge of limb-length has been argued to constitute, along with knowledge of limb volume, a higher-order system of knowledge of body space. This, in turn, was argued to be an essential third element of a proprioceptive knowledge system, of which cutaneous and articular systems are the other two elements. It has been suggested that values for registered limb-length are established over the lifetime of an individual through cross-calibration with the other elements of the proprioceptive knowledge system and with the other spatial systems (visual and auditory).

PART II

EXPERIMENTS ATTEMPTING TO DEMONSTRATE RECALIBRATION OF REGISTERED LIMB-LENGTH

General Introduction

As noted in the introduction to Part I, present interest in the potential modification of limb-length resulted from an experimental failure to find a likely and predicted joint angle recalibration in a prism wearing task. Utilizing procedures previously found to produce significant adaptation to prismatic displacement of the visual field (Harris, 1963; Craske, 1966a), a series of three unpublished experiments by Craske (1976) failed to demonstrate adaptive changes at the elbow joint when this was the only movable joint. The theoretical underpinnings of these latter experiments are described below with reference to Figures 1a and 1b.

Using base-up (downward-displacing) prisms and obscuring the pointing arm from view, Craske (1976) postulated that when subjects attempted to point to the real target (RT), they would move their forearm from the vertical starting position through an angle (ϕ) to a final pointing position thereby bringing it opposite the apparent target (AT) (Figure 1a). Subsequently, with error feedback, (allowing subjects to simultaneously see both their pointing arm in

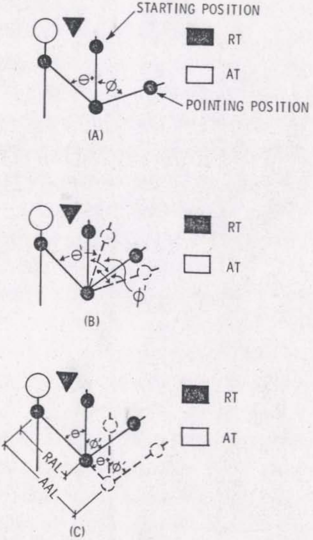

FIGURE 1

Illustrations of Potential Systems of Adaptive Changes
In Registered Position of the Forearm and
Registered Limb-Length (see text)

RT = real target; AT = apparent target

RAL = real arm length; AAL = apparent arm length

its final position and the visual target) subjects would find that they had missed (overextended), even though both the angle through which they had moved their arm and its final position 'felt right' (Figure 1a).

With additional trials, it was predicted that subjects would gradually correct their pointing and accurately locate the real target by moving their arm from the starting position through a new smaller angle (ϕ') thereby bringing their forearm opposite the real target (Figure 1b — solid lines). Since they would still be aiming for the apparent target, however, the motion of the forearm through the smaller angle (ϕ') should 'feel wrong' unless it is accompanied by a change in the registered angular starting position of the forearm (such that the angular difference between the real and apparent starting position is equivalent to the angular difference in the position of the arm when it is pointing at the real target as opposed to when it is pointing at the apparent target). Such a change resulting in a new 'felt' starting position of the forearm would make sense of both the movement and the final pointing position, as the angle through which the arm must now travel to reach the apparent target (Figure 1b — dotted lines) is (ϕ'), the angle through which the arm actually travels when subjects accurately locate the real target. The recalibration thus provides a system for accurate pointing. It was, consequently, predicted that a high level of accuracy on the pointing task should be coincident with a complete recalibrated change of registered position of the forearm with respect to the upper arm; that is, adaptation of the elbow joint. It should be noted, however, that adaptation should also result in a change in the apparent angular distance of the forearm from the arm, even though subjects are unable to see their arm in the starting position. The initial angular distance between arm and forearm is noted by the angle (θ) (Figure 1a); but the apparent angular distance following adaptation must be somewhat greater (θ') (Figure 1b).

Craske's (1976) failure to demonstrate adaptation at the elbow joint seriously calls into question the notion that in general, "....adaptive change is associated only with the used joint in the case where movement is restricted to one joint (Craske, 1975, page 128)" (see also, Hamilton, 1964). Additionally, since the subjects in these experiments did learn to accurately locate (point to or aim at) targets while wearing displacing lenses, it appeared necessary to postulate an alternative adaptive mechanism.

The nature of the above-mentioned experiments appeared to preclude the liklihood of adaptation at other joint positions and previous research (Pick and Hay, 1964; Hay and Pick, 1966) suggested that under these conditions a recalibration of the registered position of the eye in the head should occur more slowly. A consideration of all other potential mechanisms which might subserve the observed adaptive changes yielded only one possibility: a recalibrated change in registered arm length. An explanation of this potential phenomenon is given below with reference to Figure 1c.

It was noted above that subjects require some form of perceptual change or adjustment to serve as a basis for accurately moving their pointing arm through the smaller angle (ϕ') (Figure 1b); that suggested by Craske (1976) was a recalibration of registered forearm position with respect to the elbow joint. An alternative method might result from a recalibration of registered arm length if that recalibration resulted in an apparent lengthening of the arm. That is, if the adaptation task leads to a change in apparent arm length such that the resulting apparent arm length (AAL) (Figure 1c) is now actually somewhat longer than the real arm length (RAL), a system is provided whereby he can use the currently-registered elbow angle to point accurately to displaced targets (Figure 1c — dotted lines). This is achieved because the apparent lengthening geometrically preserves the smaller angle (ϕ') without altering any of the other angular relationships (i.e. he moves his forearm as if his arm was that much longer). In particular, the angular distance (θ) of the arm and forearm is unchanged, although the visually-apparent distance of the forearm from the eyes would be greater.

It should be noted that such a system would appear to require some additional changes in calculated positions of the body with respect to the environment. Since objective position of the elbow is fixed in this task, an extension of the arm would appear to require some revision of the apparent distance of the body from the object (usually a table) on which it is fixed. (However, possibly the two systems can operate independently depending on task requirements. Or, perhaps, one system is subordinate to the other and automatically readjusted by changes in the other).

An additional experiment was performed by Craske (1976) in an attempt to explore this hypothesis. He had subjects shoot a light-beam gun at vertically-arranged targets on a board roughly 2 m away while viewing through downward-displacing prisms. As before, movement was permitted only at the elbow during this adaptation task.

Craske's measure of registered arm length consisted of a marker which could be moved foreward and backward along a track which ran parallel to, and which was in close proximity to, a subject's adapted arm. Both the track and the arm were hidden from view. Following completion of adaptation trials, subjects were asked to indicate when they thought the marker was directly opposite the tip of their longest finger. Although adaptation appeared to result from the pointing (shooting) task, no experimental differences were found with this measure of registered arm length.

A reconsideration of Craske's experiment suggested two potential sources of difficulty. First, the 'light-beam' adaptation task was particularly difficult for subjects due to the extensive distance of the targets (small changes in joint angle producing large changes in displacement of the point of light at the level of the target), and although they reached criterion on this task, the reliability of the adaptation could be questioned. Second, and possibly more important, Craske's method of obtaining estimates of registered arm length was not necessarily appropriate to the adaptation process under investigation. As noted in Part I, visual estimates of body distances can lead to considerable error. In this case, however, the subject's arm and the visually-estimated distance did lie in the same plane of extra-somatic space which should improve accuracy. However, there was no kinesthetic component to the judgement task (i.e. subjects did not point with their other arm but simply verbally indicated when they thought the marker was opposite), so that the judgement was solely in the visual modality with kinesthetic factors serving only as a stimulus. It may be the case that the absence of a kinesthetic component to the judgement task either does not bring the full extent of the kinesthetic system to bear on the task, or overrides the adaptation effect, or both.

To check on this latter possibility, a pilot study was undertaken in which the adaptation task was the same as that employed by Craske above, but in which a new measure of registered limb-length was employed. It was considered that an appropriate approach to the latter problem might exist in requiring subjects to make a voluntary movement in which a knowledge of the length of the arm would be a necessary and integral part and in which any changes in performing the task would be interpretable solely in terms of a change (recalibration) in arm-length values. The type of task suggested in Part I, in which subjects have to locate a known or stimulated point on their body while their vision is restricted, seemed most suitable. The additional requirement that subjects keep their arm straight while performing the task was, of course, essential; and a well-known body landmark target (such as the knee, ankle, or foot) to which subjects could reach without elbow or wrist flexion (e.g. not the head or upper torso) was considered desirable.

In this pilot study, a modified replication of Craske's experiment, subjects aimed at targets through two eleven-dioptre, base-down (upward-displacing) prisms in the adaptation task (each subject also received a control task which differed from the adaptation task only in that no prisms were used). Using the rationale outlined above for potential arm length changes, it was predicted that adaptation should result in a recalibration of registered arm length such that the arm is perceived to be shorter (than e.g. in the control task). This is simply the reverse of the change outlined earlier and illustrated in Figure 1c.

To measure arm length, each subject was placed in front of a plexiglas panel against which they pressed their right knee. They were then required to bend down from the waist over the panel and with their right arm held stiff and extended at the elbow and wrist, attempt to place a marker pen held in the right hand directly opposite their right knee. This procedure resulted in subjects making pen marks on a single piece of graph paper. The marks were later scored for vertical distances between points made before and after the adaptation task. The differences in mean scores was used as a direct estimate of the change in registered arm length occurring as a result of the adaptation task. If the difference between the two means was due to subjects overreaching the target during adaptation trials, this was considered to be an indication of an apparent shortening of limb-length (e.g. in compensation for the shorter arm); while if the difference was due to subjects underreaching the target, it was considered to be indicative of an apparent lengthening. A more detailed description of this method of deriving arm length measures is given below in Experiment 1 and is also discussed in Experiments 2, 3, 5, and 6.

The results of this pilot study showed no overall statistical difference between adaptation and control groups (subjects served as their own controls with respect to the registered arm length measure), although all subjects reached criterion on the adaptation task itself. Non-statistical perusal of the data, however, suggested that approximately half of the ten subjects used in the study showed extensive and consistent changes in registered arm length in the predicted direction while the other half showed no consistent changes. The presence of the former group was considered to be an encouraging sign that recalibrations of arm length can be effected and provided impetus for further investigation. It also suggested that such a process may be only one of two or more potential adaptive mechanisms in a given individual and that it will not necessarily be the preferred choice for all subjects in any given adaptation task.

On the basis of the findings by Craske (1976) which suggested that adaptive recalibrations of joint angle at the elbow may not occur when movement is restricted to that joint, and on the basis of the above-described pilot study, which suggested that recalibration in registered arm length may, in fact, take place, a series of experimental investigations was undertaken with the purpose of confirming or disconfirming the existence of the latter type of adaptive change. Some knowledge of the principles of such a system once established, and its place in the domain of kinesthetic and motoric systems were considered desirable secondary goals.

Experiment 1

The aforementioned pilot study was only of heuristic value in examining the hypothesis that prism adaptation can lead to recalibration in registered arm length, but it did lend encouragement to the notion that such a phenomenon does, in fact, exist. In particular, it suggested that while some subjects adapt to prisms in this fashion, others possibly display a preference for some other adaptive system. The most likely alternative system would be an adaptive change of registered position of the arm with respect to a joint (Harris, 1963; Craske, 1966a), although a less-likely source might potentially be complete adaptation with respect to registered position of the eyes in the head. This is less likely because the majority of studies in this field suggest that the preponderance of initial adaptive changes take place with respect to the articular joints and that complete adaptation of the eye/head system is established only after a considerable period of exposure, possibly only after several days (see Hay and Pick, 1966; Pick and Hay, 1964). Therefore, even though the experiments by Craske (1976), described in the General Introduction to Part II, failed to show adaptation at the elbow, it was felt that another major effort to confirm or disconfirm adaptation at this or any other joint, was in order at this stage of investigation, particularly if it could be combined with a major attempt to demonstrate adaptive changes in registered arm length.

Besides the elbow joint, only the shoulder joint could be conceived of as being a potential site of adaptive change. Figures 2a and 2b illustrate how a recalibration of the registered position of the arm with respect to the shoulder could conceivably result in successful adaptation. Figure

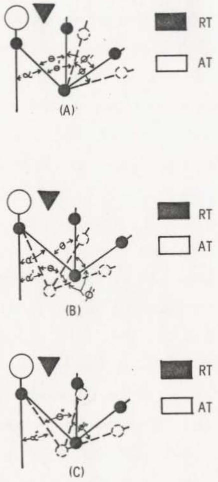

FIGURE 2

Illustrations of Potential Systems of Adaptive Change In Registered Position of Forearm and Arm with Respect to the Shoulder and Elbow Joints (see text)

RT = real target; AT = apparent target

2a is a reproduction of Figure 1b and shows the relationship between the real starting and pointing position of the arm (solid lines) and its apparent starting and pointing positions (dotted lines) during adaptation trials when recalibrated change of registered forearm position takes place with respect to the elbow. Besides the geometric preservation of the angle (ϕ'), there is an angle (α) between the arm and the body with respect to the shoulder, which is assumed constant.

Figure 2b shows the change in perceived arm position that would accrue if there was a recalibration of registered arm position with respect to the shoulder. In this instance the arm is perceived as being closer to the body (Figure 2b — dotted lines) than it actually is (solid lines) as a result of the recalibration, which in effect reduces the angle (α) to a somewhat smaller angle (α') since the elbow is fixed in place. However, this recalibration is not necessarily any different than that which would occur if the joint was freely moving. In any event, the adaptive change provides a system whereby a subject can move his arm through the angle (ϕ') and be accurate in locating targets, as this required angle (see above) is geometrically preserved by the recalibration at the shoulder. The recalibration also preserves the angular arm/forearm distance (θ) (Figure 2b), however, as with the recalibration of forearm position, it also results in a change in the distance of the perceived starting position of the forearm from the eye. Furthermore, the recalibration also requires (as noted for potential change in registered arm length) a change in apparent distance of the body and the table on which the elbow is fixed, as the elbow must be somewhat lower in its new (apparent) position. As a consequence, it is not clear which of the two types of recalibration (at the elbow and at the shoulder) would be most parsimonious. Recalibration of the arm with respect to either the elbow or shoulder would be the most likely source of adaptive change, but a third possibility in which a recalibration of registered arm position with respect to both joints simultaneously must be considered (Figure 2c). In this instance the recalibrations might be small at both joint sites, with the angle (α) being perceived as slightly smaller (α'') resulting in a recalibration of the arm with respect to the shoulder, while simultaneously a recalibration of the forearm at the elbow takes place in which the real angle (ϕ') is perceived to be slightly larger (ϕ'') but in which the increase in the angular distance of the arm and forearm is less than when the full adaptation takes place at this joint alone (e.g. the angle (θ) is perceived as being increased to only (θ'') (Figure 2c) which is less than (θ') (Figure 2a)). The possibility of this combined recalibration exists to the extent that the changes in elbow angle might have been small enough to have escaped detection in previous experiments. It was decided, therefore, that the first experiment should not only evaluate potential changes at the shoulder and elbow joints but should look for a possible combination of the two.

On the basis of the results of Craske (1976) and the previous pilot study, it was predicted for the present experiment that adaptation to prismatic displacement occurring when movement of the arm was permitted only at the elbow joint, would result in a recalibration of arm length but not a recalibration of arm position with respect to either joint location. A second minor hypothesis was held, however, that while this phenomenon should hold true for most subjects, those subjects not showing adaptive changes in arm length would show adaptive changes at either the elbow or shoulder joints or both.

Although both the experiments by Craske (1976) and the present pilot study utilized adaptation tasks which permitted movement only at the elbow, some concern was felt that the rather large (2m) distance of the subject from the target was problematic, particularly as many subjects had much difficulty acquiring accuracy in the task. Furthermore, as noted by Ogle (1964), prisms produce varying types of distortions of the optical image, one of which is "....an increasing angular magnification of the image toward the apex in the base-apex meridian (1964, page 130) (see also Ames, Ogle, and Gliddon, 1932)." Given a 2m distance, this distortion might be extensive enough to cause significant changes in depth perception and, hence, affect the adaptation process accordingly. It was decided, therefore, to design a new apparatus which could efficiently combine 1) an adaptation task utilizing a target that was close to the subject, with 2) a system for measuring changes in one or more joints.

METHOD

Subjects: A total of 15 paid volunteer subjects of either sex participated in this study. Prior to entering the study, each subject was given a test for large ocular phoria, using a standard Maddox rod. Subjects with deviations of plus or minus four or greater were not permitted to participate in the study since a heterophoria could produce a fixation disparity of sufficient degree to significantly alter the perception in depth of the target (and, hence, alter the experimental conditions). This effect could also be magnified by viewing through displacing prisms since these may act differentially on each eye; and also, since they produce their own distortions of the visual image (c.f. Moses, 1975; Ogle, 1964). This subject restriction was also used in Experiments 2 and 3.

Prior to the first experimental session, each subject was given a complete explanation of the experimental procedure but no information as to its nature or purpose. All positions and movements required of subjects were first demonstrated by the experimenter.

Format: Each subject participated in two experimental sessions, each lasting approximately one hour. Subjects served as their own controls; and thus, one session was an experimental session in which subjects viewed targets through displacing prisms, while the other was a control session in which all conditions remained the same except that no prisms were used.

Both the experimental and control sessions consisted of two parts: 1) a prismatic adaptation task in which subjects pointed to vertically arranged targets and 2) a set of tasks for the measurement of perceived joint angles and arm length. A number of these sets of dependent variable measurements was taken prior to the adaptation task and constitute pre-experimental scores, while others were taken after each block of trials of the adaptation task and which, therefore, constitute post-experimental scores. Subjects were also subdivided according to whether they received the control or experimental session first (see below). Finally, an arbitrary decision was made to use base-up, downward-displacing prisms in the study. According to the theoretical rationale given earlier, any changes in registered arm length should be in the direction of an apparent lengthening of the limb.

Apparatus and Tasks: Each subject was required to perform five separate tasks. One was the adaptation task, noted above. Four constituted a set of measurement tasks of which three were movements requiring subjects to estimate joint angles and one was a movement requiring subjects to locate a particular landmark on the body (in order to derive an estimate of arm length). All tasks were performed while subjects sat in a chair in front of the experimental apparatus. This is illustrated in Figures 3a and 3b. Figure 3a gives a side view (subject's left-hand side) of the apparatus, while Figure 3b gives an overhead view from the subject's rear right-hand side. Any given subject sat in the small low chair, along side and to the right of which was a 50 X 50 cm plexiglas marking panel (Figure 3a). The chair was fixed to the floor and the panel supported with steel rods, climpex holders, and clamps. Directly in front of the subject was a 1.2 X 0.9 m plexiglas target panel. This panel was constructed of two complete sheets of transparent plexiglas separated by small pieces of plexiglas around the top, bottom, and inner edges of the

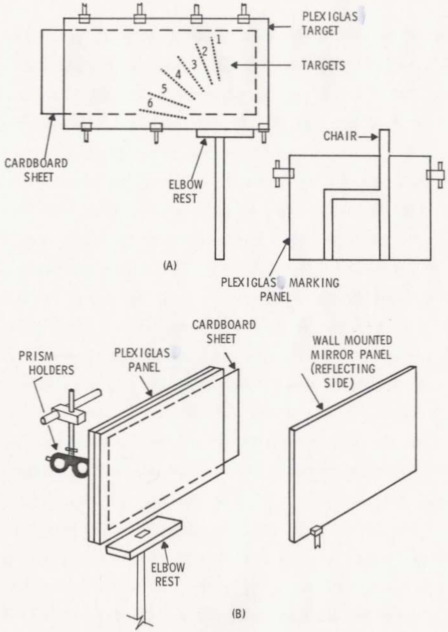

FIGURE 3

Experimental Apparatus used in Experiment 1

A — Side View
B — Overhead View

panel. This arrangement permitted the insertion of a white opaque cardboard sheet 5 cm smaller than the panel on the top and bottom sides and 10 cm longer in length. With the sheet in position, subjects could not see through the target panel. However, the sheet could be pulled back by the experimenter to permit a subject a complete view of the right-hand side. Attached to the left-hand side of the target panel were six striped targets numbered one through six. These targets were always visible to subjects. Each was of equal length (20 cm), and they were arranged in a radiating fashion in a quadrant with the centre of the elbow rest serving as axis. The targets were spaced approximately 10 degrees from each other and were at a distance of about 25 cm from the centre of the elbow rest at their lower end. The elbow rest was constructed of foam; and there was, in addition, a smaller, 4 X 4 cm, foam button on which subjects were to place and keep their lateral epicondyle (elbow).

Mounted on the wall, 1 m from the target panel (to the subject's right as he is seated) was a large 1.5 X 1 m mirror with the reflecting side facing the apparatus (illustrated in Figure 3b only). The mirror was used in the measurement of joint angle (to be described below). Prism holders were mounted on the left-hand side of the target panel using an aluminum rod and clamps (illustrated in Figure 3c only). Subjects leaned very slightly forward to fit their noses into the holder which could be adjusted in any direction to provide subjects with an adequate viewing perspective. Adjustments were made in the position of the holders during practice trials so that subjects were satisfied that they had a full view of the six targets at all times.

As mentioned, subjects were required to perform five separate tasks. The first of these was an adaptation task in which subjects viewed the targets through the prism holders. These contained no prisms during control sessions but held two 11 dioptre, base-up (downward-displacing) wedge prisms during experimental sessions (see below). The cardboard sheet was always in place at the beginning of each trial, so that subjects could not see their right hand or arm. At the beginning of each trial, subjects held their right arm in the upright position (perpendicular to the floor) with their lateral epicondyle on the foam button. The right hand was held in a fist, except for the index finger which was held out straight, and the right forearm faced inward, palm toward the pane. The entire right arm was about 2 cm away from the right-hand side of the target panel.

