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Contributions to Workload of Rotational Optical Transformations

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ABSTRACT

An investigation of visuomotor adaptation to optical rotation and optical inversion was conducted with students from undergraduate and graduation populations at the University of Nevada, Reno.

Experiment I examined the visuomotor adaptability of subjects to an optically rotating visual world with a univariate repeated-measures design. It was found that subjects exhibited statistically significant adaptation on a button pushing task as measured by the visuomotor reduction of effect and the visuomotor negative aftereffect.

Experiment IA tested one major prediction of a model of adaptation put forth by Welch (1978). Welch predicted that the "aversive drive state" that triggers adaptation would be habituated to fairly rapidly. Anxiety levels were considered to be an overt manifestation of the "aversive drive state" and so subjective levels of anxiety were measured during the exposure periods using a ten-point Likert scale. It was found that anxiety levels did follow the prediction of the model of adaptation by decreasing significantly over the exposure periods.

Experiment II was conducted to investigate the role of motor activity in adaptation to optical rotation. Specifically, this experiment contrasted the "reafference hypothesis" and the "proprioceptive change hypothesis."

Based on the results of no significant differences between the active movement and passive movement with contours conditions, it was concluded that the "proprioceptive change hypothesis" may be a better explanation for the process of adaptation. However, since significant adaptation occurred in all four experimental conditions, it was suggested that some type of cognitive adaptation was present.

Experiment III examined the role of cognition, error-corrective feedback, and proprioceptive and/or reafferent feedback in visuomotor adaptation to optical inversion. Four independent groups were contrasted on a target pointing measure, with the amount and speed of adaptation predicted to be in the following order: gradual inversion, active movement; gradual inversion, no movement; immediate inversion, active movement; and immediate inversion, no movement. The results conformed to the predictions in terms of the visuomotor reduction of effect but, with the visuomotor negative aftereffect, the orders of the gradual inversion, no movement condition and the immediate inversion, active movement condition were reversed. It was concluded that the results generally supported the "information hypothesis."

Implications for research and implications for practice were suggested for all experiments.

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CHAPTER I

INTRODUCTION

In the past, numerous studies have been conducted to investigate perceptual and/or performatory adaptation to artificial rearrangements of sensory systems (e.g., see Welch, 1978). Among the more salient of these visual rearrangements are some of the following: displacement of the visual world via wedge prisms (e.g., see Hay, Pick, & Ikeda, 1965; Welch & Warren, 1984), reversal of the visual world via right-angle prisms or mirrors (e.g., see Harris & Harris, 1984; Logvinenko & Zhedounova, 1981), inversion of the visual image via double convex lenses or amici roof prisms (e.g., see Dolezal, 1982), minification of the visual world with convex mirrors (e.g., see Rock, 1965; Scheuhammer & Timney, 1982) and magnification via concave mirrors (e.g., see Foley, 1965; Ross & Lennie, 1972), tilting of the visual image via two dove prisms in tandem (e.g., see Callan & Ebenholtz, 1981, 1982), scrambling the optical structure of the visual image by rearranging or destroying adjacent optical elements (e.g., see Ogle, 1968), and inducing curvature of the optical image with concave lenses (e.g., see Vernoy & Luria, 1977). Without fail, all of these rearrangement studies have attempted to assess some aspect of perceptual and/or performatory adaptation under the assumption that knowledge of how the visual and visuomotor systems function when inputs are distorted will help elucidate the normal operation of these systems. Highly related to this assumption is the assessment of visual and visuomotor plasticity (Dolezal, 1982, pp. 13-15; Welch, 1978, pp. 11-12). In other words, how malleable or modifiable is the visual system? Such a question has practical implications for the ability of humans to adapt to novel and exotic environments such as those encountered during space flight and air travel. Perhaps subjects can be trained to become super perceivers, whereby they can function competently in a wide variety of bizarre situations.

Statement of Purpose

The present study ascertained the ability of subjects to adapt, in a visuomotor sense, to an optically rotating world. The purpose was to assess the plasticity of the visuomotor system to a new and novel sensory distortion that had not been previously reported in the literature. In addition to its theoretical importance, this assessment had practical implications for aerospace medicine.

Review of the Literature

History of Visual Transposition Research

Despite the fact that no attempts have been reported in the literature to adapt to an optically rotating world, this type of visual rearrangement is highly related to the historical aims of visual transposition research and is, in fact, a logical extension of those studies.