To start, the experimenter called out the number of one of the six targets (according to a pre-determined random order). The subject would then extend his forearm downward moving only at the elbow and attempt to bring his index finger opposite the cited target. When satisfied that his finger was directly across from the target, he pressed it in against the panel and held it there. The experimenter then drew back the cardboard sheet allowing the subject to see through the panel and noted the accuracy of his performance. The sheet was held in this open position long enough for the experimenter to certify a hit or miss and for the subject to get a satisfactory view of his index finger in relation to the target (usually 3 to 5 seconds). A hit was predefined as any part of the index finger directly opposite the target stripe, from the subject's viewpoint (some slight parallax problems emerged here from the difference between the experimenters' and subjects' visual directions and subjects were asked to concur on questionable calls with deference going to them). Subjects were also instructed not to move their fingers once they had placed it opposite a target, and to keep it there until the cardboard sheet had been replaced. Subjects were given four to five practice trials on this task prior to each session (without prisms).

In the second task (first of the four measurement tasks), subjects attempted to locate their right ankle with a pen held in their right hand. Prior to the experimental session, when each subject was seated at the chair, his right foot was positioned so that the heel pressed firmly against a heel marker and the lateral malleolus of the ankle pressed lightly against the plexiglas marking panel (Figure 4). He was asked not to move his foot from this position for the duration of the experiment. Each subject was then shown that slight pressure against the panel with the lateral malleolus would assist him in locating it during the task. Subjects were permitted freedom of movement of all joints except the right elbow, wrist, and knee. The right foot, as noted, was positioned somewhat posteriorly so that it, in fact, fell just anterior to the shoulder in the normal sitting position. Thus, only a very slight movement foreward with the upper torso or a slight extension of the arm at the shoulder brought the hand in the same vertical plane as the ankle. Figure 4 illustrates this position.

In the task, itself, each subject was given a marker pen which he held in his right hand. He then held his right arm out over the plexiglas panel and attempted to align it opposite to where he felt his ankle to be (defined as the right lateral malleolus for present purposes).

FIGURE 4

Illustration of Subject Attempting to Position
A Marking Pen Opposite his Ankle (Lateral Malleolus)
In Experiment 1

During this alignment, subjects were required to keep their right arm stiff at the elbow and wrist joints and to hold the marker pen in the fingers parallel to the floor (horizontally) in the manner that one would hold a pen. Any type of movement was permitted at the shoulder joint. A horizontal swing of the right arm in the saggital plane could be effected by extension or flexion at the shoulder joint. Up-and-down (vertical) movements of the right arm could be achieved either by raising or lowering the upper torso or by raising or lowering the shoulder (with or without rotation of the scapulae).

When satisfied that the pen was directly opposite the centre of their lateral malleolus, subjects brought the pen in against the panel, thereby making a single mark on recording graph paper which had been previously placed there. Subjects were then required to straighten up prior to repeating the procedure. No time limits were placed on any part of the trial, with subjects being encouraged to take as much time as they felt they needed to achieve maximum accuracy. The major movement in the task was a bending of the whole upper torso at the hip, although rotation of the shoulders at the scapulae undoubtedly occurred as well.

Subjects were given at least two (and permitted up to five) practice trials at this task prior to each experimental session. During the last of these practice trials (in which the marker pen was capped), 21.5 cm X 28 cm graph paper was positioned on the panel using double-sided adhesive tape. Rather than position the graph paper with respect to the subject's ankle (for reasons stated below), the subject was asked, after one or two practice trials, to perform the task but to hold the pen in place opposite his ankle. The experimenter then slipped the paper under the pen and positioned it so that the pen fell roughly in the centre of the paper. This was done regardless of the position of the subject's ankle. The graph paper was then left in place for the duration of the session.

The graph paper was not positioned with respect to the ankle alone because it was deemed too difficult, if not impossible, to determine an absolute centre of the ankle or to communicate that spot to the subject. Even though the lateral malleolus constitutes a reasonably small area, there is considerable variation in its size and shape from person to person. Since two sets of markings were required of subjects (before and during adaptation trials — see below), it was felt that the relative difference between the two sets would provide an adequate index of change in registered arm length as discussed above. Subjects were, thus, instructed to aim for the centre of the ankle whereever they determined that to be and to aim for the same spot throughout the experiment. Appendix A illustrates the marks made by one subject after performing this task, the blue marks being those made prior to adaptation and the red marks being those made during adapation trials. Subjects were blindfolded in this, as in all measurement tasks.

In the third task, designed to evaluate changes in joint angle at the shoulder, subjects were asked to hold their arm straight out in front of them (in the saggital plane), thereby approximating a ninety degree angle at the shoulder/torso. Instructions were only for the arm to be held straight out in front, however; and the experimenter demonstrated the position to each subject prior to the experiment. In the fourth task, designed to evaluate changes in joint angle at the elbow, subjects rested their elbow on the pad with their forearm extended and were then asked to flex the arm at the elbow until they thought a ninety degree angle had been formed at that joint. The last task, designed to evaluate changes in both elbow and shoulder joints simultaneously, was performed in the manner of the previous task, except that subjects brought their forearm up to the 'upright' position (in which the forearm is perpendicular to the floor) (see Figure 6). It can be reasonably easily ascertained that this judgement does, in fact, require both knowledge of the elbow joint angle and shoulder joint angle simultaneously and a misjudgement at either site would be capable of distorting the judgement. Once each task was performed by the subject, he was required to hold it in that position until the experimenter indicated that he had completed his measurements. Subjects remained seated in these, as in all tasks.

To measure joint angles, a system was devised using two plexiglas plates which could be attached to the target panel in any position by means of clamps and two-sided adhesive tape. On each panel an arc was scribed and marked in degrees throughout its length. For measuring shoulder angle the radius of the arc was 40 cm (an average wrist-to-shoulder distance), with the ninety-degree point falling in the centre of the plate (Figure 5). Points below this mark decreased towards zero, and points above increased in the direction of 180, although the arc did not reach these points in either case. To measure shoulder angle, a small black mark (1 cm in length) was made on the left side of each subject's wrist (at the level of the ulnar styloid process). Prior to the experiment, during practice trials, the plate was positioned on the left-hand side of the target board so that when subjects held their arms out straight the black mark on the arm was aligned with the ninety-degree mark on the plate. Two to four trials were made so that the plate was fixed adequately with respect to both the vertical and horizontal directions.

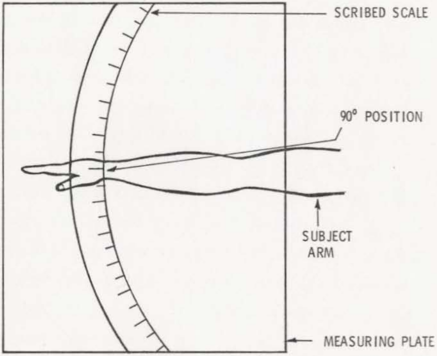

FIGURE 5

Illustration of Scribed Plate for
Measurement of Straight-Out Arm
Position in Experiment 1

To read the angle during experimental trials, the experimenter viewed the right arm from the left side of the target panel, that is through the target panel and the measuring plate and directly opposite the black mark on the wrist. The experimenter then moved his own head and body until the subject's arm was aligned with its image in the mirror behind it. Only when the two were aligned was the angle of the black wrist mark read off from the plate to the nearest whole angle and recorded. Some error occurred as a result of slight movements of subjects' arms during measurements; however, it was felt that this influence balanced out in either direction over the course of the experiment.

For measuring elbow angle and the upright position, the radius of the arc scribed on the second plate was 20 cm (an average elbow-to-wrist distance) (Figure 6). A second black mark was made on each subject's wrist, but this mark was placed in the centre of the inside of the wrist (i.e. roughly opposite the lunate facet). The point on the arc on the plate which was aligned with the vertical (upright) was given a value of 90 degrees. Points to the left of this mark increased in units of one degree of arc, while points to the right decreased by the same amount. The ninety-degree point on the plate was aligned with the black mark on subject's wrist during practice trials. With the plate positioned as described, it was expected that subject's

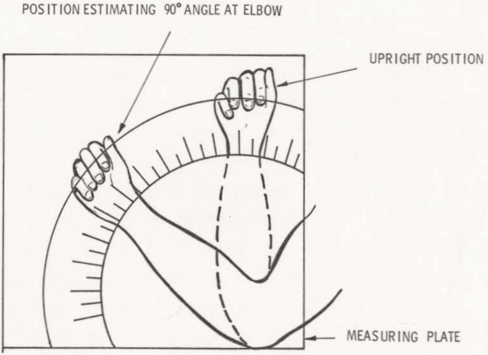

FIGURE 6

Illustration of Scribed Plate for Measurement
Of 90 Degree Angle at the Elbow (Solid Lines)
And for Measurement of the Upright Position
(dotted lines) in Experiment 1

scores would centre around the ninety-degree point when they formed the upright position and around 135 degrees (90 + 45) when they formed the ninety-degree elbow angle. Reading of the angles in both tasks were carried out as described above for the shoulder-angle task.

PROCEDURE

The experiment, itself, consisted of two sessions run on two separate days. Subjects served as their own controls so that one session was a control session and one an experimental session. Eight subjects received the experimental session before the control session, and seven subjects received the control session first. The assignment of subjects to groups was made by generating a random binary order prior to the experiment and assigning subjects in the order in which they signed up for the experiment on the basis of this series.

As mentioned, two 11-dioptre, base-up (downward-displacing) wedge prisms were used in the experimental sessions while no prisms were used in the control sessions. Following practice trials in either of the experimental sessions, subjects were blindfolded, and began the experiment proper by performing ten blocks of the four measurement tasks, each task being performed once in each block. All four tasks within each block were randomly varied using a pre-arranged randomly-generated series, but the same overall pattern was used for each subject.

Following the ten blocks of four tasks (resulting in 40 separate measurements), blindfolds were removed, and subjects adjusted their heads into position under the prism holders. They then performed the adaptation task to criterion. Criterion in this instance was three consecutive hits. On reaching criterion, subjects were again blindfolded, and they performed one block of the four measurement tasks (the first post-adaptation measures). The adaptation task and single blocks of the measurement tasks were then alternated until a total of ten of each had been completed. This marked the end of the session. A total of ten pre-adaptation scores and ten post-adaptation scores were, thus, obtained for each of the four measurement tasks. For the measurement of registered arm length, a blue marking pen was used for pre-adaptation trials and a red pen for post-adaptation trials. Subjects were not permitted to see the marks they had made in either session until the completion of the entire experiment.

RESULTS AND DISCUSSION

Figure 7a presents the pre/post adaptation means for experimental and control conditions for subjects' estimates of the straight-out position. This graph shows that the pre-

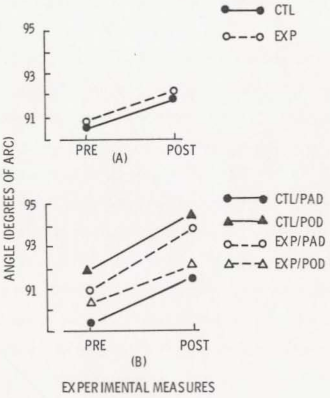

FIGURE 7

Pre/Post Changes in Shoulder-Joint Angle (Straight-Out Position) in Experiment 1

A — Data for all Subjects (N = 15)

B — Data for Pre-adapted Group (PAD) (N = 8); and Post-Adapted Group (POD) (N = 7) adaptation means were nearly equal for the control and adaptation conditions (90.3, s = 2.59 and 90.6, s = 3.10 respectively), and both were approximately two degrees greater at post-test (92.6, s = 2.70 for the control condition and 92.8, s = 3.90 for the experimental condition. No difference would appear to exist between the conditions.

To test for significant differences among the means, a three-way mixed model analysis of variance was performed on the data. This analysis was carried out using the Balanova Computer program (1968) as were all subsequent analyses of variance in the present study. Observations made during the experiment suggested that some differences might exist depending on whether subjects received the control session or adaptation session first. Consequently, this was made the first factor of the analysis (order) and subjects were nested within this factor only. The second factor was conditions (control vs. adaptation) while the third factor was repeated measures (pre/post). Table 2 presents the summary for this analysis.

This analysis revealed a significant main effect for measures indicating that there was, in fact, a true two-degree change in angle from pre- to post-measure for both experimental and control conditions. The absence of a significant condition-by-measures interaction shows the lack of differences between the two conditions and confirms the prediction that adaptation does not result in a recalibration of this joint.

TABLE 2

Summary of Results of Analysis of Variance of Subjects' Estimates of the Straight-Out Arm Position — Experiment 1

Source	SS	df	MS	F	P
Order	11.75	1/13	11.75	0.43	N.S.
B. Subjects	353.00	13	27.15		
Conditions	0.77	1/13	0.77	0.08	N.S.
Order X Conditions	57.38	1/13	57.38	6.29	<.05
W. Subjects	118.44	13	9.11		
Measures	77.52	1/13	77.52	30.98	<.01
Order X Measures	0.57	1/13	0.57	0.23	N.S.
W. Subjects	32.53	13	2.50		
Conditions X Measures	0.01	1/13	0.01	0.01	N.S.
Order X Conditions X Measures	1.97	1/13	1.97	3.65	N.S.
W. Subjects	7.01	13	0.54		

The analysis, in addition, revealed a significant order-by conditions interaction suggesting that adapting before or after the control session did have some bearing on the results.

An examination of the three-way interaction depicted in Figure 7b shows a two degree pre/post increase in all conditions regardless of order but also appears to show that the mean shoulder angle in both pre- and post-measures are approximately two degrees lower for the <u>second</u> session regardless of whether this was a control or experimental session. This effect is seen more clearly by considering the means of the two-way (order-by-conditions) interaction. The mean score of pre-adapted subjects is 92.19 in the experimental condition (received first) and 90.14 in the control condition (received second). However, among post-adapted subjects, the results are opposite; the mean in the experimental condition (received second) is 91.11 while the mean in the control condition (received first) is 92.98. Therefore, it would appear that some change occurs in the first session which results in a drop in judged angle during the second session regardless of the experimental condition. Since the values of the second session are closer to 90 degrees, it would appear that the change is simply one of increased accuracy for the task.

This increased accuracy effect explains the order-by-conditions interaction, but it does not explain the pre/post change of two degrees occurring in all groups. The latter change would appear to be some type of postural after-effect, probably resulting from the body-and-arm position held during the adaptation task (e.g. while subjects were pointing at the targets). In this task the angle at the right shoulder between the body and the arm was probably in the range of 75-80 degrees while subjects rested their arm on the elbow pad, and this is considerably greater than the angle maintained at that joint under normal circumstances. This difference would appear to be a sufficient condition to involve postural persistence (Jackson, 1954) of one or two degrees and thereby provide a reasonable explanation of the changes occurring in both experimental and control groups. Neither of these two noted effects are of particular importance to the present hypothesis, and further analyses were not undertaken. The important finding for present purposes was the absence of the conditions-by-measures interaction which supports the expectation that prismatic adaptation does not occur at the shoulder joint, given that the movement is restricted to the elbow joint.

Figure 8a presents the pre/post adaptation means for experimental and control conditions for subject estimates of a ninety-degree elbow angle. It suggests that both conditions declined very slightly from pre- to post-test but that no difference exists between them. The means are 108.9 (s = 6.50) and 108.2 (s = 7.37) for the pre- and post-means of the control condition respectively and 109.0 (s = 6.82) and 107.9 (s = 6.49) for the pre/post means of the experiment condition respectively.

A three-way analysis of variance performed on these data is summarized in Table 3.

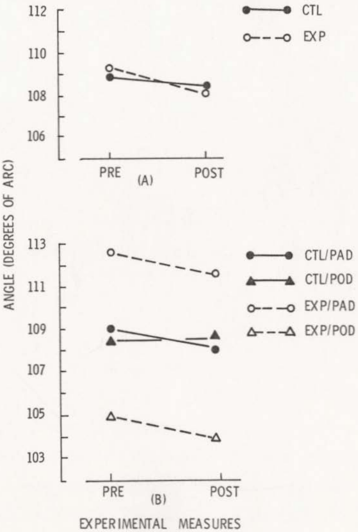

FIGURE 8

Pre/Post Changes in Elbow-Joint Angle
(90 Degree Position) in Experiment 1
A — Data for all Subjects (N = 15)
B — Data for Pre-adapted Group (PAD) (N = 8);
and Post-adapted Group (POD) (N = 7)

TABLE 3

Summary of Results of Analysis of Variance for Subjects' Estimates of Elbow-Joint Angle — Experiment 1

Source	SS	df	MS	F	P
Order	231.74	1/13	231.74	1.54	N.S.
B. Subjects	1954.46	13	150.34		
Conditions	0.10	1/13	0.10	0.00	N.S.
Order X Conditions	217.06	1/13	217.06	10.19	<.01
W. Subjects	276.96	13	21.31		
Measures	11.88	1/13	11.88	2.21	N.S.
Order X Measures	0.37	1/13	0.37	0.69	N.S.
W. Subjects	70.03	13	5.39		
Conditions X Measures	0.94	1/13	0.94	0.44	N.S.
Order X Conditions X Measures	1.18	1/13	1.18	0.55	N.S.
W. Subjects	27.70	13	2.13		

As with the measure of shoulder-joint angle, the failure to detect a significant conditions-by-measures interaction supports the prediction that adaptive changes do not occur at this joint. But, also, in accordance with the previous analysis, there is a significant order-by-conditions interaction. A plot of the means of the three-way interaction (order-by-conditions-by-measures) is given in Figure 8b. This appears to be almost a mirror image of the results for judgement of the straight-out position depicted in Figure 7b. As with the previous results, the scores in the second session appear lower than those in the first, regardless of whether or not they are experimental or control conditions. The two-way interaction (order-by-conditions) means for pre-adapted subjects are 112.09 in the experimental condition (received first) and 108.61 in the control condition (received second). However, among post-adapted subjects, the experimental mean is 104.34 (received second) while the control mean is 108.49 (received first). This pattern is nearly identical to that found with previous measure and would, therefore, also appear to reflect increased accuracy. However, it is difficult to ascertain whether the drop from the first to second session actually does reflect increased accuracy for the angles measured in this task do not directly correspond to elbow angles but reflect only change in angle. Considering the first analysis, however, an increase in accuracy resulting from familiarity with the task is the most likely hypothesis. Although interesting in its own right, this interaction was not of particular concern for the present hypothesis and was not pursued further. It appears to be the case from the foregoing analysis that adaptive changes do not take place at the elbow joint. This lends support to the unpublished findings of Craske (1976) as noted in the Introduction to Part II.

For subject's estimates of the upright position, the pre/post control means are 94.29 ($s = 3.47$) and 93.17 ($s = 4.13$)

respectively and for the experimental condition they are 94.30 (s = 4.12) and 93.83 (s = 4.28) respectively. Since these means are so close, there appeared little point in presenting a graphic display. The summary of the three-way analysis of variance for this variable is presented in Table 4 and shows the complete absence of significant main effects and interactions of any kind.

TABLE 4

Summary of Results of Analysis of Variance for Subjects' Judgement of the Upright Position — Experiment 1

Source	SS	df	MS	F	P
Order	61.24	1/13	61.24	1.35	N.S.
B. Subjects	589.42	13	45.34		
Conditions	1.91	1/13	1.91	0.11	N.S.
Order X Conditions	46.30	1/13	46.30	2.78	N.S.
W. Subjects	216.41	13	16.65		
Measures	10.00	1/13	10.00	3.34	N.S.
Order X Measures	1.50	1/13	1.50	0.50	N.S.
W. Subjects	38.89	13	2.99		
Conditions X Measures	1.38	1/13	1.38	1.38	N.S.
Order X Conditions X Measures	0.06	1/13	0.06	0.06	N.S.
W. Subjects	13.00	13	1.00		

Since the judgement of the upright requires knowledge of both elbow and shoulder angles, this analysis would appear to suggest that adaptation does not result in small recalibrations of both joint angles simultaneously.

The preceding three analyses have demonstrated three points. First, it is clear that prismatic adaptation does not result in a recalibration of either the elbow or shoulder joints, nor any combination of them, when movement is restricted to the elbow joint. Second, the adaptation task, itself, did lead to small changes from pre- to post-test in both experimental and control conditions for shoulder angle estimates; and these changes are consistent with postural persistance at the shoulder. Finally, significant changes in task performance occurred from the first to the second session for both shoulder-joint and elbow-joint estimates, regardless of whether the first session was experimental or control; and this effect has been interpreted as reflecting an increase in accuracy in task performance where subject responses are possibly approaching some form of constant.

In the Introduction, a secondary hypothesis was suggested that subjects who do not adapt by recalibrating arm length would show adaptation at joint angles. Non-statistical examination of the performances of individual subjects showed no evidence of any single individual producing adaptive changes at a joint regardless of change of arm length.

The last dependent variable to be examined in this experiment was derived from the marks made by subjects during their attempts to locate their ankle. As the marks made by subjects on the graph paper in the ankle-location task had no absolute or fixed point from which they could be measured, the following scoring procedure was adopted. The ten pre-adaptation marks for each session for each subject were scored by measuring their vertical distance from the top line of the graph paper (in mm). A mean of these values was taken but rounded to the nearest cm. This mean distance was taken as the new origin from which all points were to be measured (remeasured in the case of pre-adaptation marks). The purpose of this method of scoring (hereafter referred to as the altered-origin method) was, in the absence of a fixed target point, to bring all the pre-adaptation means in all conditions and groups closer to the same value without artificially altering their distribution or variance. This new origin was subsequently given the value of 127 mm (5 inches) simply to avoid negative values during scoring and analysis. Means for each subject were calculated for pre- and post-adaptation scores, and these means were entered into all subsequent statistical analyses. This particular measure will hereafter be referred to as the ankle-location distance. Changes in this measure can be interpreted as noted earlier (i.e. increase in ankle-location distance can be taken as a direct indication of apparent shortening of registered arm length, while a decrease reflects an apparent lengthening).

The mean changes in ankle-location distance are illustrated in Figure 9a and appear to indicate a small pre/post increase in mean distance in the experimental condition. The direction of change is, however, opposite to that predicted prior to the experiment since a lengthening of subjective arm length (as predicted) should produce a decrease in mean distance. A summary of the three-way analysis of variance for this measure is given in Table 5.

This analysis shows that all main effects and all interactions were significant including the three-way interaction (order-by-conditions-by-measures). The means of this interaction are plotted in Figure 9b. It appears fairly clear from the graph that all significant effects can be safely attributed to the single and substantial pre/post change in pre-adapted (PAD) experimental condition.

As a check, however, some tests for simple effects were carried out following Winer (1971) (using a modified error term for comparing between subjects). Within the pre-adapted group, the experimental condition yielded a significant pre/post change ($F = 15.81$, $df = 1/13$, $P < .01$). The control condition was on the contrary not significant ($F = 0.07$, $df = 1/13$, N.S.).

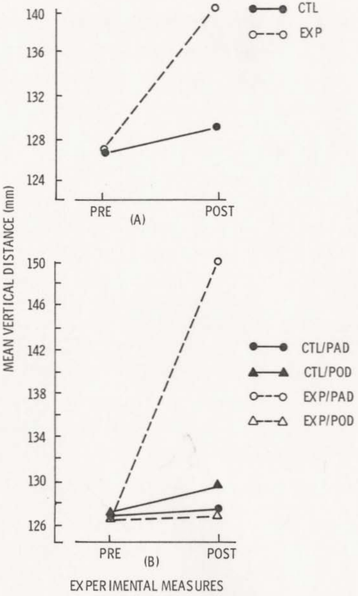

FIGURE 9

Pre/Post Changes in Mean Vertical Distance in the Ankle-Location Task in Experiment 1

A — Data for all Subjects (N = 15)
B — Data for Pre-adapted Group (PAD) (N = 8); and Post-adapted Group (POD) (N = 7)

In the post-adapted group, the experimental condition did not produce any significant differences (F = 0.02, df = 1/13, N.S.) nor did the control condition (F = 0.37, df = 1/13, N.S.).

TABLE 5

Summary of Results of Analysis of Variance for Ankle-Location Task — Experiment 1

Source	SS	df	MS	F	P
Order	64.55	1/13	64.55	6.39	<.05
B. Subjects	131.24	13	10.10		
Conditions	73.26	1/13	73.26	7.00	<.05
Order X Conditions	95.38	1/13	95.38	9.11	<.05
W. Subjects	136.05	13	10.47		
Measures	146.95	1/13	146.95	13.73	<.05
Order X Measures	62.78	1/13	62.78	5.86	<.05
W. Subjects	139.17	13	10.71		
Conditions X Measures	65.10	1/13	65.10	5.72	<.05
Order X Conditions X Measures	95.51	1/13	95.51	8.38	<.05
W. Subjects	148.10	13	11.39		

Since the extensive pre/post increase in mean vertical distance for the ankle-location task occurred only among pre-adapted subjects, a change in this variable cannot strictly be cited as demonstrating a specific locus of adaptive change. Since subjects in the post-adapted group also adapted to prismatic displacement; and since this did not occur at either the elbow or shoulder joints, another site or system of adaptation must be considered (possibly the registered position of the eyes in the head). A re-examination of the experimental task, however, suggested a possibility that the adaptation procedure might also have been interpreted as a distance task due to the nature of the placement of targets (e.g. radiating outward). The comments of some subjects appeared to reflect this possibility (e.g. "I thought my arm was further out than that"). If this was the case, then adaptation may also have occurred in a system involving depth perception.

Neither of these two possibilities, however, explains the change in the estimates in the ankle-location task among pre-adapted (PAD) subject. Two general possibilities present themselves: 1) that the task is measuring something other than registered arm length; and 2) that an apparently non-adaptive arm length change has taken place.

In the first instance, the only other possibility of explaining change in mean vertical distance in the ankle-location task would be if there was a recalibration of the judged horizontal position of the two shoulders with respect to the body. That is, if the left shoulder were assumed lower than normal and the right shoulder higher (in the coronal plane), this might explain why subjects overextended in attempting to locate their ankle. However, two objections can be raised here. First, the adaptation task calls for a lengthening of arm length in order to locate targets (see Introduction) and, at best, a recalibration of the right shoulder angle in an upward direction mimics the effect of apparent arm shortening. Such a change, therefore, cannot assist in prismatic adaptation. Secondly, there is no inherent explanation in this hypothesis as to why pre-adapted subjects alone should show this change. Overall, then, change in horizontal shoulder position would not appear to be a useful hypothesis.

As noted in Part I, arm shrinkage can occur in times of unusual cerebral events. Melzack and Bromage (1973) found shortening effects of this sort during anesthetic block of the brachial plexus when phantom limb effects emerged. A re-analysis of the data of Gross et al (1976) suggested that shrinkage occurred during periods of limb disuse. On this basis, it might be assumed that in difficult tasks, such as prismatic adaptation, a change in the registration of certain dimensions of body geometry is made on a trial-and-error basis in an attempt to find a solution. If apparent arm length shrinkage is a commonly-employed or easily-accessable mechanism of this type, then it may have been invoked in this instance, even though it did not result in fulfilment of an adaptive function. It would, also, have to be assumed, however, that the adaptive changes which did lead to accurate target location took place entirely in the eye/head system or in a depth perception system.

In summary, the present experiment failed to find a clear locus of adaptation to vertical prismatic displacement of the visual field. It confirmed a lack of such changes at the elbow and shoulder joints, as well as a combined change at those joints. An unusual change in the ankle-location task, suggesting an apparent shortening of registered limb-length, occurred among subjects who received the adaptation session before the control session but not vice versa. The possibility that this reflected some form of trial-and-error mechanism which in this instance failed to produce adaptation was considered. The real locus of change in this experiment was thought to be most likely in the eye/head system. The change in the ankle-location task does, however, lend some support to the notion that changes in registered arm length can take place even if its reason for existence is not understood.

Experiment 2

The first experiment provided only very weak evidence for a change in registered arm length. An apparent shortening of limb-length which served no apparent adaptive purpose was thought possibly to have resulted from a sudden introduction of prismatic displacement in a novel environment. This finding, while of heuristic value, was far from providing an experimental demonstration of recalibration of registered arm length.

Two directions for further study presented themselves at this point. First, an attempt could be made to expand the previous study and determine where, in fact, all adaptation effects were taking place, when in this process a subject might invoke a recalibration of arm length, whether a change in the rotation of the shoulder had taken place and so forth. Or second, subsequent experiments might attempt further changes in procedure in a search for sufficient conditions to drive a predicted change in registered arm length in an entire group of subjects. The latter route was, in fact, chosen, as it was felt that a determination of the existence or otherwise of such a mechanism was of more initial importance than determining the locus of adaptation in the present paradigm to which a return could always be made in the future.

It was decided to continue having subjects perform prismatic displacement tasks moving only at the elbow joint, but two factors were isolated for change. First, it was felt that the adaptation task should be changed to eliminate any possibility that subjects might perceive that they were dealing with a distance task, as was suggested to be the case for some subjects in the previous experiment. Second, it was considered that possibly some of the difficulties in establishing registered arm length changes lay in using body landmarks as targets. This was considered to be a source of difficulty because the area defined as 'the knee' (pilot study) or 'the ankle' (Experiment 1) can be open to wide interpretation as to location within as well as between subjects. It was, also, considered that because the body landmark task was not precise, subjects did not attempt to be as precise in their responses as they might have been if the target had been more clearly defined.

In response to the first consideration (distance), it was decided to revise the adaptation task again, in order to more clearly make it a task in which targets varied along a vertical dimension and one in which there was little or no ambiguity concerning the absence of depth perception. In regard to the second task, it was felt that stimulating a small point on the body might serve as a better type of target for obtaining judgements of arm length, since subjects would have a very precisely-defined location at which they could aim. One foreseen problem, however, was that the skin readily habituates to a probe held in position, so that a device would have to be devised that would permit probing of the target spot on demand. Finally, it was felt that in order to more adequately demonstrate that prismatic adaptation results in arm length changes, it should be shown that upward displacement by prisms should result in an apparent shortening of registered arm length while downward displacement by prisms should result in an apparent lengthening within the same experimental context according to the rationale given earlier. It was, therefore, decided to test two groups of subjects, one group performing the adaptation task while viewing through base-down (upward-displacing) prisms and the other viewing through base-up (downward-displacing) prisms. Using the rationale outlined in the previous experiment, it was predicted that subjects in each prism condition should show the corresponding changes in apparent arm length noted above.

METHOD

Subjects: A total of 19 paid volunteer subjects of either sex participated in this study. Any subject entering the study was required to pass a test for large ocular phoria (see Experiment 1). Instructions, demonstrations, and practice trials were also given as in Experiment 1.

Format: Each subject participated in two experimental sessions, each lasting approximately one half hour. Subjects served as their own controls; and thus, one session was an experimental session in which subjects viewed targets through displacing prisms, while the other was a control session in which all conditions remained the same, except that no prisms were used in the task.

Both the experimental and control sessions consisted of two parts: 1) an adaptation task (as noted above) in which subjects pointed to vertically-arranged targets; and 2) a dependent variable task in which subjects attempted to locate a point on their leg stimulated by a probe. This task was used to derive estimates of registered arm length and measures were taken before and after the adaptation task in both experimental conditions.

Apparatus and Tasks: Both the adaptation task and the probe-location task were performed while subjects sat in a straight-backed chair in front of a large table. This is illustrated in Figure 10a and close examination will show

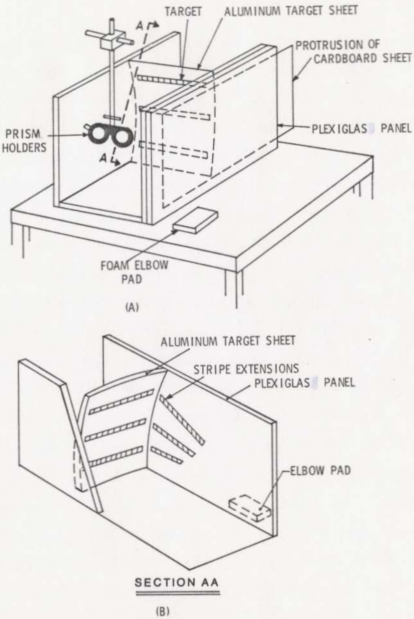

FIGURE 10

Experimental Apparatus Used in Experiment 2

A — Front View

B — Section AA

that the apparatus has been constructed simply by taking the plexiglas target panel used in Experiment 1 (Figure 3a), removing the target stripes, and attaching it to two sides of a plywood frame. The plywood frame was 1.2 m in length and 0.6 m in height. The width of the bottom sheet of the plywood frame was 0.6 m. The prism holders were suspended approximately 15 cm (lengthwise) inside the space created by the frame. An aluminum sheet was bent into a concave shape along the vertical axis (so each of its targets would be equidistant from the viewer) and placed within the apparatus frame such that each target was approximately 50 cm from the prism holders (and approximately the same distance from the elbow since this was in the same plane as the prism holders). The target sheet had three striped tape targets running its width. These were separated from each other by 10 cm and numbered just below the centre of each stripe.

Targets were, thus, arranged in a vertical array and were of equal distance from subjects' eyes so that location of any of the three targets would not be interpreted as being one of extension into non-haptic space (depth). Some difficulty, however, was created as a result of variations in the actual length of subjects' forearms. Each target was deliberately fixed roughly at a 50 cm distance from eye and elbow to index finger tip length. This particular placement of stripes was done to accomodate subjects with long forearms so that when pointing to targets, their arms did not extend beyond the targets. For subjects whose forearm length was such that their index finger, while pointing, fell short of the targets, guide stripes were placed along the inside of the plexiglas panel running between each of the three targets and half the distance to the elbow rest (Figure 10b). The guide stripes were utilized so that if a subject's right-hand index finger did fall short of the target, itself, the striped extension would clearly indicate whether or not he was pointing directly at the target. The system was used, therefore, simply to avoid any ambiguity in obtaining feedback about accuracy.

The adaptation task required subjects to point accurately at one of the three targets as specified by the experimenter. The entire procedure was identical to that used in Experiment 1, except that the number of targets in the present instance was reduced by half to three, and the subject looked straight ahead at the target rather than sideways. As in Experiment 1, trials were performed with subsequent error feedback (by pulling back the cardboard sheet) and subjects were required to reach an adaptation criterion of three successive hits. Subjects viewed the targets through the prism holders with or without two base-down or base-up, 11-dioptre wedge prisms (see below).

In the probe-location task, subjects sat in the same chair as that used in the adaptation task. Along the right side of the chair was a large plywood panel approximately 1 m in length and .5 cm in height. The arrangement of panel and chair was nearly the same as that depicted in Figure 4, except that the chair was considerably larger. Subjects sat in the chair in the position shown in Appendix B (except that the right hand and leg were used) with their right leg close to the inner side of the plywood panel.

In order to more sharply define a body target, a probe was designed and constructed which would stimulate a small spot on a subject's leg. The probe device is illustrated in Appendix C. It was constructed out of clear plastic, aluminum, and velcro strips for attaching around subject's legs. The cylinder was spring loaded so that it was necessary to apply a force to the disc end of the plunger in order to push through the blunt probe tip. Appendix C shows the plunger slightly depressed and the probe equally extended.

The probe device was attached to the right side of each subject's leg by means of velco strips, so that the flat disc end of the plunger just rested against the plywood panel and the slightly-concave section was against the leg.

It was left in this position for the duration of the experiment. This arrangement is illustrated in Figure 11a. Thus, a slight push of the subject's leg against the probe device in the direction of the plywood board caused the blunt end of the probe to be pushed into his leg. Subjects could control the force of the probe in this fashion. Subjects were given a number of practice trials on stimulating their leg with the probe and told that this spot was to be their target.

Locating the probed position on the leg with the right hand and arm was performed almost identically to the ankle-location tasks described in Experiment 1. Graph paper was placed on the outside of the plywood panel and positioned exactly according to the method used in the previous experiment. Each subject was given a felt-tip marking pen and asked to line it up opposite the spot stimulated by the probe. When satisfied with the location of the spot, he made a mark on the graph paper. The position assumed during this task is illustrated in Appendix B (see also Figure 11a) except that neither the target panel nor the probe device are shown. Thus, for each trial, subjects would push against the probe and either hold the probe continuously or repeatedly stimulate the leg (they were given the choice) and at the same time line up and mark the position of the probed target. Instructions regarding the use and position of the right hand and arm were given as in the previous experiments.

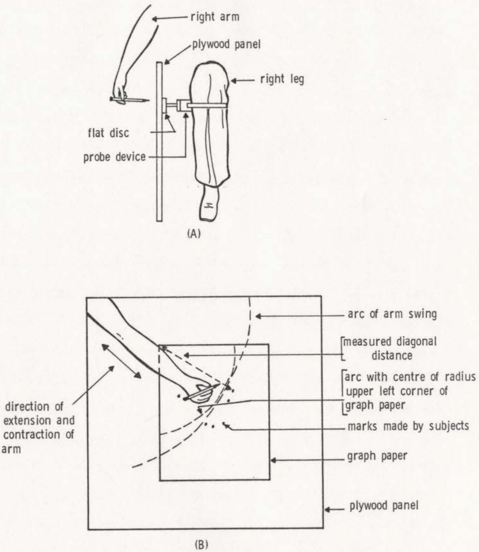

FIGURE 11

Apparatus and Subject Positions in the
Probe-Location Task in Experiment 2
A — Right Leg Position Showing Placement of Probe Device
B — Right Arm Position Showing Extension and
Contraction in Diagonal Direction

PROCEDURE

As noted earlier, the experiment consisted of two separate sessions run on two separate days. Subjects served as their own controls so that one session was a control session and one an experimental session. Ten of the nineteen subjects performed the adaptation task with the prisms placed in a base-up (downward-displacing) position, while nine subjects viewed through base-down (upward-displacing) prisms. Subjects were randomly assigned to groups by using a pre-arranged order as described in the previous experiment.

Following practice trials in any given session, a subject was blindfolded and required to perform ten trials of the probe-location task. The blindfold was then removed. He placed his head into position under the prism holders and performed the adaptation task to criterion (three consecutive hits). Reaching criterion was followed by one trial of the probe-location task. Subsequently, the two tasks were alternated nine more times reaching a total of ten trials for each task. Consequently, there were ten graphed marks made prior to adaptation and ten made post-adaptation. All general instructions were given as in Experiment 1.

RESULTS AND DISCUSSION

Scoring of marks made on the graph paper in the probe-location task was performed using the altered-origin system as outlined in Experiment 1 and scored in the vertical direction. Observations made during pilot sessions, however, suggested that because subjects were required to move or reach forward to some extent, they may have withdrawn or extended their arms more along a diagonal with respect to the graph paper. Appendix B illustrates the position taken by subjects in this task. The slight forward lean and forward position of the arm should be noted in this illustration.

Figure 11b shows a common position of the right arm with respect to the graph paper in this task. The direction of extension and contraction should be noted, as well as the arc of the swing of the arm with the shoulder serving as centre of radius. It was felt that taking the distance of each point from the shoulder would provide the most accurate axis of measurement for this task. However, due to the nature of the task, giving complete freedom of movement to the shoulder at all times, this axis of measurement could not be obtained. It was felt that an approximation to this shoulder/hand axis would be the diagonal of the graph paper running from the upper left to the lower right-hand corner. If, therefore, the centre of rotation of arm swing were in effect altered so that it fell at the upper left-hand corner at the graph paper, the absolute distance of each point from the origin could be taken regardless of angle, as the arc described with axis at the upper left corner approximates the arc generated at the shoulder. Furthermore, extreme deviations of the two arcs occur only at the fringes of the graph paper; and very few subject marks fell in these areas.

Therefore, in addition to vertical distances of points, a second scoring method for diagonal distance was devised. This was done using a slightly revised altered-origin system as follows. For each subject the distance of all points from the upper left-hand corner of the graph paper was calculated regardless of direction by employing a standard square on the hypotenuse formula using the vertical and horizontal dimensions of each point. After this, a mean of all the pre-adaptation points were taken and rounded to the nearest centimeter. This was made the arbitrary origin and its value was then subtracted from all pre- and post-adaptation scores. Thus, the pre-adaptation cluster of points defined the theoretical locus of the target as in the first experiment. Finally, the constant 127 (mm) was added to all scores for convenience of analysis.

The means of the scoring of points in the vertical direction are plotted in Figures 12a and 12b. Figure 12a gives the experimental and control values for the base-up group while Figure 12b gives those for the base-down group. For subjects in the base-up condition, there appeared to be little change in either group. For subjects in the base-down group, both experimental and control conditions displayed increases in mean distances, but there appeared to be little difference between the two. The results of the three-way analysis of variance performed on this data are presented in Table 6. The first factor was prism condition (base-up or base-down) and is labelled PRISMS. Subjects were nested only within this factor. The second factor was experimental condition (experimental versus control) and the third factor was repeated measures (pre/post).

As can be noted from Table 6, none of the main effects nor any of the interactions were significant. It can be concluded, therefore, that no experimental changes took place with respect to vertical measures alone.

Figures 13a and 13b present the means for diagonal measures. First, these two figures appear to reflect an overall increase in distance values for all groups and conditions. For the base-up condition, however, the experimental group shows a substantially greater increase than the control group, whereas for the base-down condition,

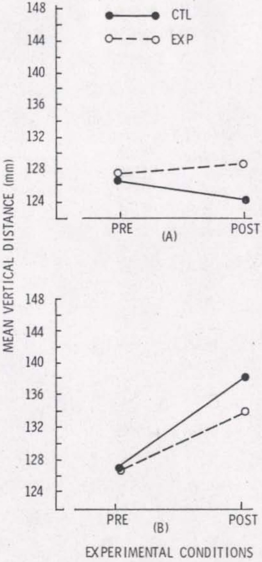

FIGURE 12

Pre/Post Changes in Mean Vertical Distance in The Probe-Location Task in Experiment 2 (N = 19)
A — Base-up Condition (N = 10)
B — Base-down Condition (N = 9)

TABLE 6

Summary of Results of Analysis of Variance for Probe-Location Task — Experiment 2 — Vertical Distance Measure

Source	SS	df	MS	F	P
Prisms	83.25	1/17	83.25	1.53	N.S.
B. Subjects	924.29	17	54.37		
Conditions	0.25	1/17	0.25	0.01	N.S.
Conditions X Prisms	19.63	1/17	19.63	0.81	N.S.
W. Subjects	410.91	17	24.17		
Measures	50.91	1/17	50.91	0.86	N.S.
Prisms X Measures	73.57	1/17	73.57	1.25	N.S.
W. Subjects	1000.49	17	58.85		
Conditions X Measures	0.25	1/17	0.25	0.01	N.S.
Prisms X Conditions X Measures	12.06	1/17	12.06	0.48	N.S.
W. Subjects	423.92	17	24.94		

little difference appears to exist between the two groups. Table 7 presents the analysis of variance summary for these data, the factors being labelled as those in the above analysis.