Historically, visual transpositions have been investigated to answer two related, although somewhat different questions. Ever since Johannes Kepler demonstrated in 1604 and 1611 that the retinal image is inverted, philosophers and some early psychologists began to speculate about the means by which humans are capable of perceiving the world as right-side-up (cited in Walls, 1951, pp. 53-83). To explain this seeming paradox, Descartes proposed that the image on the retina must be reinverted by the brain in order to perceive up-down and left-right in their proper locations (cited in Walls, 1951, pp. 53-83). Accordingly, these philosophical speculations led to the two related research questions referred to previously. First, why does the world appear to be right-side-up when the reflected light imaged on the retina is upside-down and left-right reversed (i.e., inverted) as a result of passing through the lens of the eye (Welch, 1978, p. 109)? Second, is an inverted retinal image required for normal upright vision to occur, or can modifications of the retinal image be adapted to (Welch, 1978, p. 109)?

The first question is based on an assumption of isomorphism between the retinal image and the final percept. In addition, a level of correspondence is assumed between the neurophysiological processes and neuroanatomical structures underlying perception and the actual resulting percept. These assumptions and, therefore, the first question, have been shown to be clearly nonsensical with the advent of modern coding theory (e.g., see Uttal, 1973). No such isomorphism exists between the object imaged on the retina and the electrochemical code for the object in the visual pathway. Instead, electromagnetic energy is transduced into electrochemical energy at the visual receptors, the rods and cones, and is subsequently coded in the neurons throughout the visual pathway (Goldstein, 1984, pp. 45-61). Therefore, we need not assume that stimulation of the lower part of the visual cortex should denote up and stimulation of the upper portion should denote down. Likewise, although similarities exist between the image of the object on the retina and the perception of the object, there is no absolute one-to-one correspondence between the two. The retinal image is not only inverted but is two-dimensional in form, which the perceptual end product clearly is not.

The second question is considerably more worthy of investigation since it does not assume the foregoing isomorphisms. This question, instead, merely addresses the degree and locus of modifiability or plasticity of the visual system. In other words, can subjects be exposed to inverted or reversed visual worlds and expect either visual or visuomotor adaptation to occur, or is there an innate, and possibly unmodifiable, connection between the inverted retinal image and right-side-up vision? If the latter view were correct, it would follow that an infant must have an inverted retinal image for normal upright spatial perception. Indeed, many early theories of space perception supported this notion. This was, in fact, the guiding question in Stratton's (1896, 1897a, 1897b, 1899) pioneering experiments with visual transpositions. These experiments, as well as several others, appear to be relevant for the proposed experiments in the present study since the question of visuomotor plasticity is and was of paramount concern.

In Stratton's experiments a monocular device was worn that provided a 45-degree field of view and rotated the image to an inverted position by means of two pairs of double convex lenses inside a tube. Stratton attempted, first for three days and later for eight days, to determine if an optical reinversion of the retinal image could be adapted to in order to arrive at correct phenomenal perceptions of uprightness. As a phenomenological study of visual and visuomotor adaptation, more or less normal everyday activities were engaged in during the course of each experiment and, in the end, Stratton exhibited almost complete visuomotor adaptation. In the second experiment, in particular, Stratton achieved relative competence in many tasks required for daily existence. So, for example, on the fifth day of the second study he wrote, "At breakfast with the lenses on, the inappropriate hand was rarely used to pick up something to one side. The movement itself was easier and less wayward; seldom was it in an entirely wrong direction" (Stratton, 1897b, p. 355). However, the question of whether an inverted image is necessary for upright visual perception was never answered satisfactorily because, although he occasionally reported that the world appeared to be right-side-up for brief periods of time while concentrating on his academic work, he never unequivocably demonstrated perceptual adaptation to the transposition (see Appendix I for definitions of perceptual adaptation and performatory or perceptuomotor adaptation). Further evidence that perceptual adaptation did not occur was provided by the effects observed following the removal of the optical device, in that the visual world appeared upright immediately. If perceptual adaptation had occurred, the world should have appeared inverted upon removal of the lenses. Nevertheless, visuomotor negative aftereffects and compensatory head-movement induced changes were observed, thus providing additional evidence of visuomotor adaptation (see Appendix I for definitions of visuomotor reduction of effect and visuomotor negative aftereffect).