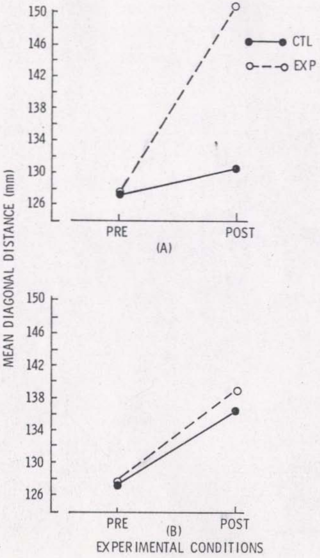

FIGURE 13

Pre/Post Changes in Mean Diagonal Distance in the Probe-Location Task in Experiment 2 (N = 19)
A — Base-up Group (N = 10)
B — Base-down Group (N = 9)

TABLE 7

Summary of Results of Analysis of Variance for Probe-Location Task — Experiment 2 — Diagonal Distance Measure

Source	SS	df	MS	F	P
Prisms	4.50	1/17	4.50	0.06	N.S.
B. Subjects	1310.20	17	77.07		
Conditions	98.00	1/17	98.00	4.47	<.05
Prisms X Conditions	56.71	1/17	56.71	2.58	N.S.
W. Subjects	372.99	17	21.94		
Measures	418.30	1/17	418.30	5.46	<.05
Prisms X Measures	4.24	1/17	4.24	0.06	N.S.
W. Subjects	1301.87	17	76.58		
Conditions X Measures	99.36	1/17	99.36	4.42	N.S.
Prisms X Conditions X Measures	57.70	1/17	57.70	2.57	N.S.
W. Subjects	381.44	17	22.44		

This analysis yielded significant main effects for experimental conditions (experimental/control) and for repeated measures (pre/post). Since a significant conditions-by-measures interaction had been predicted, planned comparisons for simple main effects were carried out among the cell means using the within subjects error term given in Table 7.

In the base-up group there was a significant pre/post difference between the experimental means (127.0, s = 0.00 and 150.1, s = 13.50 respectively) (F = 9.18, df = 1/17, P < .01) but no significant difference between the pre/post control means of 127.1, s = 0.89 and 130.1, s = 8.33 respectively (F = 0.16, df = 1/17, N.S.). It is clear, therefore, that for subjects in the base-up condition, there was a significant experimental effect resulting in a substantial increase in distance made by subjects while attempting to locate the position of the probe. Interpreted in terms of registered arm length, this implies an apparent shortening, a finding precisely opposite to that predicted.

For subjects in the base-down group, there were no significant differences between either the experimental pre/post means (127.0, s = 0.00; and 138.79, s = 48.23 respectively) (F = 2.12, df = 1/17, N.S.) or the control pre/post means (127.0, s = 0.00; 136.50, s = 46.17) (F = 1.37, df= 1/17, N.S.). Therefore, despite the apparent increase in distance of location marks in both groups, no changes in registered arm length appears to have taken place within the base-down group. An apparent shortening had been predicted.

The overall results for the diagonal measure have given nearly opposite results to those predicted, as was the case of the pre-adapted subjects in Experiment 1.

In view of the consistency of the two sets of results using base-up prisms, a substantial alteration of the conceptualization of the mechanism of change in registered arm length appears necessary. Although the two experiments are supportive of the notion that arm length changes of some kind do take place, it is clear that the sufficient conditions for driving those changes are not understood. Furthermore, in the case of base-up prisms, the consistency in the two sets of experiments seems to suggest that the apparent change in arm length does serve an adaptive function, although at present the means by which this occurs is not understood.

A re-examination of the problem at this stage did not reveal any further ways in which a change in registered arm length alone could lead to adaptation. However, one possible solution which combines changes in registered arm length with changes in apparent target depth did emerge from the reanalysis. Although rather unusual, it does present a possible explanation for the findings of these first two experiments. The theoretical rationale for this new proposal is given below with reference to Figures 14a — c. Figure 14a is essentially a reproduction of Figure 1c and shows the different starting and final pointing positions of the real and apparent arm in the case where adaptive change in registered arm length was predicted to have resulted from subjects locating targets

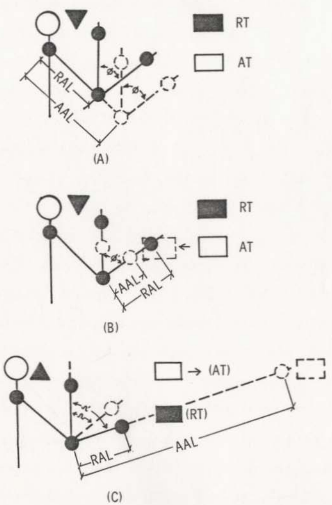

FIGURE 14

Illustrations of Potential Systems of Adaptive Changes In Registered Limb-Length and Apparent Depth (see text)

RT = Real Target; AT = Apparent Target

RAL = Real Arm Length; AAL = Apparent Arm Length

while viewing through base-up prisms. It should be noted, as discussed earlier, that it is the required movement through the smaller angle (ϕ') (smaller than ϕ — Figure 1c) in order to accurately locate targets that requires the recalibration. The predicted apparent lengthening of the arm would geometrically preserve the angle (ϕ'), but, to date, the two sets of experimental results using base-up prisms have given evidence of the directly opposite effect, an apparent shortening.

Figure 14b shows a possible mechanism by which an apparent shortening of registered arm length might result in the base-up condition. If during the adaptation task the brain makes the assumption that there has been a change in the perceived depth of the apparent target, such that it is now perceived as being closer (Figure 14b) than originally estimated in the first few trials, then a movement of the pointing arm through the angle (ϕ') resulting in a successful location of the target coincides (geometrically intersects) with the apparent position of the target. However, in order to account for this coincidence, the brain would also have to assume that the forearm is somewhat shorter (AAL — Figure 14b) than the real arm length (RAL). Thus, an apparent shortening of registered arm length, coupled with a change in the apparent depth of the target, provides a system by which a subject can utilize the current registered position of the forearm with respect to the elbow in order to accurately locate the real targets.

As noted earlier, Ogle (1964) has discussed the asymmetric angular magnification and distortion that results from viewing through a flat opthalmic prism (page 130). If there is, in fact, increasing magnification toward the apex in the base-apex meridian, then it is reasonable that this could provide a cue for a change in perception of apparent depth such that (in the present case) the objects in the lower half of the visual field are seen as closer than those in the upper half (e.g. the slant of the field is changed). If this is so, then the errors of overextension in target-locating trials which occur in the first few trials of the adaptation tasks may be interpreted by subjects as a misperception of the depth of the target. It is not that the prism distortion results in a complete change in perceived depth that could serve the required adaptation but that it provides a cue on the basis of which the brain can make a further assumption concerning a change in depth which is suitable to the task at hand. However, recalibration of apparent depth, as noted, requires a corresponding change in registered arm length to complete the adaptive system.

Thus, the proposed combination of two adaptive changes is sufficient to explain the changes in registered arm length occurring among pre-adapted subjects in the first experiment and among all base-up subjects in the second experiment. The absence of such a change among post-adapted subjects in the first experiment could be explained on the basis that by first performing the adaptation task without prisms, subjects became familiar with the real depth cues in the experimental apparatus to the extent that a potential change in apparent depth was untenable. On the surface, this appears to be a reasonable assumption.

If this new proposal provides an adequate explanation for adaptive changes in the base-up condition, then the converse should hold true in the base-down condition. That is, there should be an apparent lengthening of registered arm length occurring with a change of depth perception in the opposite direction to that suggested in the base-up condition. Figure 14c shows the relative positions of the real arm (solid lines) and apparent arm (dotted lines) in this instance. To point to the apparent target, now perceived as higher than the real target, a subject would, however, extend his arm forming the angle (Ω) (Figure 14c) at the elbow, find he had missed that target (under-extended), and gradually produce new forearm positions until he had reached a successful solution by producing the position with an elbow angle equal to (Ω') (which, of course, initially feels wrong). In order to make sense of the new angle, according to the previous system, he would have to assume that the apparent target (AT) is, in fact, much further away than it was originally perceived to be. Correspondingly, the apparent arm length must also be longer.

However, from the geometry of the situation, it can be seen that the extent of change is much greater than that required in the base-up instance. The apparent target would have to be seen as much further away and the forearm as very long indeed (AAL — Figure 14c). It would not be surprising, therefore, if the brain rejected this solution altogether; and if so, it would explain the absence of change in the base-down group.

As mentioned, this solution is neither elegant nor parsimonious. Yet, it does explain the consistently unpredicted results found in these first two experiments. Furthermore, it must be remembered that the predictions were based on guesses about a simple way in which the brain might operate and were not based on previous theory or even hard experimental data.

In summary, Experiment 2 revealed significant apparent shortening of registered arm length in subjects viewing through base-up (downward-displacing) prisms. These findings were similar to those in Experiment 1. No significant changes were found among subjects viewing through base-down prisms. Both sets of findings plus the findings of Experiment 1 implied that a new conceptualization of the mechanisms involved in registered arm length was necessary. A two-fold mechanism requiring an assumption of a change in apparent depth and an apparent shortening of forearm length was proposed for the base-up condition. It was argued that a similar mechanism was unlikely to occur among subjects in the base-down condition. At this stage it still seemed necessary to further explore this situation to more firmly establish the pattern of change.

Experiment 3

Based on Experiments 1 and 2, it was predicted that differential results should accrue depending on whether subjects viewed through base-up or base-down prisms and on whether or not they had previous experience with the apparatus and task. In particular, it was hypothesized that subjects viewing through base-up prisms should show evidence of an apparent shortening of registered arm length if they receive the experimental session first but not if they receive the control session first, while those viewing through base-down prisms should show no evidence of recalibration in arm length in any condition. Since this experiment is essentially a replication study, it was felt that examination of both prism conditions in the same subject might be of interest, and this feature was incorporated into the study.

Two features of the previous experiment were considered somewhat undesirable. First, the horizontal distance between a subject's hand and his leg while he was trying to locate the probed position was felt to be too large (see Figure 11a). The combined distances of 1) the length of the pen between the fingers and the tip of the pen (average 5 cm); 2) the thickness (2 cm) of the plywood panel; and 3) the distance from the flat disc of the probe device to the tip of the probe (approximately 10 cm) gave a minimum total distance of 16 cm between hand and leg, which is possibly too far for optimum accuracy. Consequently, an attempt was made to eliminate this problem, primarily by eliminating the probe (see below) and, also, by having subjects hold the pen closer to the tip.

The second methodological problem that arose in the previous experiment concerned the need to approximate and calculate a diagonal distance as an estimate of registered arm length. A more direct measure (as in the vertical distance in Experiment 1 and the pilot study) was considered desirable. To deal with this difficulty, a correction in the method of the placement of the graph paper was made (see below).

METHOD

Subjects: A total of 16 paid volunteer subjects of either sex participated in this study. Any subject entering the study was required to pass a test for large ocular phoria and all instructions, demonstrations, and practice trials were given as for Experiments 1 and 2.

Format: Each subject participated in three experimental sessions, each lasting approximately one half hour. Subjects served as their own controls, and, thus, two sessions were experimental sessions in which subjects viewed targets through displacing prisms (once in the base-up condition and once in the base-down condition) while the third session was a control session in which all conditions remained the same except that no prisms were used in the task.

The experimental and control sessions consisted of two parts: 1) an adaptation task (as noted above) in which subjects pointed to vertically-arranged targets and 2) a dependent variable task in which subjects attempted to locate a point on their leg stimulated by a probe. This task was used, as in the previous experiment, to derive estimates of registered arm length and measures were taken before and after the adaptation task.

Apparatus and Tasks: All tasks and equipment were identical to those in Experiment 2 with the following exceptions: The probe device used in Experiment 2 was replaced by putting a small nail through the plywood panel and blunting its end. Subjects were positioned in the chair and asked to keep their right foot in place at all times. Each subject could then push his leg against the new probe at will to stimulate a spot on his leg. The spot always fell somewhere between the knee and ankle and usually around the middle of the lateral side of his leg segment. The spot stimulated by the probe was the target for each subject. The location task was otherwise as in Experiment 2. The effect of the rearrangement was to bring the right arm and leg much closer together (5-6 cm) while marking was taking place.

As noted, a second change was made with respect to placing of the graph paper. While subjects performed practice trials prior to the experiment, the experimenter aligned the paper so that the pen fell consistently in the middle and that the centre line of the graph paper fell along the axis of the subject's arm (shoulder to wrist). He did this by aligning as closely as possible the centre of the shoulder with the line passing through the centre of the graph paper. It was clear that subjects' shoulder positions would move during the experiment, but it was felt that this method of alignment would obviate the need for calculation of the diagonal.

PROCEDURE

The experiment consisted of three sessions run on three separate days. Each subject received two experimental sessions and one control session spaced between the two experimental sessions. Nine subjects received the base-up condition first followed by the control condition (no prisms) and then the base-down condition. Seven subjects received the base-down condition first followed by control and base-up conditions.

The tasks required of subjects in each experimental session were exactly those of Experiment 2. It was predicted that subjects in the base-up group would show evidence of an apparent shortening of registered arm length provided that they were in the group which received the base-up condition first but not if they were in the group which received it after the base-down and control sessions (i.e. which gave prior visual exposure to the apparatus). No experimental changes were expected among subjects in the two base-down groups or the control group.

RESULTS AND DISCUSSION

Scoring of marks made by subjects was performed using the altered-origin system described in Experiment 1. Three factors were entered into the present analysis. The first was order of experimental tasks; that is, either the base-down or the base-up condition first. This was termed the order factor. The second factor was experimental conditions (base-up versus neutral versus base-down), and the third factor was repeated measures (pre- and post-adaptation). Figure 15a shows the pre/post changes for the three experimental conditions for subjects in the base-up-first group, while Figure 15b shows the same display for subjects in the base-down-first group. Both figures show an increase in the estimated distance of the probed location in all conditions, indicating a possible positional aftereffect. For subjects in the base-up-first group (Figure 15a), the base-up condition shows a substantially-greater increase than either of the other two groups (neither of which differ from each other). This is as predicted on the basis of the results of Experiments 1 and 2. Third, no differences appear to exist among the three conditions in the base-down-first group (Figure 15b).

A summary of the three-way analysis of variance performed on these data is given in Table 8.

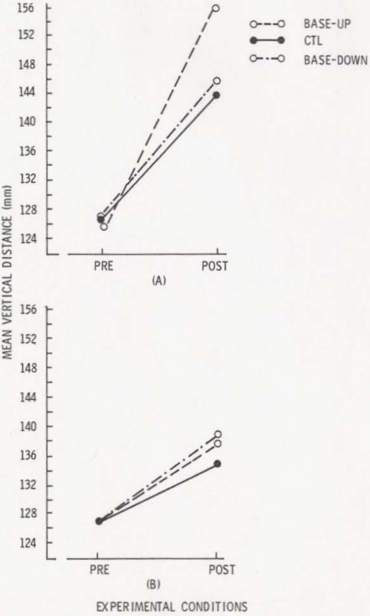

FIGURE 15

Pre/Post Changes in Mean Vertical Distance in Probe-Location Task in Experiment 3

A — Base-up First Subjects (N = 9)
B — Base-down First Subjects (N = 7)

TABLE 8

Summary of Results of Analysis of Variance for Probe-Location Task — Experiment 3

Source	SS	df	MS	F	P
Order	104.13	1/14	104.13	2.88	N.S.
B. Subjects	506.34	14	36.17		
Conditions	38.65	2/28	19.32	2.46	N.S.
Order X Conditions	20.81	2/28	10.40	1.33	N.S.
W. Subjects	219.82	28	7.85		
Measures	1112.48	1/14	1112.48	31.83	< .01
Order X Measures	114.34	1/14	114.34	3.27	N.S.
W. Subjects	489.28	14	34.95		
Conditions X Measures	35.27	2/28	17.63	2.27	N.S.
Order X Conditions X Measures	20.70	2/28	10.35	1.33	N.S.
W. Subjects	217.65	28	7.77		

This analysis yielded a significant main effect for repeated measures indicating that the combined post-experimental mean of 133.7 (s = 7.32) is significantly larger than the overall pre-experimental mean of 126.9 (s = 4.30). There were no significant interactions. Since a significant order-by-conditions-by-measures interaction had been predicted, planned comparisons were subsequently carried out among the cell means using the within subjects error term given in Table 8. In the base-up-first group, all conditions showed significant pre/post changes as expected from the above analysis. The pre/post means of 126.7 (s = 0.27) and 156.0 (s = 5.94) in the base-up condition are significantly different (F = 38.44, df = 1/14, P < .01). The pre/post means of 126.5 (s = 0.17) and 144.7 (s = 4.32) in the control condition are also significantly different (F = 14.85, df = 1/14, P < .01). The pre/post means of 126.8 (s = 0.29) and 146.0 (s = 4.60) in the base-down condition are significantly different (F = 16.46, df = 1/14, P < .01). These results confirm the significant main effect for measures noted in the above analysis.

Figure 15a shows clearly that all pre-experimental means were roughly equal. Comparisons were subsequently initiated to test for simple main effects among post-adaptation means. The post-adaptation mean of 156.0 in the base-up condition is significantly different from that of the control condition (144.7) (F = 5.71, df = 1/14, P < .05). The base-up mean is also significantly different from the post-adaptation mean of 146.0 in the base-down condition (F = 4.78, df = 1/14, P < .05). The base-down and control condition means on the other hand clearly do not differ (F = 0.08, df = 1/17, N.S.). These results, therefore, confirm the prediction that experimental changes would be noted in the base-up condition, in terms of an apparent shortening of registered arm length.

For subjects who received the base-down condition first, the pre/post changes were very similar. All conditions showed a significant change from pre- to post-adaptation. In the base-up condition, the pre/post means were 127.0 (s = 0.33) and 138.5 (s = 6.87) and these differed significantly (F = 4.62, df = 1/14, P < .05). In the control condition, the pre/post means were 126.7 (s = 0.27) and 135.7 (s = 2.93) respectively and these were not significantly different (F = 2.82, df = 1/14, N.S.). In the base-down condition the pre/post means were 127.1 (s = 0.33) and 139.7 (s = 7.20) and these were significantly different (F = 5.47, df = 1/14, P < .05). Since the pre/post control change was significant in the base-up-first group and since the pre/post changes in all other conditions were significant, the pre/post change in the present control condition, while not significant, were in the right direction and can be regarded as meaningful. On the whole, these consistent pre/post changes clearly point to the effects of a positional aftereffect.

As in the base-up-first group, there appeared little point in testing for differences among the pre-adaptation means (see Figure 15b). The post-adaptation mean of 138.5 in the base-up condition did not significantly differ from the post-adaptation mean of 135.7 in the control condition (F = 0.27, df = 1/14, N.S.) nor from the post-adaptation mean of 139.7 in the base-down condition (F = 0.05, df = 1/14, N.S.). Similarly, the control and base-down condition post-adaptation means did not significantly differ (F = 0.54, df = 1/14, N.S.). This confirms the absence of significant differences among these conditions.

The positional after-effects observed in this experiment were also noticed in Experiment 2 and to a minor extent in Experiment 1 but did not reach significance at either of those times. It would appear to be most easily ascribed to a postural persistence in the rotation of the shoulders in the horizontal plane with respect to the body and head. While pointing at targets for extensive periods of time, subjects assume a position in which the right (pointing) shoulder is somewhat lower than the left, particularly as subjects are placing a great deal of the weight of the upper torso on the right elbow. It is very likely an aftereffect of this shoulder position, which produces the noted change in mean vertical distance in the probe-location task, which is common to all groups.

The foregoing analysis, thus, confirms the results of both Experiments 1 and 2 in the light of the theoretical rationale given above. With movement permitted only at the elbow, subjects viewing targets through base-up (downward-displacing) prisms produce experimental changes which are consistent with a two-part adaptation mechanism in which they perceive the target as being closer and their forearm shorter. However, this occurs only if the subject is not familiar with the experimental apparatus, as suggested by Experiment 1 and supported here. The converse of this process does not take place among subjects viewing through base-down (upward-displacing) prisms. They, along with base-up subjects with prior experience, must adapt in some other manner, possibly in the eye/head system. Taken as a whole, the three experiments show that while recalibration in registered arm length is not an exclusive mechanism in producing adaptive changes in the noted tasks, it does constitute a real system for adaptive change. The experiments, thus, would appear to confirm the notion, discussed in Part I, that the brain does, in fact, have a knowledge of limb-length and that this knowledge is subject to modification under appropriate circumstances. The experiments also indicate that arm length recalibrations in prismatic adaptation tasks are likely to be very complicated in nature and imply that further experimentation on registered arm length phenomena may well be more profitable using a different methodology.