Since the time of Stratton's original experiments, numerous replications of his work have been attempted. Over thirty years later, Ewert (1930) had three subjects wear binocular inverting devices for periods of time ranging between fourteen to sixteen days. Unlike Stratton, Ewert utilized objective, laboratory tests of adaptation, including such tests as reaching for visual, tactual, or auditory targets; card sorting; and indicating the perceived location of objects. Once again, a very significant visuomotor reduction of effect and a visuomotor negative aftereffect were found, but even temporary perceptions of upright vision were absent over the course of the study.

A replication of Stratton's original experiments was carried out by Peterson and Peterson (1938) with only minor modifications. They had a subject wear a binocular inverting device for fourteen days and, while the subject engaged in normal everyday activities, the effects of the optical distortion were measured through the use of phenomenological reports of perceptual and behavioral experience. Even though significant visuomotor adaptation was obtained, these investigators also failed to demonstrate perceptual uprighting of the visual world.

A longer study of adaptation to visual inversion was performed by Snyder and Pronko (1952). Snyder wore two unit-powered inverting telescopes which provided a clear binocular field of view of 20-degrees. In practice, however, the inverting telescopes were set so that they converged slightly, thus, permitting binocular vision only for near objects. Snyder wore this device for a full thirty days, replacing it with a blindfold before going to sleep. Unlike the previous studies reported, this study was specifically designed to assess visuomotor performance in a more detailed fashion. Several issues were examined but the primary concern was with the extent to which visuomotor performances, well-practiced before exposure to the inverting device, would be disrupted upon donning the lenses. Also, they were concerned with the subsequent continued learning or relearning of the visuomotor skills after donning the rearranging device. As a consequence of this emphasis, Snyder and Pronko were only peripherally interested in perceptual adaptation and reported, incidentally, that, although the world came to look familiar after thirty days of inversion, it remained inverted. As with the previously discussed studies, a large visuomotor reduction of effect and a large visuomotor negative aftereffect were observed during and following the exposure period respectively, indicating that performatory adaptation had taken place.

Perhaps the most extensive series of investigations on visual transpositions was conducted by Erismann and Kohler at the University of Innsbruck in Austria (Erismann, 1947; Kohler, 1951, 1955, 1962, 1964), as well as by some of their colleagues (Kottenhoff, 1957; Kruger, 1939; Taylor, 1962). Again, as with so many studies of transposed vision, Erismann and Kohler relied almost exlusively on phenomenological reports of visual, visuomotor, and behavioral experience. Possibly of more significance for perceptual and performatory adaptation, however, is the fact that Erismann and Kohler had their subjects engage in a number of very demanding physical and perceptual tasks, such as skiing, fencing, and mountain climbing while wearing up-down or left-right reversing goggles. These strenuous subject-environment interactions may have been a necessary prerequisite for perceiving the world as right-side-up, since Erismann and Kohler reported more instances of perceptual adaptation than any previous or subsequent investigators. They claimed that subjects were often able to perceive the world as right- side-up, but only after visuomotor adaptation was clearly present.

Evidence for Erismann and Kohler's assumption of the necessity for strenuous physical exertion can be found in Richard Held's "reafference hypothesis." According to this view, "Active movement with its accompanying sensory feedback is an essential condition for adaptation under circumstances in which no other important source of error information is available" (Held, 1968a, pp. 57-58). This hypothesis is, however, still very controversial and will be examined in more detail at a later point in this introductory section.

A more recent long-term study of adaptation to optical inversion was conducted by Hubert Dolezal (1971, 1977, 1982) for five weeks in 1971 in Greece. Dolezal wore inverting prisms attached to a football helmet that provided a field of view of 46-degrees by 115-degrees; a considerably larger field of view than utilized in previous studies of visual transpositions, with the possible exception of the experiments of Stratton. It is commonly thought, however, that Stratton's estimation of a 45-degree field of view for his rearranging device was inaccurate due to the fact that, even with modern technological breakthroughs in optical design, more recent investigators have found it difficult to obtain such a large field of view (Brown, 1928, p. 121; Dolezal, 1982, p. 57; Ewert, 1930, p. 201).

Another unique feature of the Dolezal study was an experiment performed in which the field of view was restricted prior to the main prism exposure period. Dolezal wore two paper tubes for six days which limited his field of view to 12-degrees. Since no other previous investigator had established a limited field of view as a baseline for departure, this research was very valuable in pointing the way to possible confounding effects of the limited field of view, exclusive of the visual rearrangement. As Dolezal concluded, many of the effects that occur during exposure to an optical transforming device are actually caused by the small field of view, rather than the optical distortion produced by the device. In fact, Dolezal found that all of the following were disrupted by a smaller field of view to at least some extent: "orientation in the immediate environment, equilibrium and balance maintenance in locomotion, complex visually guided action; and veridical perception of events, of self, and of the layouts of the visual world" (Dolezal, 1982, p. 73).

The Dolezal study was also interesting because of the unique view of perceptual adaptation put forth. Dolezal claimed that seeing the world right-side-up again was not essential for perceptual adaptation, and that reports of short-term uprighting of the visual image by Stratton and by Kohler were only the result of linguistic ambiguities. Instead, it was pointed out that coming to see the world in a consistent, familiar fashion again, after the normal period of disorientation, was tantamount to perceptual adaptation. More specifically, Dolezal defined perceptual adaptation in terms of the following end products: "phenomenal experiences become consistent, verbal descriptions become consistent, and looking behavior becomes errorless." Using these criteria, Dolezal postulated that perceptual, as well as performatory adaptation had occurred over the five week course of the study.

In summary, then, numerous studies have demonstrated visuomotor adaptation, and therefore visuomotor plasticity, to static transpositions of the visual world. A logical extension of these studies was to assess visuomotor adaptation and plasticity to dynamic optical transpositions via a device that would optically rotate the world at a constant speed.

Experiment I

The question Experiment I addressed was whether subjects , were capable of exhibiting significant short-term visuomotor adaptation to dynamic optical rotational transformations. Because it was not known whether this would occur, the null hypothesis was formulated prior to the beginning of this experiment. Since the goal was simply to determine if subjects could adapt, a simple univariate repeated-measures (Treatments X Subjects) design was utilized (see Appendix B). The repeated-measures experimental conditions consisted of the following: baseline with the experimental apparatus in place and upright but not rotating, and an exposure condition with the experimental apparatus in place and rotating at a fixed, predetermined rate. The performance measure for this experiment consisted of response time for a button pushing task. The advantages of this type of performance measure were thought to be three-fold. First of all, numerous studies of visuomotor adaptation to displacement of the visual world have utilized finger pointing performance measures so that standardization of these measures has been accomplished in experimental perception laboratories around the world. Finger pointing tasks are, therefore, considered to be particularly appropriate response measures of visuomotor coordination to optical distortions (Welch, 1978, p. 7). Second, since the goal of subjects was to perform the task as rapidly as possible, response strategies, such as waiting until the world appeared upright, should have been attenuated, if not eliminated. Finally, the use of a relatively simple performance measure, that could be mastered by all subjects within a few trials, should have eliminated practice effects on the performance measure alone. In addition, the baseline conditions also served as a control to indicate if any practice effects were occurring over the course of the experiment.

A Model of Visuomotor Adaptation

A model of adaptation that would account for visuomotor adaptation to optical rotation in Experiment I has been proposed by R.B. Welch in his hallmark book, "Perceptual Modification: Adapting to Altered Sensory Environments" (1978, pp. 279-286). According to Welch, the presence of a "registered discrepancy" in the nervous system, as a consequence of distorted vision produced by the rearranging device, induces an "aversive motivational state" in the organism that triggers an "adaptive process." The "adaptive process," in turn, results in a reduction of the "registered discrepancy" created by the rearranging device. Simultaneously, rapid habituation to the discrepancy takes place, leading to a lowering of the "aversive drive state" that triggered adaptation in the first place. Therefore, habituation to the "registered discrepancy" will also cause an attenuation of the "adaptive process" before complete adaptation is achieved. At any point in this sequence of events, it is possible to elicit a response, verbal or motor, from the organism to assess the current state of the "registered discrepancy." This response is mediated by a "control process" involving various factors that may influence the response, such as strategies and response biases.

A full account of the model would obviously be much longer and involved than this brief synopsis but, for the purposes of this investigation, a more detailed description is unnecessary. Of interest in the present experiment is the nature of the "aversive drive state" and whether subjects do, indeed, habituate to the "registered discrepancy," thus, shutting down the "aversive drive state" and the resulting adaptation. These issues will be addressed following a brief examination of predictions derived from the model.