Introduction to Experiments 4, 5, and 6

Experiments 1 through 3 have provided experimental evidence that adaptive changes to prismatic displacement of the visual fields can result in recalibrations of the knowledge of limb-length and, thus, argue strongly for the existence of this adaptive mechanism. Two theoretical problems, however, prevent the proposal from being as conclusive as it might be. First, the theoretical framework which was originally forwarded to predict arm length recalibrations has not been upheld. Instead, a more complicated and somewhat unwieldy explanation had to be devised requiring changes in both depth perception and registered arm length and which was, in addition, highly dependent on the amount of subject's prior experience. The new proposal provided a potential explanation of the findings of Experiments 1 and 2 (particularly the base-up restriction aspect) and was replicated and, hence, somewhat justified by Experiment 3. It is nevertheless clearly not a parsimonious solution, although it is the simplest conceived to date. Hence, it was apparent, as a result of these first three experiments, that further elucidation of the relative role of arm length recalibrations, as they occur in prism studies, was going to require considerably more effort and experimentation and that such work was not going to attack the question as directly as would be desired.

The second problem confronting the study of registered arm length changes at this stage was that only an apparent shortening had been demonstrated thus far. As noted in earlier discussions (in Part I), there was a possibility that an arm shrinkage mechanism was available for a variety of short- and long-term adaptive requirements; but there was no evidence that its counterpart, apparent lengthening, took place. The present experiments presumably did not show apparent lengthening because the required changes modality. Introducing a perceptual discrepancy in the visual modality in order to produce changes in registered limb-length clearly produced unforeseen problems according to the first three experiments, although this strategem has been eminently suitable for producing changes in the articular system according to past research.

It was consequently thought that a kinesthetic analogue to prismatic displacement of the visual field might be sought. In particular, it was felt that if a subject, while blindfolded, pointed with one arm to a specified location on the other, and found, with subsequent error feedback that he was consistently incorrect, he might be forced to produce an appropriate recalibration of limb-length. This might occur, for example, if the subject kept aiming at his wrist but kept hitting his elbow.

Further detailed consideration of the problem led to the design and construction of an instrument which could conceivably perform the desired function. It was termed a 'kinesthetic recalibrating device' (KRD) and is illustrated in Figure 16, which gives a top view of a subject operating the device. The effect of the KRD is simply that when the button is depressed on one side, the probe sticks out at some point further down its shaft on the other side. The KRD is used by having a subject place one of his arms (the left arm in Figure 16) along an arm rest mounted at

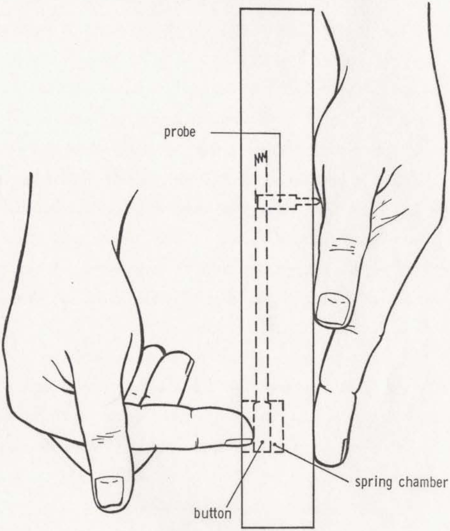

FIGURE 16

The Kinesthetic Recalibrating Device (KRD)
Used in Experiments 4, 5, and 6

the edge of the rear side and holding it stiff and extended at the elbow. The wrist and the hand are also stiff and the fingers are extended. The fingers rest against a stop at the anterior end of the device. A subject holds his other arm stiff at the elbow and wrist but keeps his hand semi-pronated and curled into a fist except for the index finger which is crooked perpendicular to the arm. Initially, he holds his pointing hand at some distance from the button, usually about 60 degrees of arc. He then swings his arm in and hits the button. As subjects are usually blindfolded for this task, they occasionally miss. When this occurs, a subject locates the button by feeling around the instrument, finding the button, and then depressing it before swinging his arm back to the 60-degree point to begin another trial. When the button is pressed, the probe on the other hand is pushed in to his other hand or arm further down. That is, with both arms fully extended, a subject will hit the button with his right arm at its length, but the probe will hit his other hand in the palm or even in the wrist or forearm. It is in this fashion that the kinesthetic discrepancy is created.

Photographs of the KRD are given in Appendices D and E. As can be seen from the appendices, the KRD consists of two basic parts. First, there is a spring-loaded button at the anterior end which returns to its original place when released. Second, the button is directly attached to a calibrated slide bar which traverses the remaining length of the device. The slide bar moves in accordance with the button. On the slide bar is a movable rider which can be readjusted and fixed at any place on the slide bar. The centre of its position can be read through a small slit. The scale on the slide bar is distance in mm from the centre of the button and the rider can be readjusted from 50 up to 240 mm from the button centre. The rider holds a replacable probe, and the entire KRD is mountable simply by means of a single bolt. The probe is sharp but will not pierce the skin.

THE FUSION EFFECT

It was originally thought that in order to create a kinesthetic discrepancy of any effect, subjects would have to be kept from seeing the device. It was felt that somehow subjects would have to be led to believe that the KRD probe was actually directly opposite the button, possibly by allowing them to see a dummy device. A number of pilot trials quickly made it apparent that this would be unnecessary. What actually occurred in using the device was this: if a person closed his eyes, swung his arm over a short distance and depressed the button, he was initially aware of a discrepancy between where his pointing arm hit the button and where the probe hit his other hand, regardless of whether or not he had previously seen the KRD. His right finger was hitting the probe; but the probe was hitting him in e.g. the palm, and he was aware of this discrepancy. If more button-pressing trials were given relatively rapidly, however, (e.g. every two to three seconds) most subjects began to feel that the right finger was closer to the probe position than it was on previous trials. Usually within ten trials, but sometimes up to 15 or 20, the right finger eventually felt as if it were directly opposite the probe, even though a subject knew it was not. Provided the subject continued to press the button regularly, the effect remained constant at this stage. This was termed the 'Fusion Effect', and it appears to be a powerful phenomenon. It seems to occur as if the brain, without visual information, cannot accept the notion that a force applied by a part of the body can act at any other site in space other than that directly opposite the body part which serves as the locus of the force (in this instance in the index finger). Thus, even though a subject knows from his visual memory of the KRD and from his stored knowledge of physical mechanics that a force could act in this peculiar fashion, without immediate visual information to the contrary, the brain insists on accepting the alternate hypothesis that it had inaccurately perceived the position or length of either of the two arms.

As soon as a subject opens his eyes, the immediate perceptual experience of the pointing finger and the probe being aligned is gone. Although there has been little time to establish the parameters of the fusion effect, the sudden change from one perceptual experience to another when subjects open their eyes seems very similar to an experimental phantom limb phenomenon observed by Bromage and Melzack (1973) in which there is a sudden fusion of the phantom and real limb when subjects viewed their anesthetized arm after experiencing the phantom for a time. They referred to a sudden loss of the phantom experience as a fusion, however, whereas in the present case the latter term is used to refer to an effect resulting from use of the KRD.

Examination of the fusion effect promises to be an interesting study in its own right. In the meantime, the entire process seemed ideally suited to producing recalibrations in limb-length, since some adaptive change in apparent arm length or arm position would appear to have to accompany fusion. Indeed, pilot studies tended to confirm this expectation with gross errors in judgements of location resulting from use of the KRD device.

Finally, it was decided that a KRD control device would be necessary to create appropriate control groups. This was duly designed and constructed and is illustrated in Appendices F and G. The control device is exactly the same as the KRD except that the probe is directly opposite the button. This should, therefore, produce no kinesthetic discrepancy provided that the two arms are initially accurately calibrated against each other.

Although it was predicted that recalibration of limb-length would occur as a response to kinesthetic displacement using the KRD, several modes of action were considered possible. First, using the right arm to depress the button, the left arm alone could undergo an apparent lengthening. This is illustrated in Figure 17a. Alternatively, the right arm could undergo an apparent shortening (Figure 17b). There is also the possibility that both an apparent lengthening of the left arm and an apparent shortening of the right arm might occur simultaneously (Figure 17c). If the latter were the case, however, it might easily be confused with a recalibration of the angle of the shoulders relative to the head. This is depicted in Figure 17d. This latter possibility could, in fact, confound the experimental results if equal changes were found in both arms. On the other hand, if a change was observed in a single arm only, it is difficult to see how this could have resulted from a shoulder-joint change. Since a change in registered position of the shoulders could be a contaminating factor, it was also felt that it would be important to insure that there was not a shifting of the shoulders while operating the KRD.

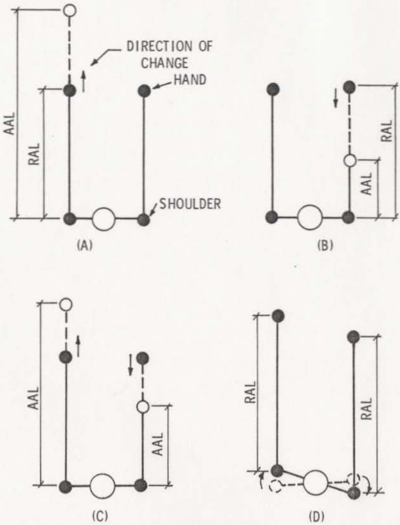

FIGURE 17

Illustrations of Potential Systems of Adaptive Changes in Registered Arm Length and Registered Position of the Arms with Respect to the Shoulders (see text)
RAL = Real Arm Length; AAL = Apparent Arm Length

With all of these factors in mind, three additional experiments were undertaken to attempt to further demonstrate the reality of perceived arm length changes.

Experiment 4

Since this was the first experiment with the KRD and its control device, it was felt that some attention ought to be paid to the manner in which the KRD altered the relationship between the two arms, although it was apparent that doing so would not necessarily permit a differentiation of the four hypotheses outlined in the Introduction. A subsequent Experiment 5 was, thus, designed and intended for this purpose. As a result, the two experiments were run simultaneously with subjects being assigned to one or the other experiment by means of a pre-arranged randomly-generated order. For clarity and logic, however, the two experiments are discussed separately, with the simpler Experiment 4 being presented first.

For the present experiment, it was predicted that an adaptive change in registered arm length in one or the other or both arms would result from the adaptation (KRD) task and that this would be indicated by a change in the accuracy in which subjects attempted to locate a target on one hand with a pen held in the other hand.

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METHOD

Subjects: A total of 14 paid volunteer subjects of either sex participated in this study. All general instructions, demonstrations, and practice trials were given as in previous experiments.

Format: Each subject participated in two experimental sessions, each lasting approximately one half hour. Subjects served as their own controls; and, thus, one session was an experimental session in which subjects performed an adaptation task using the KRD, and one was a control session differing only from the former in that the KRD control device was used in place of the KRD.

Both the experimental and control sessions consisted of two parts: 1) an adaptation task (as noted above) in which subjects used the KRD control device and 2) a dependent variable task (probe-location task) in which subjects attempted to locate a position stimulated by a probe on one of their hands with a pen held in their other hand (see below). This latter task was used as a measure of any changes of registered position of the two arms with respect to each other, and measures were taken before and after the adaptation task in both experimental conditions.

Apparatus and Tasks: The KRD task was performed basically as outlined in the introduction to the two experiments. Subjects used their right hand for depressing the button, while the left hand, wrist, or arm became the site for stimulation by the probe. The KRD and arm rest were mounted by means of aluminum rods and clamps on a platform. The platform could be raised or lowered by means of two jacks. In the first session, the apparatus was adjusted so that the KRD was at a comfortable shoulder height while subjects stood in front of it. This height was measured and used for adjustment in the second session. The apparatus and task were thus arranged so that while operating the KRD, both of the arms of each subject would be held at the same height to prevent a vertical postural after-effect of the shoulders. It was also insured that both arms were held perpendicular to the shoulders while operating the KRD to prevent any effect of a horizontal rotation at the shoulders.

Subjects were blindfolded during the task, as they were at all times during the experiment. They had a brief opportunity to see the KRD but were given only partial explanations as to its function or purpose. All practice trials were given only with the KRD control device. Subjects were told that the probes on both devices were designed to assist them in locating the button with their right hand, and the overall purpose of the study was to see how well they could learn to use the probed left hand to guide the right hand to the button. They were told further that they must, therefore, concentrate as much as possible on the relationship that resulted when the right hand was depressing the button and the probe was hitting the left hand. In fact, subjects were instructed to pause momentarily (e.g. 0.5 seconds) at the bottom of the press, just long enough to observe this relationship. They were then to release the button, return their right arm to the starting position and immediately begin another trial (these were performed continuously in groups of ten — see below). The total time taken to perform one complete trial was between one and two seconds. Subjects practiced the movement at the beginning of the first session, and the experimenter ensured that at all times during the experiment the subjects were performing at a rate of no less than 1 trial per two seconds.

The probe-location task required subjects to locate a spot on one hand using a marking pen held in the other. This was done in the following fashion: Prior to the experiment, the experimenter made a small black dot near the centre of each of the subject's palms. These became targets. While performing the task, a subject would stand just to one side of the KRD apparatus and hold both arms out in front of him, palms inward with the two hands separated by about .8 m. This position is illustrated in Figure 18a. The experimenter stood directly in front of the subject and placed a pen in one of the subject's hands. He then held the subject's other hand by the finger tips and pressed a small probe (attached to a long rod) into the black mark in the centre of the palm (see also Figure 18b). The subject then brought the pen forward, moving only that hand, and attempted to hit the point stimulated by the probe. When the pen was brought within 2 to 3 cm from the palm target, the probe was removed in order not to interfere with the marking. The time taken from removal of the probe and placing of the mark was usually no greater than one second. When he had made one mark, he returned his hand to the starting position. The experimenter then either repeated the procedure using the other hand or guided subjects to the apparatus to perform the adaptation task.

This probe-location task differed from earlier tasks in that subjects obtained feedback concerning their performance and, therefore, were particularly aware of any large discrepancies between the probe position and their location attempts. Unlike previous tasks, this could

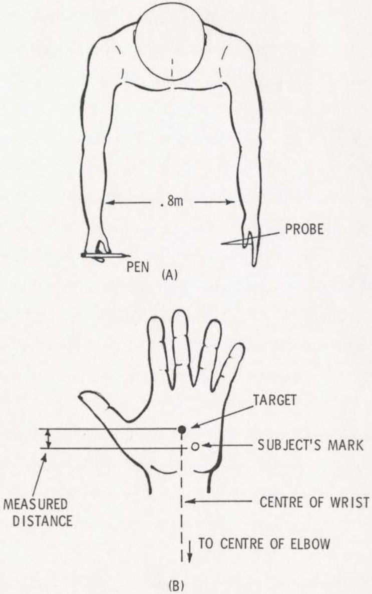

FIGURE 18

Two Aspects of the Probe-Location Task in Experiment 4
A — Position of Subject During Probe-Location Task
B — Illustration of Subject's Palm and the Relationship of Target and Subject Marks during Scoring

lead to an attempt at correction which would improve performance in the pre-adaptation trials but possibly minimize adaptive effects in the post-adaptation trials. In the latter instance, however, both the extensive time periods and the amount of other activity of the arms between single trials was thought to be adequate to minimize this effect. Subjects often noted the discrepancy between the probe and pen locations but were told simply that they would have the best chance of improving their performance by concentrating on aiming at where the probe was felt to be.

Although initially the arms were held approximately equidistant from the body, once the target hand was held by the experimenter, subjects often rotated their bodies somewhat so that the target arm was closer to being perpendicular to the head and body. This tendency was observed but neither encouraged nor discouraged, although the target arm was held firm and not allowed to move during the marking. This type of shift was not permitted during operation of the KRD, however.

PROCEDURE

The experiment proper consisted of two sessions held on two separate days, each subject receiving an adaptation (KRD) session and a control session. Seven subjects received the adaptation session before the control session and seven subjects received the control session first.

In the adaptation session subjects began by performing the probe-location task. In the first trial, the pen was held in the right hand, and the left palm mark served as a target. For the next trial, the hand functions were reversed, the left hand holding the pen and the right palm mark serving as a target. The task was subsequently alternated from hand to hand until a total of seven marks had been made on each hand. These pre-adaptation trials were made with a blue marking pen. Subjects then immediately proceeded to the adaptation task in which they were required to hit the button on the KRD with their right hand for ten consecutive and continuous trials. No criterion was set for performance, but subjects were led to believe from the pre-experimental instructions that their performance was being recorded. After this first block of trials, subjects again performed the probe-location task but made only one judgement marking the left hand with the right and using a red marking pen (subsequently used for all post-adaptation trials). This was followed by another block of ten trials of the adaptation task which was again followed by one trial of the probe-location task, except this time the left hand was used to mark the right. Blocks of ten trials of the adaptation task were subsequently alternated with one trial of the probe-location task (and within the latter task, the two hands were alternated) until a total of seven post-adaptation marks had been made on each hand (i.e. resulting from 14 blocks of the adaptation task). In addition, the distance of the probe from the centre of the button was increased by 4 mm in between each block of the adaptation task, so that by the last (14th) block the probe was 112 mm away from the centre. From unsystematic reports of subjects, it appeared that most were unaware of the single changes in probe distance from block to block, but most did notice an overall increase across the 14 blocks, presumably from estimates made prior to fusion in each block of adaptation trials.

The control sessions were identical to the adaptation sessions, except that the KRD control device was employed; and, thus, no change in the probe distance could be made. At the end of either session, blindfolds were removed; and the experimenter measured the marks on each hand.

RESULTS AND DISCUSSION

The experimenter scored the marks of subject's hands by means of vernier calipers, distances of each point from the target being read in mm. The line running from the centre of the elbow joint through the centre of the wrist was used as a reference axis and distances were measured parallel to this axis. Figure 18b illustrates the topographical relationships used in this scoring method. Marks falling posterior to the target mark were read negatively, while those falling anterior were read positively.

For each subject, separate means were taken for the seven pre-adaptation marks and the seven post-adaptation marks for each of the hands, resulting in a total of four separate means for each session. For convenience of scoring and analysis, the constant 127 mm (5 inches) was added to each mean.

Separate analyses were performed for each hand. However, it is clear that the measures are not independent, since a change in the perceived position of either the left, the right, or both hands could result in the same type of corrective shift of the arms with respect to each other regardless of which hand was serving as target. Thus, it did not appear to be possible to interpret the scores as reflecting a recalibration of the left arm, the right arm or both. As a result, a method for combining the data for the two hands was established. The object of the method was to derive a meaningful pre/post score combining right- and left-hand changes for both experimental and control conditions. A combined pre-adaptation score was derived simply by taking a mean of the two mean distances of the marks from the target. Since there was no experimental intervention at this stage, no alteration of scores was necessary.

The effect of a recalibration of the apparent length of each arm, however, was expected to operate differentially on the manner in which marks were made on the two hands. It was predicted that marks made on the left hand would fall in the positive direction (anterior to the target mark, distal to the elbow), while those made on the right hand would fall in the negative direction (posterior to the target mark, proximal to the elbow). If a recalibration did, in fact, take place, therefore, a simple averaging of the two sets of post-adaptation scores would result in arithmetical cancellation of this differential effect.

An alternative method of scoring post-adaptation marks was, therefore, developed as follows: For each subject, the mean distance between pre- and post-adaptation marks on the right hand was calculated, and its absolute value was added to the original pre-adaptation mean. The resulting value (always positive) became the new post-adaptation mean and the unaltered post-adaptation mean for the left hand was subsequently taken and used as the final post-adaptation mean.

Figure 19 presents the pre/post changes for the experimental and control conditions for mean distances in the probe-location task. Since the changes are in the positive direction, this means that the changes in locating the target were as predicted. While using the right hand to

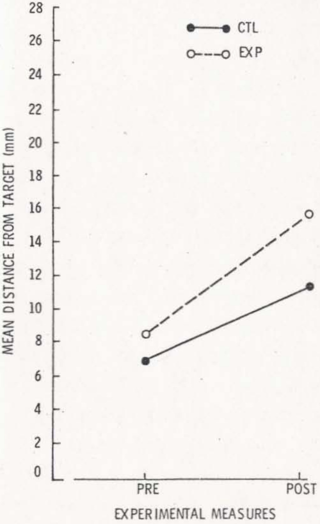

FIGURE 19

Pre/Post Change in Mean Distance From Target
In the Probe-Location Task in Experiment 4
(N = 14)

locate the target, subjects consistently hit in front of the target mark (away from the body), and while using the left hand to locate the target, they consistently hit posterior to the target mark (closer to the body). Such a pattern shows a clear shift of the perceived position of the two arms with respect to each other in the directions illustrated in Figures 17 a — d. Furthermore, according to Figure 19, this change appears to occur in both experimental and control conditions, although more extensively in the former.

To test for significant differences among the means, a three-way analysis of variance was performed on the data. The first main factor was order; that is, whether subjects received the adaptation session before the control session or vice versa. The second factor was conditions (experimental versus control) and the third factor was repeated measures (pre/post). The results of the analysis are summarized in Table 9.

As can be noted from Table 9, there is a very high F ratio for repeated measures which is significant at the 0.01 level. This large ratio clearly reflects the substantial pre/post changes occurring in both groups. No other main effects or interactions were significant. Since a significant conditions-by-measures interaction had been predicted, planned comparisons for simple main effects were carried out among the cell means using the within subjects error term given in Table 9.