One major prediction formulated from this model of adaptation is that exposing subjects to the optical distortion in increments should result in greater amounts of adaptation. Exposure to the optical distortion would, presumably, create an "aversive drive state" which, in turn, would trigger the process of adaptation to the "registered discrepancy." Before full adaptation was achieved, however, the subject would habituate to the "registered discrepancy." An additional increment of exposure would create another "registered discrepancy" in the nervous system, thus, reactivating the "aversive drive state" and the "adaptive process" until habituation occurred again. Eventually, the fullest possible adaptation to the "registered discrepancies," created by the distorting device, would be achieved. Evidence to support this prediction can be gleaned from experiments by Ebenholtz and associates (Ebenholtz, 1969; Ebenholtz & Mayer, 1968). They found a linear increase in adaptation to optical tilt when the tilt increments increased by 5-degree or 8-degree steps. This result contrasts with the negatively accelerated acquisition curves that are typical for sensory rearrangements that have a constant value throughout the experiment. In addition to the findings of Ebenholtz and associates, Experiment III of the present investigation also examined this model prediction (see Results and Discussion sections for Experiment III).

Experiment IA

Another prediction of this model is that adaptation reduces the "registered discrepancy" while, simultaneously, habituation occurs to the discrepancy. In either instance, the aversive nature of the "registered discrepancy" becomes less severe over the exposure period (Welch, 1978, pp. 281-282). However, up to this point in the discussion, the nature of the "aversive drive state," postulated by Welch, has not been made clear. Welch (1978, p. 280) claims that the aversive nature of the drive state is a consequence of an innate response to discrepancy in the nervous system, or a result of previous punishing experiences, or both. For example, optical rotation, even at the slow rates of rotation in Experiment I, produces mild nausea, vertigo and disorientation. These symptoms of motion sickness are likely due to innate physiological responses that are, in turn, modulated by previous experiences. The overt behavioral manifestation of the "aversive drive state" would likely be increased levels of anxiety. Therefore, if this model of adaptation proposed by Welch is accurate, a reduction in the aversive nature of the "registered discrepancy," as measured by anxiety levels, should occur over the course of exposure to optical rotation. Experiment IA examined this issue through the use of a univariate repeated measures design (see Appendix B). During exposure periods only in

Experiment I, subjective levels of anxiety were verbally taken from subjects immediately preceding each target pointing measure. Subjective levels of anxiety in subjects was measured on a ten-point Likert scale, ranging from 1-2=very calm to 9-10=very anxious (see Appendix C for complete Likert scale). It was suggested, prior to the beginning of the experiment, that a significant reduction in anxiety levels ("aversive drive states"), over the course of the two exposure periods, would provide support for the model of adaptation as outlined by Welch (1978, pp. 279-286). However, since it was not known whether the model of adaptation was correct prior to the beginning of the experiment, the null hypothesis was formulated for this experiment.

Relation to Theories of Visuomotor Adaptation

A second major purpose of this investigation was to ascertain the processes underlying any instances of adaptation to an optically rotating world in Experiment I. Many hypotheses have been put forth to explain the adaptive process but two, in particular, have inspired more research and polemics than any others: Held's "reafference hypothesis" and the "proprioceptive change hypothesis." In the following subsections, each of these hypotheses will be examined along with their applications to the present study.

The reafference hypothesis. According to the "reafference hypothesis," self-produced motor activity is essential for visuomotor adaptation to optical distortions of the visual world (Held, 1980, p. 72; Held & Hein, 1958). In Held's view, a neural copy of the efferent signal is produced and held in a "correlation storage" whenever a motor act is initiated. At the same time, reafference is produced from stimulation of the retina as a consequence of observing self-produced motor activity. In normal perceptual experience, the visual reafference is correlated and a bond is strengthened with the efferent neural copy. However, when an optical distortion is introduced, a decorrelation between the efference and reafference is produced because the initiation of a motor response elicits the "expected reafference" which is now discrepant with the "new reafference" from the retina. Visuomotor adaptation, then, consists of a recorrelation between the efferent neural copy and the new reafferent inputs. This means that adaptation can only occur when active movement (self-produced motor activity) is initiated. This is true because active motor outputs, ostensibly, call up old reafferent signals from memory as a comparison with the new reafferent signals. In this manner, corrections in motor activities can be made to recorrelate with the "new reafference." By the same token, passive motor ouputs would not be expected to produce visuomotor adaptation, since this form of motor activity would not revive the old reafferent signals to be compared with the "new reafference."