TABLE 9

Summary of Results of Analysis of Variance for Target Location Task — Experiment 4 — Combined Arm Changes

Source	SS	df	MS	F	P
Order	0.46	1/12	0.46	0.01	N.S.
B. Subjects	1080.50	12	90.04		
Conditions	92.16	1/12	92.16	3.34	N.S.
Order X Conditions	36.90	1/12	36.90	1.33	N.S.
W. Subjects	331.37	12	27.61		
Measures	494.45	1/12	494.45	35.22	<.01
Order X Measures	0.18	1/12	0.18	0.12	N.S.
W. Subjects	168.46	12	14.04		
Conditions X Measures	22.20	1/12	22.20	2.60	N.S.
Order X Conditions X Measures	0.04	1/12	0.04	0.00	N.S.
W. Subjects	102.31	12	8.53		

Significant pre/post changes were noted for both the experimental condition ($F = 42.54$, $df = 1/12$, $P < 0.01$) and the control conditions ($F = 17.97$, $df = 1/12$, $P < 0.01$) reflecting the large repeated measures effect noted in Table 9. Further comparisons indicated that no differences existed between the two pre-adaptation means ($F = 1.41$, $df = 1/12$, N.S.) but that substantial differences do, in fact, exist between the post-adaptation means ($F = 12.04$, $df = 1/12$, $P < 0.01$). This would argue strongly that group differences do, in fact, exist above and beyond the pre/post changes. Hence, tests for simple effects indicate first that significant pre/post changes occurred in both experimental and control conditions but second that there is a significantly greater increase among experimental subjects. On the surface, this latter finding would indicate that a recalibration of registered arm length has occurred in one or the other or both of the arms as a result of exposure to the KRD. Without examination of the arms individually, however, it does not appear possible to rule out the possibility that a recalibration of the perceived position of the arms with respect to the shoulders had taken place, as discussed in the introduction to these two experiments.

The pre/post (repeated measures) changes in mean distance scores, which are common to both experimental groups, need to be explained. One possibility for this pre/post increase is that the changes represent a positional aftereffect resulting from the held positions of the arms during the adaptation task. The left arm in this task is held in position, such that it pushes firmly against the stop at the end of the KRD apparatus. After placing the left arm in this fashion, subjects were sometimes observed to move the right shoulder slightly distally to the left shoulder. If accompained by a slight step backwards with the right foot, this gives a substantial increase in power to the right arm while swinging to the button. It also results in a freer swing. However, it realigns the shoulders with respect to the KRD similar to that illustrated in Figure 17d. Persistance of this horizontal rotation at the shoulder could account for the increase in mean distance scores from pre- to post-test, which is common to both experimental and control groups.

A second possibility for this pre/post increase would be related to a discrepancy in the relative positions of the two arms during the adaptation task when the KRD control device is used. As noted earlier, when depressing the button on the KRD devices, subjects have their index finger held roughly perpendicular to the hand. When using the control device, it is the tip of the finger which hits the button. The probe, however, hits the left hand in the region of the first or second phalange of the index or middle finger (i.e. at some distance behind the left fingertip). Thus, there is a discrepancy between where the button is touched by the right hand (finger tip) and where the probe hits the left hand (third joint). It was expected that the brain would make allowance for this difference as a result of the known position of the right index finger (i.e. because the index finger is crooked, the outward distance from shoulder to finger tip is now shorter than the distance from shoulder to finger tip in the left hand when the index finger is extended). However, if these joint angles are not accurately taken into account, it is possible that the discrepancy forces an adaptive change of the type produced by the KRD, although of a much lesser magnitude. Such a change resulting in a recalibration of apparent arm lengths would result in mean distance changes in the probe-location task in the same direction as the KRD but to a lesser extent, and this would conform to the noted findings. From the present data, it does not seem possible to separate the two hypotheses.

Figures 20a and 20b show the pre/post experimental/control changes for each hand used separately as a target. Figure 20a shows the mean changes when the target is located on the right hand and illustrates a substantial decrease in both groups with little superiority for either.

Figure 20b shows the changes in means when the target is located in the left hand. Here there is an increase away from the target and a fairly clear superiority for the experimental group. The pre-adaptation means are also somewhat displaced anteriorly from the target but not quite as extensively as in the former case. It would appear, however, that a somewhat anterior placement of marks is the form of the constant error in this task. Although different patterns emerged when each target hand was viewed separately, it was decided to further explore the relative differences in the adaptive changes in each arm separately by focusing attention on more independent measures of registered arm length. This, in fact, was done in anticipation of this need by performing Experiment 5 simultaneously.

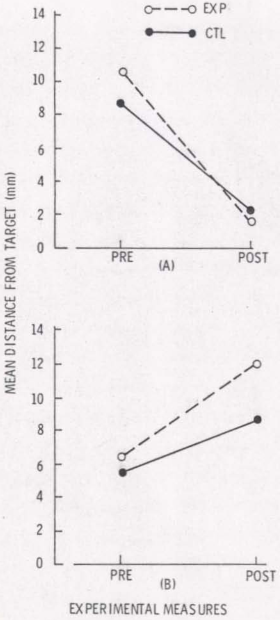

FIGURE 20

Pre/Post Changes in Mean Distance From
Target in the Probe-Location Task in Experiment 4
A — Right-Hand Target
B — Left-Hand Target

Experiment 5

This experiment is largely a replication of Experiment 4, except that more subjects were used and a different method of judging arm length was utilized. Prior to the experiment, a re-examination of the various tasks previously used as arm length estimates was made to determine which appeared most efficacious. Previous tasks were knee location (pilot study), ankle location, and probed leg location. This non-statistical examination suggested that the knee-location task was best, as it required the least body movement from subjects and used the most direct up-and-down movements. It was, in general, also felt to have provided the most accurate measures. Consequently, it was chosen for the experiment. It was further decided that both arms would have to be examined separately using this task, in order to clearly determine the role of each arm.

Based on the theoretical outline given in the Introduction to Experiments 4 and 5, it was predicted that the effect of the KRD adaptation task should result in a recalibration of registered arm length of one or the other or both of the arms.

METHOD

Subjects: A total of 36 paid volunteer subjects of either sex were used for this study. All instructions, demonstrations, and practice trials were given as in previous experiments.

Format: Each subject participated in two experimental sessions, each lasting approximately one-half hour. Subjects served as their own controls, and thus, one session was an experimental session in which subjects performed an adaptation task using the KRD, and one was a control session, differing only from the former in that the KRD control device was used in place of the KRD.

Both the experimental and control sessions consisted of two parts: 1) an adaptation task (as noted above) in which subjects used the KRD or KRD control device and 2) a dependent variable task (body part location task) in which subjects attempted to locate the centre of their knee while blindfolded. The latter task was used as a measure of registered arm length, as was the ankle-location task (Experiment 1). Eighteen subjects received the experimental session first, while eighteen had the control session first.

Apparatus and Tasks: The KRD adaptation was performed precisely in the manner described in Experiment 4. The knee-location task was very similar to the ankle-location task given in Experiment 1. In the present instance subjects stood in front of the apparatus table which held the KRD. To either side of him was a 2 cm plywood marking board (approximately 1 m X 1 m), each being attached at one end to the end of the table and anchored to the floor at the other by means of rods and clamps. With this arrangement, a subject could turn either to the left or right to perform the knee-location task. In the task itself a subject would face the marking board, press one of his knees against it, and bending over the board at the waist, would attempt to align a pen opposite his knee. All permitted and unpermitted movements and positions were as given for the ankle-location task in Experiment 1, the critical aspect being that the marking arm was held straight. The position assumed by subjects during this task is illustrated in Appendices H and I (side and front views). As with the ankle-location task, subjects made their marks on prealigned graph paper. When turned to the right-hand side marking board, subjects attempted to locate their right knee with their right hand; and while turned to the left, they marked their left knee with their left hand. All remaining aspects of this task were as described in Experiment 4.

PROCEDURE

Subjects performed 14 blocks of ten trials of the adaptation task, as in Experiment 4, using either the KRD or KRD control device. The procedure for the task was identical in both experiments. Prior to adaptation, subjects performed seven trials of the knee-location task with each hand giving a total of 14 separate location estimates. After the first adaptation block, the single marking was done to the right side. After the second block, this single trial was performed to the left side. The alternation of side was continued after each adaptation block until a total of seven post-adaptation markings had been made on each side.

RESULTS AND DISCUSSION

Marks were scored in the vertical direction using the altered-origin method as described in Experiments 1 through 3.

Figures 21a and 21b present the pre/post experimental and control means for the left and right hands respectively. These would appear to indicate decreases in mean vertical distances for all conditions, with a particularly-extensive decrease for the left-hand experimental condition. A decrease in mean vertical distance means that subjects are placing their marks consistently above the knee target. Figure 21b shows, in addition, that although decreasing overall, the right-arm experimental condition shows an increase with respect to the control condition change. It should be further noted that the left-hand change (Figure 21a) is the first

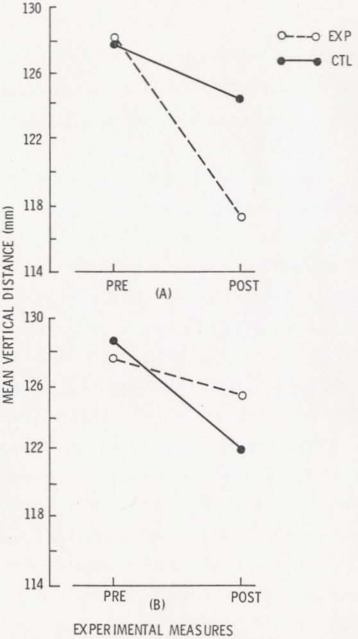

FIGURE 21

Pre/Post Changes in Mean Vertical Distance
In Knee-Location Task in Experiment 5 (N = 36)
A — Left Hand
B — Right Hand

instance in four experiments that a relative decrease in judged location has been observed during body-part location tasks (that is, suggesting an increase in apparent arm length).

A four-way analysis of variance was performed on these means. The first factor was pre-adapted versus post-adapted subjects (order) and subjects were nested only within this variable. The second factor was hands (left or right). The third factor was experimental conditions (experimental/control), and the fourth factor was repeated measures (pre/post). A significant hands-by-conditions-by-measures interaction was predicted. Table 10 presents the summary of this analysis.

As noted in Table 10, a significant main effect for repeated measures and a significant hands-by-conditions interaction was found in addition to the predicted hands-by-conditions-by-measures interaction. Since it is quite apparent that both hands are operating independently in these two tasks and that this is the source of the HANDS effect of the three-way interaction, it was decided to test each hand separately for simple effects using the within subjects error term.

TABLE 10

Summary of Analysis of Variance for Knee-Location Task In Experiment 5

Source	SS	df	MS	F	P
Order	63.76	1/34	63.76	0.89	N.S.
B. Subjects	2448.53	34	72.02		
Hands	45.18	1/34	45.18	3.95	N.S.
Order X Hands	18.23	1/34	18.23	1.59	N.S.
W. Subjects	389.10	34	11.44		
Conditions	6.97	1/34	6.97	0.59	N.S.
Order X Conditions	29.11	1/34	29.11	2.44	N.S.
W. Subjects	405.19	34	11.92		
Measures	312.52	1/34	312.52	4.27	<.05
Order X Measures	50.34	1/34	50.34	0.69	N.S.
W. Subjects	2490.94	34	73.26		
Hands X Conditions	91.05	1/34	91.05	13.82	<.01
Order X Hands X Conditions	19.46	1/34	19.46	2.95	N.S.
W. Subjects	223.99	34	6.59		
Hands X Measures	25.02	1/34	25.02	1.85	N.S.
Order X Hands X Measures	12.15	1/34	12.15	0.90	N.S.
W. Subjects	460.17	34	13.53		
Conditions X Measures	12.43	1/34	12.43	0.97	N.S.
Order X Conditions X Measures	22.37	1/34	22.37	1.75	N.S.
W. Subjects	434.67	34	12.78		
Hands X Conditions X Measures	76.70	1/34	76.70	11.15	<.01
Conditions X Measures	14.30	1/34	14.30	2.08	N.S.
W. Subjects	233.94	34	6.88		

For the left hand, analysis of pre/post change showed a highly-significant decrease in the experimental condition. The pre-adaptation mean was 126.9 (s = 0.32) and the post-adaptation mean was 116.5 (s = 7.08). A test for simple effects yielded an F ratio of 44.41 (df = 1/34) which is significant at the .01 level. The control pre/post means (126.9, s = 0.32 and 123.8, s = 6.41 respectively) failed to show a significant change (F = 3.96, df = 1/34, N.S.). In addition, a test for differences between the post-adaptation means shows that they are in fact, significantly different (F = 139.42, df = 1/34, $P < .01$). These findings clearly and unambiguously show an extensive experimental effect of KRD adaptation. Interpreted in terms of the present hypothesis, this should be viewed as indicating a substantial perceived change in registered arm length indicative of an apparent lengthening.

For the right hand, a somewhat different situation arises. Testing of the pre/post means showed that while the experimental pre/post means (127.66, s = 1.07 and 125.45, s = 9.07 respectively) did not differ (F = 1.98, df = 1/34, N.S.), there was a significant decrease in distance between the control means (127.18, s = 0.92 and 121.82, s = 5.32 respectively), the F ratio being 11.54, df = 1/34, $P < .01$. As confirmation, the post-adaptation means were found to significantly differ (F = 34.48, df = 1/34, $P < .01$) but not the pre-adaptation means (F = 0.60, df = 1/34, N.S.).

This finding would imply a meaningful experimental change in right-hand performance. In Experiment 4, it was suggested that a change of the registered lengths of the two arms with respect to each other might occur as a result of an imposed experimental error in the KRD control device (see above). Since this pre/post change was significant in that experiment, it should be the case that the same effect occurs in the present experiment and is the source of the significant pre/post change in the right-hand control group. If this is assumed to be the case, then the absence of a significant pre/post change in the experimental groups can be viewed as an arithmetic cancellation of the different effects arising from: 1) the pre/post changes common to both experimental groups and 2) the pre/post change in the experimental group resulting from the true KRD adaptation effect. This would be so since each would be forcing changes in apparent length in opposite directions. Thus, were there no apparent changes in control-group values, an apparent increase in mean-distance values would clearly be evident in the right-hand group, indicating an a cating an apparent shortening of registered right-arm length. This explanation does require, however, the additional assumption that imposed changes in registered arm length can be added or subtracted algebraically.

The one difficulty with the entire explanation given above is the absence of a significant pre/post change in the left-hand control group, which presumably should behave in the same way as the right-hand control group. Therefore, either the right-hand control change was not meaningful or, more likely, the left-hand control group, which does show a substantial change in the appropriate direction is a real and meaningful change despite the fact that it does not reach significance. In an attempt at further verification of this interpretation, a test for simple effects was performed on the post-adaptation means of the two control conditions. It was found that these did not significantly differ (F = 1.72, df = 1/34, N.S.); and as such, the two should probably be regarded as a unit (i.e. of equal pre/post change).

In conclusion, the present experiment shows an extensive and unambiguous change in performance when subjects used their left hand to locate their left knee. A similar change in the opposite direction was found to have occurred in the right-hand performance, but the meaning of the change is less clear due to uncertainty concerning the nature of the two control group changes. The change in left-hand experimental condition scores indicates an apparent increase in registered arm length. This finding is of particular importance, as it demonstrates for the first time that a change in this direction can take place. It, thus, places this adaptive mechanism in the same order as that underlying joint-angle changes, in the sense that it is an adaptive mechanism which is not unidirectional.

The right-hand experimental condition changes probably also represent an apparent change in registered arm length, in this case an apparent shortening. This change, however, has to be seen against the background of pre/post (repeated measures) changes common to both control and experimental conditions. It also appears as if the apparent changes in registered length in the right arm, resulting from the KRD, are considerably less than those in the left arm. If this were the case, it would be an additional argument against the explanation that the experimental changes were due to a change in registered position of the arms with respect to the shoulders since equal changes (in opposite directions) in performance of the location task would be expected when each arm was used. The present experiment is not suitable, however, for comparing the actual distance changes between arms since the relative location tasks (left knee/right knee) used to note changes in registered arm length are not equitable (i.e. due to differences between two body sides). Further experimentation, using different tasks, will be required to establish the proportion of change in each arm under the present experimental conditions.

Experiment 6

Although the previous two experiments produced substantial evidence for a change in registered arm length, there remained, as noted, a possibility that the experimentally-derived results were due to a change in registered position of the arms with respect to the shoulders. The absence of equal changes in both arms argued against this hypothesis but nevertheless constituted only indirect evidence against this possibility. The following final experiment was initiated to rule out this one remaining objection.

The basic format of the previous two experiments was retained but minor changes in the dependent variable task were envisaged in order to avoid confounding the dependent measure as discussed above. In particular, it was felt that the solution to the problem would be to simply make the position of the arms, while performing the dependent variable task (measuring registered limb-length), orthogonal to the position of the arms during the adaptation task.

The dependent measure in Experiment 5, for example, required subjects to use their arms in the same plane (with respect to the body) as they did during the adaptation task. This position is depicted in Figure 17d which shows the arms held straight out in front of the subject in the horizontal plane perpendicular to the shoulders. This is also the position subjects held when bending over to place marks opposite their knee. In this condition there could be a transfer of both the effects of a change in registered arm length and the registered position of the arms with respect to the shoulders.

It should be expected that any change in registered position of the arms with respect to the shoulders should remain specific to the plane in which it occurs. Any registered shift of the arms and shoulders in the horizontal plane should not have relevance to tasks performed by the arms in the vertical plane. Therefore, if subjects were to perform the body-location task with their arms held parallel to the body, and hence orthogonal to the position held during adaptation, then, there would be no reason to expect any effect of an adaptive change in registered position of the arms with respect to the shoulders. A change in registered arm length, on the other hand, should be specific to the arm in question and independent of the plane of the arms in which the body-location task is performed. Consequently, it was decided to adopt this strategy in performing this experiment.

In designing this experiment, one other potential flaw was considered. This involved the fact that while the left arm was held straight out and perpendicular to the shoulder during the KRD tasks, the right arm actually rotated through several degrees of arc while swinging at and depressing the button (c.f. Figure 16) and that the position of the right hand and arm at the moment the button was being depressed was actually several degrees towards the subject's midline from the perpendicular. Examination of Figure 18a shows how a similar difficulty arose in the probe-location task in Experiment 4 with the right hand travelling over a distance of approximately .8 m to make contact with the left hand.

It was expected that these angular changes would balance out across the various conditions of the experiment and not introduce any systematic bias into the results. Nevertheless, the possibility remained that this angular discrepancy between the two arms at the moment of button pressing might in some way detract from the full effect of the KRD either by having some of the kinesthetic recalibration ascribed to a change in the registered position of the right arm or by forcing a combined recalibration of the two arms with respect to the shoulders.

To avoid any confusion in this respect, it was decided that subjects would stand directly in front of the KRD so that it fell directly opposite the midline at all times. Therefore, while operating the KRD, a subject's arms would be angled slightly inwards toward his midline in such a way that the angular discrepancy of each arm from the true perpendicular was equal (approximately 10 to 15 degrees). This position is depicted in Figure 22a.

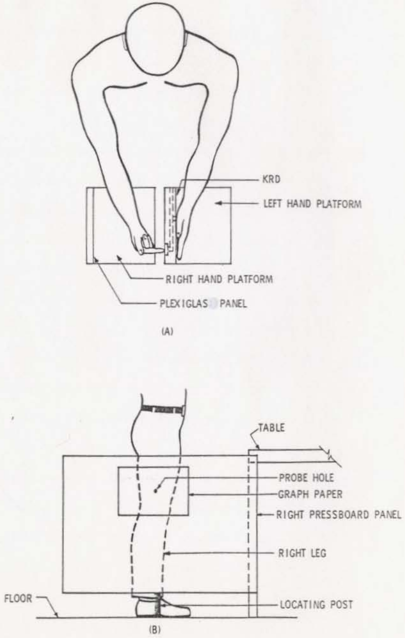

FIGURE 22

Illustrations of Apparatus and Subject Positions in Experiment 6
A — Position of Subject During Adaptation Task
B — Position of Subject's Leg During Probe-Location Task

Also, to further minimize the effects of recalibration of the arms with respect to the shoulder, it was decided to restrict the swing of the right arm to a few degrees rather than the large swing (50-70 degrees) permitted in the previous two experiments (c.f. below). Additionally, it became apparent that if the dependent variable task was to take place with the arms in the vertical plane, no extensive discrepancy could be permitted between the heights of the two arms during the KRD task. Steps were also taken to ensure this condition (c.f. below).

Finally, it had been noted on questioning subjects after the previous two experiments that many failed to notice a clear fusion effect. Although no systematic analysis was made on the basis of the presence or non-presence of a fusion effect, it was apparent that some of the subjects who individually did not show great changes in registered arm length also were not aware of a distinct fusion. This observation directly lead to the hypothesis that the fusion effect and changes in registered limb-length are covariant events. It was, therefore, felt that a better sample might be obtained if selection or division of subjects was made on the basis of whether or not they had a clear experience of kinesthetic fusion. It was predicted that subjects who clearly perceived kinesthetic fusion would also show distinct changes in registered arm length, while subjects who did not experience fusion would either show no change in registered arm length or show much smaller changes than subjects who did experience fusion.

METHOD

Subjects: A total of 19 paid volunteer subjects of either sex participated in this experiment. All general instructions, demonstrations, and practice trials were given as in previous experiments.

Format: Each subject participated in two experimental sessions, each lasting approximately one-half hour. Subjects served as their own controls; and thus, one session was an experimental session in which subjects performed an adaptation task using the KRD, and one was a control session differing only from the former in that the KRD control device was used in place of the KRD.

Both the experimental and control sessions consisted of two parts: 1) an adaptation task in which subjects used the KRD or KRD control device and 2) a dependent variable task (probe-location task) in which subjects attempted to locate the position on their leg against which a probe was being pressed.

Subjects were assigned to groups in the following manner. It was initially assumed that each subject entering the experiment would experience fusion; and consequently, each was first assigned to the fusion group and received either the experimental session first or the control session first, according to a randomly-generated series of numbers. However, if after the experimental session, a subject reported no experience of fusion, he was removed from the fusion group and assigned to the non-fusion group. Thus, subjects were assigned to the non-fusion group only after failure to perceive fusion; otherwise they remained in the fusion group. For this reason, the number of subjects who received the control or experimental session first in the non-fusion group could not be readily counterbalanced.

Of 19 subjects who completed the two sessions, 11 experienced a clear consistent fusion effect on every block of trials with the KRD device. This was the initial criterion for inclusion in the fusion group. Of the remaining eight subjects (the non-fusion group) only two failed to perceive any fusion on all blocks of trials. The remainder did experience fusion on one, two, or a few blocks but no fusion on the majority of blocks. For these subjects, when fusion was experienced, it was often towards the end of the adaptation blocks, although for some subjects, it occurred on the first two or three blocks but did not subsequently appear. Thus, it seems that complete absence of fusion is rare but partial or incomplete fusion is fairly frequent.

Of the 11 fusion subjects, six received the experimental condition first while five received the control session first. Of the eight non-fusion subjects, five received the experimental session first and three received the control session first. A reasonable balance in this group was thus achieved serendipitously and data was subsequently combined within groups without regard to session order.

Apparatus and Tasks: The adaptation task was performed essentially as in Experiments 4 and 5 with the following differences: First, the position of the KRD with respect to the subject was rigidly maintained opposite the midline (see Figure 22a) for reasons noted above. Second, an adjustable platform was built on the right-hand side of the KRD so that its height could be made and maintained equal to that of the left-hand platform thereby ensuring that the two arms were always operating at the same height (see Figure 22a). The right-hand platform was approximately 20 cm wide and terminated in a plexiglas panel which ran its length and which rose approximately 20 cm above the level of the platform (Figure 22a). This arrangement effectively restrained the right arm from swinging back beyond (roughly) the perpendicular to the shoulder. Subjects were instructed to swing the full distance between the panel and the button in each trial. This apparatus is also depicted in Appendix J.

KRD trials were performed essentially as in Experiments 4 and 5 with the following modifications: The height of the two platforms were adjusted prior to each session so that the two arms were held directly in the horizontal plane and were of equal height. Subjects were told to begin their swing by resting the back of their right hand against the plexiglas panel. They returned their arm against the panel after pressing the button before initiating a new swing.

As in the previous experiments, subjects were blindfolded during the task. Unlike the previous experiments, however, subjects were shown and practiced on the devices they used in each session and were given certain explanations as to their functions. For the control session (using the KRD control device) subjects were told that the probe pressing into their left hand would assist them in guiding their right hand to the button. They were also told that they would be performing a distinct number of consecutive trials (15) in each block. In the experimental sessions (using the KRD) subjects were told that they may or may not experience fusion after a number of trials and were given a brief explanation as to what that constituted, i.e. "You may feel as if your right hand is hitting the button directly opposite to where the probe is hitting your left hand, even though you know it isn't."

Further, they were given the following instructions: "If, as you are hitting the button, you don't feel fusion, you are to keep pressing it continuously until I (the experimenter) tell you to stop. If, however, you feel a fusion effect, say 'now' as soon as you are certain it is occurring. Keep on hitting the button even though you notice this effect." When fusion subjects said 'now', the experimenter would tell them to keep going if they had hit the button less than 10 times consecutively and tell them to stop when they had reached 10 trials. If they had pressed more than 10 times by the time they said 'now', the experimenter would tell them to stop immediately. This procedure insured that a minimum of 10 presses occurred in each block. Subjects who did not experience fusion were stopped after 25 trials in each block. In either of these three conditions, subjects immediately proceeded to the probe-location task after completing a block of ten trials (c.f. below).

The probe-location task was very similar to the probe-location tasks in Experiments 2 and 3. To the right and left of the KRD platforms, were two thin (2 mm) pressboard panels supported by rods and clamps. The right-hand panel is depicted in Figure 22b. Subjects were required, while facing forward, to locate either the right- or left-hand location posts (which were placed directly under each panel and about halfway along their lengths), with either their right or left foot, depending on which side they were performing the task. Keeping the foot in position, they then brought themselves close to the panel, assumed a comfortable stance, and rested their (right or left) leg firmly against the panel. The position of the right leg with respect to the right panel is shown in Figure 22b.

In the probe-location task, itself, the experimenter pushed a small (3 cm) probe at the end of a rod through a hole in either of the two pressboard panels (see Figure 22b) and against the leg of the subject. Both holes were placed 75 cm from the floor and directly above the location post so that for most subjects the probe hit directly in the centre of the lateral side of the leg, about midway between hip and knee. Most importantly, the constant height of the probe hole on both sides insured that the probe hit at the same height on all trials. There was some slight variation of the probe placement in the anterior/posterior direction; however, the experimenter had subjects make slight shifts of their leg prior to each marking so that the probe appeared to be hitting as close to the centre as possible. Once the probe was securely placed against the leg (taking one to two seconds), subjects then bent over the panel (while maintaining a front-facing position) and attempted to bring a marker pen directly opposite the point on his leg against which the probe was pressing. The position of subjects during this task is depicted in Appendix K. Subjects were permitted to move only from side to side (in the coronal plane) either by bending at the waist or raising or lowering the shoulders. As in previous experiments, the marking arm was held stiff with the pen held horizontally, and movement of the arm in the saggital plane was permitted only at the shoulder. Subject marks were recorded on graph paper which was centered over the probe hole prior to each session. When working at the right-hand pressboard panel, subjects attempted to locate the position of the probe against their right leg with their right hand and when working on the left-hand panel, they used their left leg and left hand. All remaining aspects of the task were as described in Experiments 2 and 3.

PROCEDURE

Subjects performed 14 blocks of trials of the adaptation task, as in Experiments 4 and 5, using either the KRD or KRD control device. When using the control device, subjects hit the button 15 consecutive times in each block. When using the KRD, subjects hit the button a minimum of 10 and a maximum of 25 consecutive times, depending on when and if they experienced fusion (see above).

Prior to adaptation trials, subjects performed seven trials of the probe-location task with each hand giving a total of 14 separate location estimates. A blue marking pen was used for these trials. After the first adaptation block, subjects performed one trial of the location task to the right side. After the second block, this single trial was performed to the left side. The alternation of side was continued after each block until a total of seven post-adaptive markings had been made on each side. A red marking pen was used for all post-adaptation trials.

The experimenter also recorded the number of trials required for subjects to reach fusion in each adaptation block.

RESULTS AND DISCUSSION

Marks on the graph paper were scored in the following manner: Since the centre of the target was known, because the probe was pushed through both the pressboard and graph paper, all marks were measured (in cm) as the vertical distance from the horizontal line which passed through the probe hole. Scores falling above this line were scored negatively, while scores falling below were scored positively. Therefore, as in previous experiments, an increase in vertical distance is indicative of subjective arm shortening while a decrease is indicative of subjective lengthening.

The constant 50 was added to all scores for convenience of scoring and analysis. For all subjects, mean pre- and post-adaptation scores were taken for each hand for each condition (experimental/control).

For each subject in the fusion group, a mean number of trials (per adaptation block) required to produce fusion was calculated. An overall average (N = 11) of 10.9 trials/block was obtained, with a range of 6.6 to 15.0 trials/block.

Figures 23a and 23b present the pre/post experimental and control means for the right hand for both fusion and non-fusion subjects respectively. For the fusion group (Figure 23a) there was a substantial increase in mean vertical distance from pre- to post-test in the experimental condition and a very slight decrease in the control condition. However, there also appears to be a substantial difference between the two conditions on the initial pre-test scores.

In contrast, the non-fusion experimental condition (Figure 23b) showed no substantial pre/post change while the control condition produced a slight decrease similar to that of the fusion group. In addition, the pre-test scores in both conditions do not appear substantially different. In fact, the only pre-test score which appears to differ

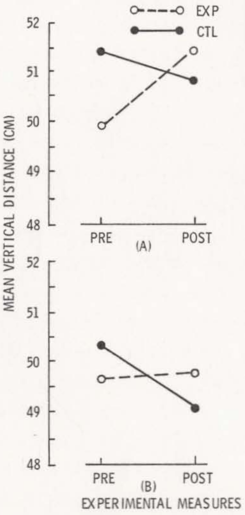

FIGURE 23

Pre/Post Changes in Mean Vertical Distance
In the Right Hand in the Probe-Location Task
In Experiment 6 (N = 19)
A — Fusion Subjects (N = 11)
B — Non-Fusion Subjects (N = 8)

substantially (greater than 1 cm) from the horizontal probe height (50) is the noted pre-test score among fusion subjects in the control condition.

Separate three-way analyses of variance were performed on the experimental means for the right and left hands. The first factor was fusion versus non-fusion (fusion) and subjects were nested only within this variable. The second factor was experimental condition (experimental/control); while the third factor was repeated measures (pre/post). A significant fusion-by-conditions-by-measures interaction was predicted. Table 11 presents the summary of this analysis for the right hand.

While the predicted three-way interaction did not emerge, a highly-significant conditions-by-measures interaction was obtained which was suggestive that there were significant experimental changes in both fusion and non-fusion groups. For clarity, the results of the fusion group will be discussed first and the non-fusion group will be examined afterwards. In the fusion group, tests for simple main effects showed that there was a significant increase in vertical distance in the experimental condition from a mean of 50.0 ($s = 2.18$) to a mean of 51.3 ($s = 1.99$) ($F = 7.84$, $df = 1/17$,

TABLE 11

Summary of Analysis of Variance for the Probe-Location Task

For the Right Hand in Experiment 6

Source	SS	df	MS	F	P
Fusion	26.83	1/17	28.63	1.89	N.S.
B. Subjects	240.95	17	14.17		
Conditions	1.29	1/17	1.29	0.51	N.S.
Fusion X Conditions	1.13	1/17	1.13	0.45	N.S.
W. Subjects	42.60	17	2.51		
Measures	0.16	1/17	0.16	0.18	N.S.
Fusion X Measures	3.93	1/17	3.93	4.40	N.S.
W. Subjects	15.18	17	0.89		
Conditions X Measures	14.24	1/17	14.24	22.43	<.01
Fusions X Measures X Conditions	0.32	1/17	0.32	0.51	N.S.
W. Subjects	10.79	17	0.63		

$P < .025$). The decrease in mean vertical distance from 51.4 ($s = 2.55$) to 50.8 ($s = 2.10$) in the control condition was not significant ($F = 1.68$, df = 1/17, N.S.). This shows clearly that there was a significant increase in mean vertical score, indicative of subjective arm shortening among fusion subjects which can be directly attributed to the adaptation procedure.

However, the large pre-test difference among fusion subjects appeared to require an explanation. A test for simple main effects showed that the pre-test means were, in fact, significantly different ($F = 9.03$, df = 1/17, $P < .01$) while the post-test means were not ($F = 1.12$, df = 1/17, N.S.). A re-examination of the data suggested that the control pre-test mean had been inflated as a result of persisting experimental effects from the six subjects who had received the adaptation session before the control session. Essentially, the adaptation effects (subjective limb-shortening) occurring in the first experimental session appeared to be still present when subjects made the pre-test marks (at least 24 hours later) in the control condition. This resulted in inflated pre-test scores among these six subjects which significantly altered the overall mean for the fusion group. However, following use of the KRD control device, the persisting experimental effects were lost and post-test scores tended to return back to average target height levels (approximately 50 cm).

Figures 24a and b show the experimental and control pre/post means for the pre-adapted (N = 6) and post-adapted (N = 5) fusion subjects respectively (for the right hand). These graphs appear to support the notion of an exaggerated pre-test control score among subjects who received the experimental condition first (pre-adapted) even though there is a small pre-test difference among the post-adapted subjects.

To test this notion further, an additional three-way analysis of variance was performed on the experimental means of 11 fusion subjects. The first factor was pre-adapted versus post-adapted (order) and the second and third factors were conditions and measures, as in the previous analysis. Table 12 presents the results of this analysis. A significant order-by-conditions-by-measures interaction was predicted.

Again, the conditions-by-measures interaction dominated the analysis, and the predicted interaction was not significant. However, tests for simple main effects were initiated as in the previous analysis. Among the pre-adapted subjects the experimental pre-test mean of 50.3 ($s = 2.62$) was substantially less than the control pre-test mean of 52.2 ($s = 2.93$). The F ratio for the test between these two means was, in fact, significant ($F = 6.69$, $df = 1/9$, $P < .05$).

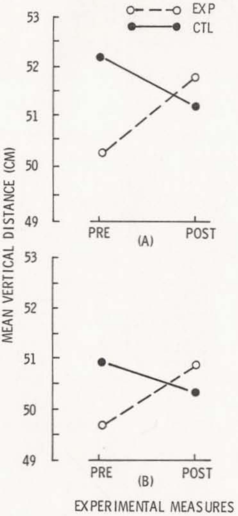

FIGURE 24

Pre/Post Changes in Mean Vertical Distance
In the Right Hand in the Probe-Location Task
In Experiment 6 for Fusion Subjects Only (N = 11)
A — Pre-adapted Subjects (N = 6)
B — Post-adapted Subjects (N = 5)

However, the two pre-test means, 49.6 (s = 1.38) and 50.9 (s = 1.62) among post-adapted subjects clearly did not significantly differ (F = 3.13, df = 1/9, N.S.). Thus, the hypothesis is statistically supported and bears out the hypothesis that the large difference in pre-test scores in the right hand among fusion subjects was, in fact, due to inflation of pre-test scores in the control session among subjects who received the adaptation session first.

TABLE 12

Summary of Analysis of Variance for the Probe-Location Task For the Right Hand Among Fusion Subjects in Experiment 6

Source	SS	df	MS	F	P
Order	11.82	1/9	11.82	0.70	N.S.
B. Subjects	152.46	9	16.94		
Conditions	3.11	1/9	3.11	0.89	N.S.
Order X Conditions	0.16	1/9	0.16	0.46	N.S.
W. Subjects	31.42	9	3.49		
Measures	0.64	1/9	0.64	0.49	N.S.
Order X Measures	0.40	1/9	0.40	0.31	N.S.
W. Subjects	11.84	9	1.32		
Conditions X Measures	13.20	1/9	13.20	16.34	<.01
Order X Conditions X Measures	0.28	1/9	0.28	0.35	N.S.
W. Subjects	7.27	9	0.81		

Returning to non-fusion subjects (Figure 23b), the experimental condition failed to show significant pre/post changes. The means were 49.6 ($s = 1.86$) and 49.8 ($s = 1.81$) respectively and did not significantly differ ($F = 0.07$, $df = 1/17$, N.S.). The control condition on the other hand did produce a significant pre/post change. These means were 50.3 ($s = 1.51$) and 49.0 ($s = 1.65$) and a test of simple effects yielded an F ratio of 5.37 ($df = 1/17$, $P < .05$).

The meaning of this latter finding is uncertain. A comparison of the two control conditions (fusion/non-fusion) did not seem warranted since the control condition for fusion subjects had been shown to have been strongly influenced by adaptation effects in the analysis described above. A comparison of pre-test and post-test means among non-fusion subjects yielded no significant differences ($F = 1.21$, $df = 1/17$, N.S. and $F = 1.58$, $df = 1/17$, N.S. respectively) which might cast some doubt on the validity of the control condition change. However, the meaning of this change will have to await further experimentation.

In summary, the results of the analysis of right-hand performance among fusion subjects are clear. The KRD produces a significant <u>change in performance</u>[7] in the probe-location task which indicates that a subjective shortening of the right arm has taken place. In fact, the effect of the recalibration appears

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[7] While there is clearly a change in performance, a rigorous analysis of the genesis of the initial and final judgements of distance is not possible given our present procedures.

so extensive that it is still present in pre-test scores in subsequent sessions 24 hours or longer after the initial experimental session (among subjects who received the experimental condition first). Changes in non-fusion subjects are at present ambiguous.

Figure 25a and b show the experimental changes among the fusion and non-fusion subjects respectively for the left hand. The control changes in both groups appear similar to the control changes in the right-hand groups; that is, they show slight decreases in mean vertical distance. However, there do not appear to be any pre/post changes among the experimental groups in both cases. Table 13 presents the summary of the three-way analysis of variance for these means. The factors were as in the first analysis of the right hand described above (Table 11).

This analysis shows conclusively that no experimental changes occurred in left-hand performance as a result of adaptation. No further analyses were initiated.

The results of the present experiment demonstrate that recalibrations of registered limb-length do occur as a result of KRD adaptation. The pattern of results of this experiment are, however, quite different from those of Experiment 5 which produced distinct changes in left-hand performance and a possible, but lesser, change in right-hand performance. The differences between the two experiments might be accounted for by the refinements in the KRD

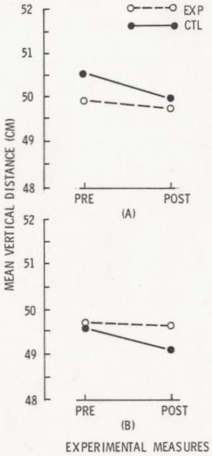

FIGURE 25

Pre/Post Changes in Mean Vertical Distance
In the Left Hand in the Probe-Location Task
In Experiment 6 (N = 19)

A — Fusion Subjects (N = 11)
B — Non-Fusion Subjects (N = 8)

TABLE 13

Summary of Analysis of Variance for the Probe-Location Task For the Left Hand in Experiment 6

Source	SS	df	MS	F	P
Fusion	6.56	1/17	6.56	0.53	N.S.
B. Subjects	211.29	17	12.43		
Conditions	0.52	1/17	0.52	0.22	N.S.
Fusions X Conditions	2.92	1/17	2.92	1.25	N.S.
W. Subjects	39.59	17	2.33		
Measures	2.06	1/17	2.06	2.61	N.S.
Fusion X Measures	0.73	1/17	0.73	0.93	N.S.
W. Subjects	13.37	17	0.79		
Conditions X Measures	0.74	1/17	0.74	1.29	N.S.
Fusion X Conditions X Measures	0.63	1/17	0.63	0.11	N.S.
W. Subjects	9.76	17	0.57		

apparatus in the present experiment, although such refinements would seem unlikely to produce such distinct differences in pattern. Another, and possibly more likely, explanation might be that the experimental changes due to changes in subjective arm length in Experiment 5 were confounded by changes in registered position of one or both arms at the shoulder as discussed earlier. This notion is somewhat substantiated by the fact that there were extensive pre/post changes in all conditions in the knee-location task in Experiment 5, which was at the time suggestive of a smaller recalibration in subjective arm length due to an effect common to both the KRD and KRD control devices. Very possibly, the common effect in that experiment was, in fact, a recalibration of registered position of the arms with respect to the shoulders and that the changes in subjective arm length were superimposed on this change. Further experimentation will be required to elucidate this position.

General Discussion

The present dissertation has forewarded and examined a proposal that there exists a central mechanism in the brain for the establishment and monitoring of values for the registered lengths of limbs and that this mechanism or system is capable of recalibration under certain circumstances in order to serve adaptive functions. This proposition has been argued logically, by example in Part I, and by two distinct experimental approaches in Part II. In presenting this proposal, it has also been necessary to make an additional argument for the existence of a mechanism underlying knowledge of limb volume, which combines with the system for knowledge of limb-length to produce a superordinate system of knowledge of limb space. Furthermore, the latter system is also considered to be a subordinate part of an even more extensive system involving all of the proprioceptive activity of a given limb and which appears to operate in a somewhat holistic fashion with respect to the entire body.

These latter suggestions follow logically from both the proposition that the brain does have a system for knowledge of limb-length and from a sparse number of clinical findings. However, it is not intended that evidence for knowledge of limb-length should in any way be dependent on these additional proposals. The theoretical rationale and experimental data for knowledge of limb-length presented in this paper are meant to stand on their own right, regardless of any other immediate implications.

Little further qualification of the arguments presented in Part I seems needed here. Since so few theoretical and experimental resources were available to answer the question of how the brain knows the length of the limbs, only a very rudimentary hypothesis for its nature could be proposed (Part I). In turn, since this latter theory is so basic, the subsequent experimental work (Part II) can neither greatly modify or expand it but rather only support or not support the overall proposal to some degree.

It is the contention of the present author that the results of the six described experiments support the present hypothesis. However, two facets of the study prevent this support from being as strong as it might otherwise be. The first aspect concerns the first three experiments which utilized the prism-adaptation methodology. The second concerns the last three experiments which used the new kinesthetic methodology.

The first three experiments were unambiguous with respect to arm length changes, in the sense that there was no other way of interpreting the changes in the various body-site location tasks that constituted the dependent variables. It is very likely that these methods could be improved on, particularly reducing the distance between the hand-held marking pen and the various body targets (stimulated or landmark); and in this respect the current methods might be revised in terms of Webers' (1852) original method of marking directly on the skin. However, in the first three experiments it is difficult to interpret the changes in these scores in terms of anything other than registered arm length.