This hypothesis has received supporting evidence from several studies. The general procedure has involved comparing groups of subjects on their ability to reach accurately for a target while wearing wedge prisms that displace the visual world laterally. During exposure, subjects were only able to see their limb against a homogenous background, without contours, so that no other source of information was available for visuomotor adaptation. The results have demonstrated significant adaptation, both in visuomotor reduction of effect and visuomotor negative aftereffect, for the active movement condition, but not for passive and no movement conditions (Held, 1968a; Held & Bossom, 1961; Held & Gottlieb, 1958; Held & Hein, 1958, 1963; Held & Mikaelian, 1964; Held & Schlank, 1959). In addition, Held has demonstrated the importance of self-produced motor activity for normal development of visuomotor coordination in various species of animals (Held, 1968b; Held & Bauer, 1967, 1974; Held & Bossom, 1961).

Despite the success of Held and his colleagues in finding an active-passive dichotomy in visuomotor adaptation, several other investigators have failed to replicate their basic results (Baily, 1972; Fishkin, 1969; Foley & Maynes, 1969; Pick & Hay, 1965; Singer & Day, 1966; Weinstein, Sersen, & Weinstein, 1964). Nevertheless, in some instances, passive exposure led to smaller levels of visuomotor adaptation than did active exposure. It is important to point out here one of the major differences that may have accounted for the discrepancies reported between the findings of Held and his colleagues and those of subsequent attempted replications. Namely, the former studies involved a homogenous background, whereas visible contours were present in the latter studies.

The proprioceptive change hypothesis. It has been suggested by several investigators that adaptation will occur when any form of salient information is available to alert the subject to the presence of an intersensory discordance between the seen and felt position of the limbs. This has come to be referred to as the "proprioceptive change hypothesis." This hypothesis, in turn, may account for some of the discrepant findings with regard to the "reafference hypothesis." Perhaps, active movement enhances the body position sense to such an extent that a recalibration of felt positions with seen positions of the limbs can be accomplished, rather than a recorrelation of efference with "new reafference." It is highly likely that when the limbs are moved actively, the felt position is more precise and conspicuous than when the limbs are moved passively (other-produced motor activity). However, according to this hypothesis, some visuomotor adaptation should be found even if the limb is moved passively, since any kind of stimulation that enhances the felt position of the limbs, via muscle spindle inputs, will result in adaptation (Welch, 1978, p. 25-26). Similarly, the muscle spindle inputs, one of the bases of the body position sense, are particularly intense during active movement of the limbs (Paillard & Brouchon, 1968). One of the reasons Held and his associates may not have found adaptation in the passive movement condition was because subjects underwent an intense relaxation training phase which may have served to reduce the salience of the muscle spindle inputs (for review, see Held & Freeman, 1963).

One means of testing the "proprioceptive change hypothesis" would be to vibrate the immobile limb in order to stimulate the muscle spindle input and, thus, to enhance the felt position of the limb. Kravitz and Wallach (1966) performed just such an experiment. They found that subjects exhibited a significant visuomotor negative aftereffect in target pointing after ten minutes of viewing their stationary, vibrated hand through 30 diopter displacing prisms. These results have been replicated under several different paradigms and they have all found significant visuomotor adaptation by enhancing the felt position of the limb in some way (Mather & Lackner, 1975, 1981; Moulden, 1971).

Adaptation in the passive condition has also been found by Melamed, Halay, and Gildow (1973), and Wallace (1975) by introducing the presence of visible contours into the background upon which the subjects viewed the prismatically displaced limb. These investigators postulated that visible contours would facilitate adaptation by enhancing the salience of the felt position of the limbs. Following experimentation, a comparison of the active and passive groups showed that the active subjects exhibited a large visuomotor negative aftereffect, the passive group with physical contours in the background also exhibited a large negative aftereffect, but the passive subjects with a homogenous background failed to show a significant negative aftereffect. As will be recalled, the studies that were unable to replicate Held's active-passive dichotomy also used physical contours in the background, whereas Held's studies were conducted against a homogenous background. Therefore, the experiment by Melamed et al. (1973) and the experiment by Wallace (1975) also support the "proprioceptive change hypothesis."

Finally, attenuation of the body position sense should eliminate or reduce visuomotor adaptation in the active movement condition if the "proprioceptive change hypothesis" is correct. In a recent series of articles, Wallace and his associates (Wallace, 1980; Wallace & Fisher, 1979; Wallace & Garrett, 1973, 1975; Wallace & Hoyenga, 1981) have demonstrated that the visuomotor negative aftereffect can be eliminated in highly hypnotic-susceptible subjects who have been given hypnotic suggestions for limb anesthesia. This is so even when low hypnotic-susceptible subjects are instructed to fake limb anesthesia.

However, Spanos, Gorassini, and Petrusic (1981) have failed to confirm the results of Wallace and colleagues. They compared a highly hypnotic-susceptible group, given a suggestion of limb anesthesia, with a group of low hypnotic-susceptible subjects told to fake limb anesthesia, and a group of control subjects given no special instructions. Even though the highly hypnotic-susceptible subjects reported significantly more limb anesthesia than the other experimental conditions, they still exhibited large pointing errors following removal of the prisms, which is indicative of a visuomotor negative aftereffect. In a later experiment, Spanos, Dubreuil, Saad, & Gorassini (1983) also failed to replicate the phenomenon of limb anesthesia reported by Wallace and colleagues.

In response, Wallace & Fisher (1982) have suggested a methodological difference that may have accounted for the discrepant findings between their studies and the Spanos et al. (1981) study. Apparently, in the Spanos et al. (1981) study, a situation during prism exposure was introduced in which the subjects were reaching for a visual target and, therefore, were receiving error-corrective feedback. Wallace and Fisher (1982) proposed that the error-corrective feedback, in turn, was visually overriding the decreased proprioceptive feedback produced by the hypnotically induced limb anesthesia. More recently, Wallace and Fisher (1984) have argued that Spanos et al. (1983) may have introduced a bias by imperceptibly altering subjects' head positions, in the direction of adaptation, when the displacing goggles were removed for the purpose of postexposure measures. This is possible only because Spanos et al. (1983) used displacing prisms mounted in goggles that were removed during postexposure, whereas Wallace and Fisher (1984) used Risley rotatable prisms which were reset to zero degrees visual distortion for the postexposure tests. In a test of this hypothesis, Wallace and Fisher (1984) found that removal of the goggles for postexposure measures did, indeed, alter head positions in the direction of adaptation to a significant extent. Therefore, the failure of Spanos and colleagues to confirm the findings of Wallace and colleagues may have been due to differences in research methodology.

In summary, then, there is widespread agreement that, at least with displacing prisms, visuomotor adaptation can result from a recalibration in the position sense, which is responsible for a reduction in the discrepancy between seen positions and felt positions of the limbs (Harris, 1980, p. 113; Welch, 1978, p. 28). Nevertheless, important differences exist between a statically displaced visual world and a dynamically rotating visual world, or even between a displaced world and an inverted or reversed visual world. The displaced image is only a minor modification of visual space perception, usually not more than an 11 to 14-degree lateral shift of the visual image to the right or left. In contrast, with a dynamically rotating world, the seen position of the body relative to the eyes appears to be constantly changing, as does the external environment relative to the eyes. This means that any recalibration in the felt position of the limbs would have to occur very rapidly at each point in a 360-degree rotation, if the "proprioceptive change hypothesis" is most efficacious. Similarly, if the "reafference hypothesis" is most accurate, a recorrelation between neural copies of motor efference and "new reafference" must occur due to movements of the limbs. Since a memory component is involved in the "reafference hypothesis," it seemed far more likely, prior to the beginning of the experiment, that subjects would be able to recorrelate efference with "new reafference" after a period of exposure to an optically rotating world, than to recalibrate felt positions of the limbs with seen positions at every point in a 360-degree rotation. However, since it was not known whether subjects could even adapt to dynamic optical transformations of the visual world, no directional hypotheses were formulated regarding expected differencess between experimental groups. Furthermore, it was thought that if differences were obtained between experimental conditions, those differences could not be attributed, with any degree of certainty, to the recorrelation of efference and "new reafference," or to the recalibration of felt with seen limb positions. These were simply theoretical explanations underlying the results of investigators, such as Held and others, and it was entirely possible that active movement and/or proprioceptive feedback might possibly enhance visuomotor adaptation to dynamic visual transpositions, without the necessity of resorting to recorrelation or recalibration explanations. Perhaps any observed visuomotor adaptation could be attributed to some new hypothesis.