The difficulty with these experiments is in the fact that a rather intricate and unparsimonious explanation had to be devised to explain the restricted conditions under which the changes in registered arm length took place. Three major assumptions were required: 1) that a change in perceived depth had taken place along with the change in registered limb-length; 2) that the subject must have had no prior experience with the apparatus which might otherwise prevent a change in apparent depth; 3) that the combined changes in apparent depth and limb depth would occur in cases of downward displacement of the visual field but not in cases of upward displacement. These rather complex restrictions, plus the fact that the locus of adaptive change for subjects not displaying changes in registered limb-length was not established, appears to imply a rather elaborate post-hoc treatment of the question which, at best, could only be regarded as highly tentative. The one redeeming facet of these experiments is that the unusual results found in Experiments 1 and 2 were replicable (Experiment 3). While not by any means proving the contention, the replication provides considerable plausibility to both the theoretical proposal and the noted experimental change.

If it is accepted, for the moment, that limb-length changes did take place in these experiments, two further questions emerge. First, why did the initially-proposed limb-length changes, which would have resulted in a single-factor adaptive solution to the prism displacement, not take place, particularly since it would appear to be a simpler, more parsimonious solution than the two-fold solution suggested further on? Second, and similarly, why did change in registered joint angle not take precedent, particularly as such changes, as discussed, do take place so readily at other joint sites?

The only immediately-forthcoming answer to both questions is to suggest that lengths of body segments are, in some way, spatially linked to apparent depth such that the absence of a change in apparent depth in the visual system inhibits a change in any other spatial system capable of signalling a change in apparent depth. That is, possibly neither a recalibration of limb-length nor recalibration of any joint whose receptor activity might signal an extension of a limb into space will take place without preceding change in depth signalled by the visual system.

The main action of certain synovial joints, particularly the hinged (ginglymus) joints, (such as those of the elbow and knee) is to extend or flex the limb in question in and out of haptic space. As noted in earlier discussions (Experiments 1 and 2), a recalibration of the elbow joint or the shoulder joint during positions of extension or flexion would have required small changes (in depth) of the apparent distance between the pointing hand and the eyes. It is possibly the presence of this aspect of the task which prevented recalibrations from taking place at those joints.

In support of this latter position is the fact that most of the adaptive changes resulting from prismatic displacement of the visual field have occurred at ball-and-socket (spheroid) joint sites and have primarily involved abductive/adductive movements of the limb at those sites. With the exception of the special case of the registered position of the eye in the head, adaptive changes have been noted at the shoulder (Harris, 1963; Craske, 1966a) and the hip (Hamilton, 1964; Mikaelian, 1970). As noted by Crawshaw (1974), there is little evidence which pertains to the other joints. However, both a questionable study by Putterman, Robert, and Bregman (1969) and a recent study by Craske (1977) have failed to demonstrate adaptive changes at the wrist.

Thus, although the evidence is scanty, it does appear reasonable, in view of the state of the literature, to take the position that changes in registered joint angle might take place either only when it does not involve a change of the position of the limb in depth or when there is a change in perceived depth in the visual system. In this respect, both joint-angle change and registered limb-length changes might require similar preconditions.

The present study would, however, appear to render this proposal incomplete. A change in apparent depth was presumed to have preceded the changes in registered limb-length in Experiment 1, and yet no joint-angle changes of any kind were found. Therefore, it would seem necessary to further complicate the matter by appending the above postulation with the condition that joint angle recalibrations which involve movement in and out of haptic space either do not take place at all, or take place only when they are not superceded by other adaptive changes (such as changes in registered limb-length).

Recalibrations of registered limb-length, on the other hand, do appear to accompany changes in perceived depth, at least as long as vision is an active part of the adaptive process. The required change in apparent visual depth explains why the simpler changes in registered limb-length, which were initially predicted, were not found.

It is clear from the foregoing discussion that proposals concerning adaptive changes on the basis of the results of Experiments 1 through 3 are very complicated and must be regarded as tentative until more is known about the relative roles of the various spatial systems which are directly concerned with changes in depth. Thus, as noted, while little ambiguity exists with regard to the source of the changes in the dependent variables in Experiments 1, 2, and 3, considerable difficulty in providing a suitable theoretical context for the changes has resulted.

Experiments 4, 5, and 6 yielded almost the reverse of the interpretive problems of Experiments 1, 2, and 3, in the sense that the latter experiments (1 to 3) were clear with respect to the changes in registered limb-length but unclear with respect to the sufficient driving conditions for these changes (and their theoretical context), while, in contrast, the former experiments (4 to 6) were clear with respect to the source of the dependent variable change (the KRD in conjunction with kinesthetic fusion) but unclear, at least for Experiments 4 and 5 in terms of interpreting the meaning of those changes. In regard to this last point, there is difficulty in determining which of the dependent variable changes in Experiments 4 and 5 reflect a change in registered limb-length, which reflect changes in registered position of the arms with respect to the shoulders, and which may be some form of interaction of both. These changes are also complicated by apparent strong positional after-effects in those two experiments.

The doubt concerning the reality of registered limb-length changes that was generated in Experiments 4 and 5 was clearly countered by the results of Experiment 6 which is not interpretable in terms of any change other than that of registered limb-length. As a result, it can be conclusively stated that certain kinesthetic discrepancies, such as that created by the KRD, will unambiguously lead to an adaptive change in registered limb-length. Therefore, the results of Experiment 6, taken in context of the rest of the dissertation, shows that there can be little doubt about the reality of a cerebral mechanism which monitors knowledge of limb-length.

However, it is the fact that the changes in registered limb-length in Experiment 6 occurred only in the right hand which creates problems for the interpretation of Experiments 4 and 5, as well as creating its own questions.

Both Experiments 4 and 5 strongly suggested that adaptive changes resulting from use of the KRD occurred in the registered length of both arms. Furthermore, Experiment 5 suggested that the left arm may be more extensively changed than the right. However, Experiment 6, the only unambiguous study with respect to registered arm length, showed changes exclusively in the right arm. This would appear to suggest that the preponderence of the changes in Experiments 4 and 5 were effects of recalibrations of registered position of the arms with respect to the shoulders, possibly superimposed on, or in addition to, changes in registered limb-length. To definitely answer these questions it would seem necessary to conduct at least one further experiment in which the dependent variable tasks compared adaptive changes in both the same and orthogonal planes at the same time.

The fact that Experiment 5 cannot be unambiguously interpreted in terms of a change in registered limb-length thereby calls into question the one instance of apparent lengthening of limb-length. Consequently, we are again left with clear evidence only of apparent shortening and hence must be open to the possibility that this adaptive mechanism is unidirectional. Further experiments attempting to confirm or disconfirm this notion would be valuable.

Finally, the fact that changes in registered limb-length may occur solely in one arm creates its own particular questions. The exclusive right arm change might be due to the fact that the right arm is the driving arm which serves as the locus of force in hitting the KRD while the left arm is a passive receptor of stimulation. Experimentally reversing the roles of the two arms should answer this question. Alternatively, it could be that it is the laterally-dominant arm which is capable of recalibration but not the contralateral limb. It is also possible that combined arm changes do occur but only when kinesthetic recalibration is more extensive, as in the instance in which registered position of the eyes in the head supercede registered position of the limbs in prism studies.

Other variables of interest in registered limb-length concern time parameters (simultaneity) of the button press and probe stimulation, the relative distances of the probe and button in terms of real arm lengths (which vary considerably among individuals), possible regions and relations of receptive fields on the skin surface, the force of the probe on the skin and the resistance of the button to press, the quality and quantity of the experience of fusion, and so on. Furthermore, it may be the case that the variance inherent in all these parameters will require attention to individual patterns of change rather than to exclusively group effects.

To further complicate the matter, more attention will have to be paid to the accuracy of performance of dependent variable tasks. The probe-location task in

Experiment 6 seemed to produce the greatest accuracy of all the experiments to date; however, many subjects were still very poor at locating the stimulated place on their leg, much more than would be expected from observation of their ordinary motor behaviour. Therefore, refinement of tasks designed to measure registered limb-length is undoubtedly needed.

Finally, on a longer-term basis, the results of the experiments within the context of the Introduction (Part I) suggest that experimentation on the kinesthetic parameter of limb volume (or circumferential distances) may provide equally-interesting findings and possibly an additional adaptive mechanism. If these two aspects of body-space can be firmly established, then relationships between these new kinesthetic components, the other kinesthetic components in the proprioceptive knowledge system, and the other spatial senses can be explored with a view to gaining new understanding of these systems as well as possibly new insights into such phenomena such as tactile localization and phantom limb.

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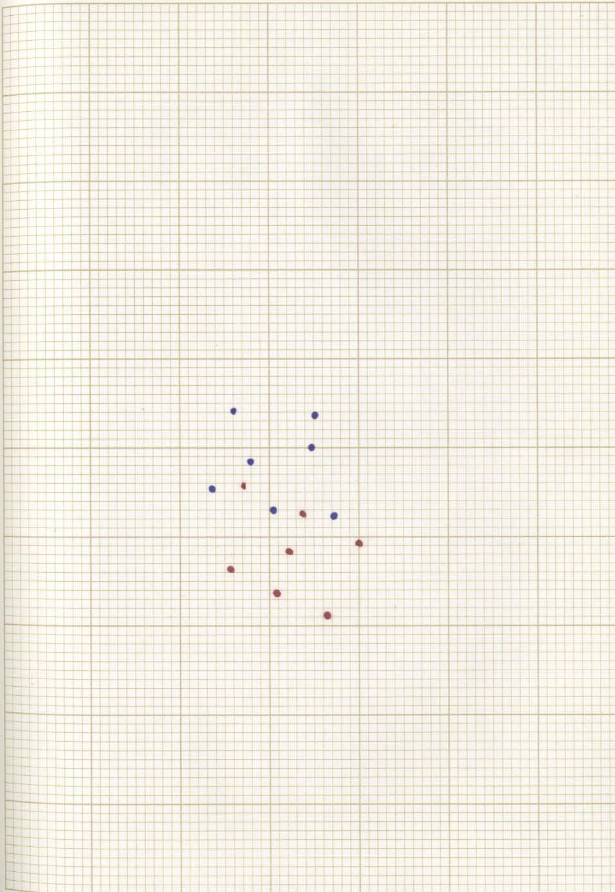
APPENDIX A

Sample of Graph Paper and Markings Made by
Subjects During Ankle-Location Task (Experiment 1)

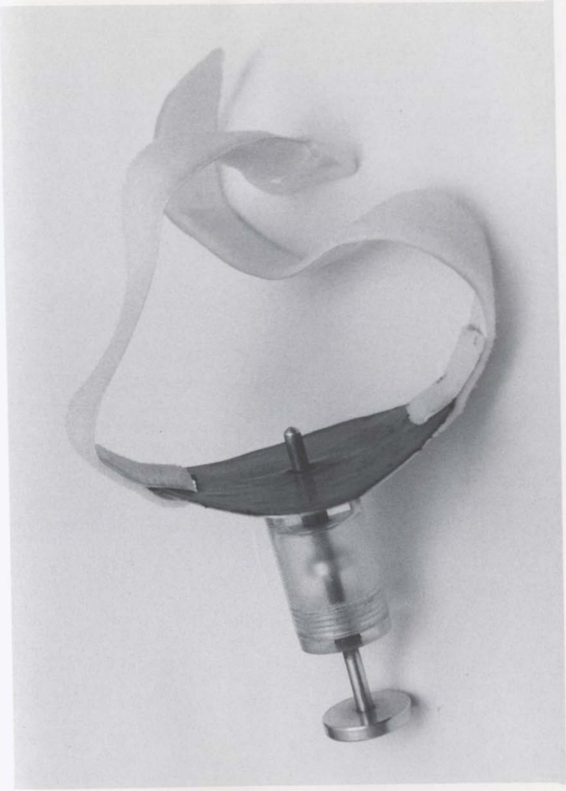


APPENDIX B

Photograph of a Subject Attempting to Position
A Pen Opposite a Stimulated Point on His Leg
(Marking Panel and Stimulating Probe Not Shown
To Illustrate Relationship of Hand, Pen, and Leg)

APPENDIX C

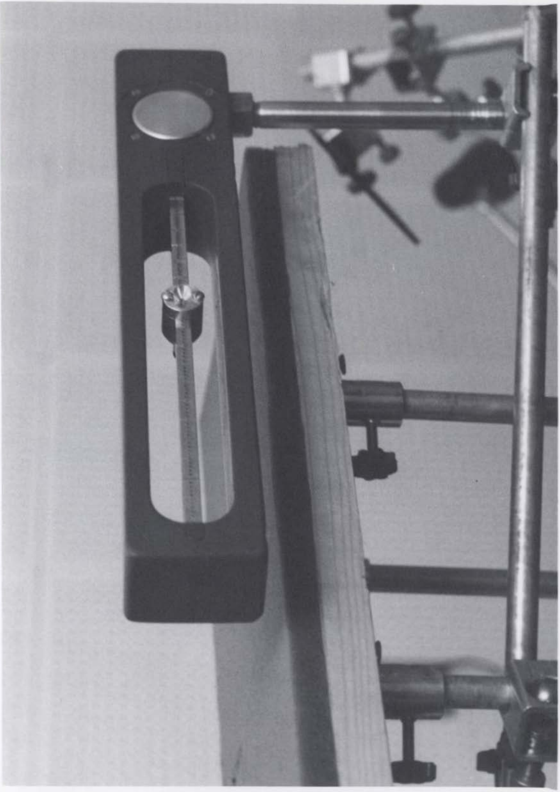
Photograph of Probe Device
Used in Experiment 2



APPENDIX D

Photograph of the Kinesthetic Recalibrating Device (KRD)

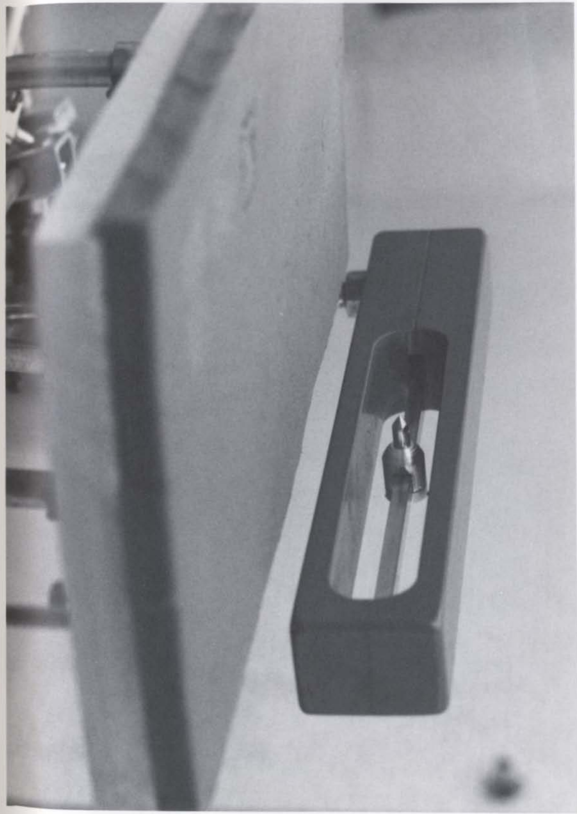
(Front View)



APPENDIX E

Photograph of the Kinesthetic Recalibrating Device (KRD)

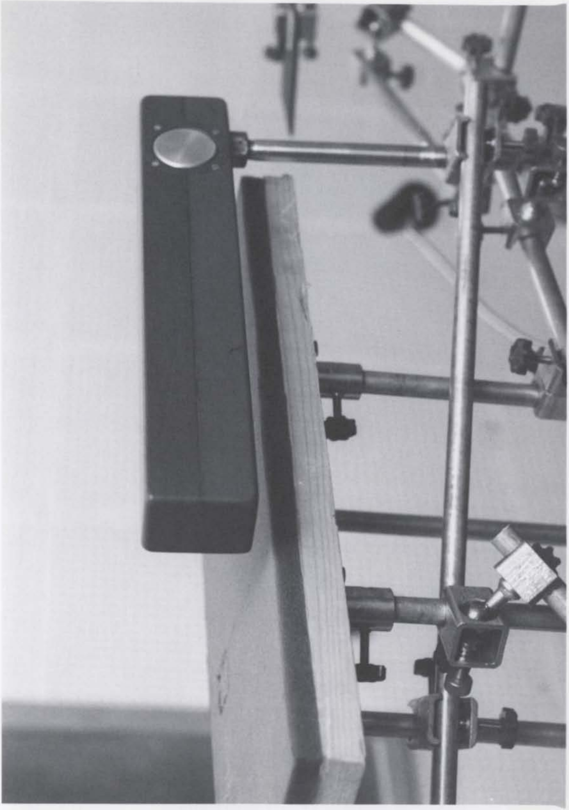
(Rear View)



APPENDIX F

Photograph of the KRD Control Device

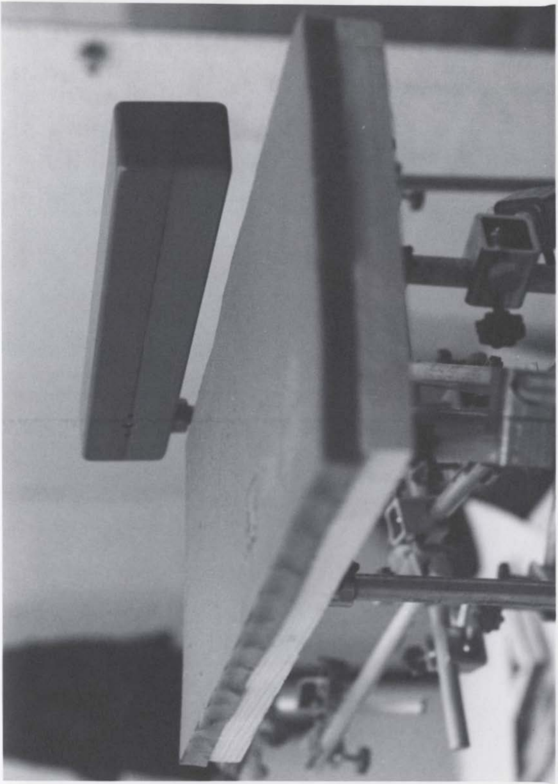
(Front View)



APPENDIX G

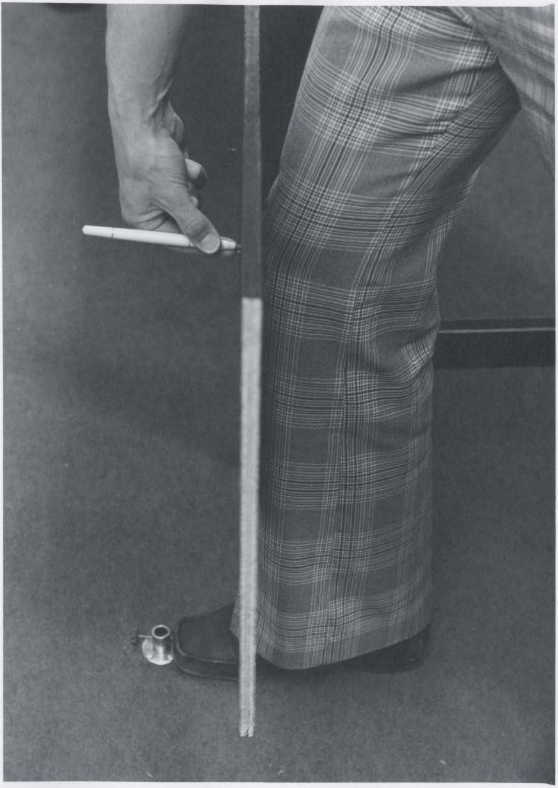
Photograph of the KRD Control Device

(Rear View)



APPENDIX H

Photograph of a Subject Attempting to Position Pen Opposite the Centre of His Knee (Side View)

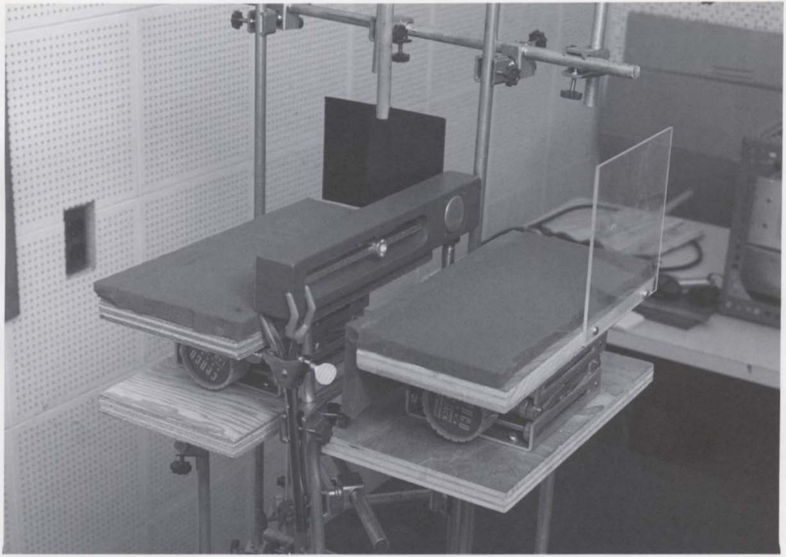


APPENDIX I

Photograph of a Subject Attempting to Position
Pen Opposite the Centre of His Knee
(Front View)

APPENDIX J

Photograph of Experimental Apparatus Used in Experiment 6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APPENDIX K

Photograph of Subject Attempting to Align Pen Opposite Point of Probe Stimulation on His Leg

(Experiment 6)