Nevertheless, it seemed reasonable to assume that self-produced motor activity and/or proprioceptive feedback would also play a role in any visuomotor adaptation that might occur to a rotating visual world, given the importance of these two sources of information in previous studies of adaptation to distorted vision. Therefore, the "reafference hypothesis" and the "proprioceptive change hypothesis" were experimentally manipulated and tested in the second experiment.

Experiment II

The second experiment utilized a two-factor mixed design with repeated measures on one factor (see Appendix B). The independent-groups variable consisted of four levels: active movement, passive movement with contours, passive movement without contours, and no movement. The repeated measures variable consisted of two levels: baseline in which the experimental apparatus was in place and upright, and an exposure period in which the experimental apparatus was rotating at a constant, predetermined rate. The dependent measure in this experiment was the same as in Experiment I: response time for target pointing to buttons marked with various visual symbols.

Since the "reafference hypothesis" and the "proprioceptive change hypothesis" have not been previously contrasted for exposure to an optically rotating world, the null hypothesis was formulated for Experiment II. However, prior to the beginning of the experiment, it was thought that more rapid and complete visuomotor adaptation in the active movement condition than in the other three experimental conditions would support the "reafference hypothesis" because of Held's claim that self-produced motor activity is essential for visuomotor adaptation (Held, 1968a, pp. 57-58). It was also thought that equivalent amounts and speed of adaptation between the active movement and passive movement with contours conditions, if both were found to be superior to the other two experimental conditions, would provide support for the "proprioceptive change hypothesis." This result would be expected from the Melamed et al. (1973) and Wallace (1975) studies in which subjects exposed to a displaced visual image showed significant visuomotor adaptation to active and passive with contours exposure conditions, but not to passive exposure without contours.

The information hypothesis. Another question related to visuomotor plasticity is whether subjects are capable of adapting to optical inversion of the visual world more rapidly and more completely if additional information about the sensory rearrangement is provided via gradual, incremental reinversion of the retinal image. The view that any salient form of information regarding the nature of the sensory rearrangement may enhance visuomotor adaptation has come to be known as the "information hypothesis" (Welch, 1978, p. 24). There are many sources of information available that could potentially produce visuomotor adaptation.

Some of the more salient are: discrepancies between old and new reafference, discordances between seen positions and felt positions of the limbs, differences between a remembered visual scene and the appearance of the scene during prism exposure, and discrepancies between the apparent location of an object and the errors that occur in reaching for it. All of these forms of information are available with gradual, incremental inversion of the visual world. However, one source of information present in gradual, incremental inversion may not be present with immediate optical inversion. Namely, the introduction of the visual distortion in gradual increments should alert the subject to a difference in the visual field without the concomitant severe confusion and disorientation that inevitably arises with immediate optical inversion. Webster (1969) has suggested that this raises the possibility subjects may compensate in a "cognitive" manner and make corrective adjustments for the optical distortion without undergoing any perceptual, sensorimotor, or motor change. The present investigation experimentally tested this proposition and attempted to elucidate the proportion of the variance accounted for by each source of information. Before outlining the details of Experiment III, a brief review of the cognitive and error-corrective sources of information is in order.

In a study by Uhlarik (1973), the effects of verbal feedback on visuomotor adaptation were assessed. Subjects were given three types of exposure feedback to visual displacement: an uninterrupted view of the moving hand with no target (concurrent display), a view of the hand at only the terminus of an action with a target present (terminal display), and verbal error-corrective feedback without a visual display (see Appendix A for definitions of concurrent and terminal displays). Despite the fact that one group of subjects received only verbal feedback, a form of cognitive information, these subjects still exhibited evidence of adaptation via a visuomotor negative aftereffect. Thus, at least some forms of "cognitive" information appear to be enough to produce specific amounts of genuine performatory adaptation.

In terms of error-corrective feedback, several relevant studies have been performed with prismatic displacement. Coren (1966) compared a condition in which subjects were allowed to make errors and then to correct them with a condition in which subjects were provided with a target and were either never allowed to make errors or were never able to correct their errors. The results demonstrated that those subjects who were allowed to correct for their errors adapted by twice the amount of the no error condition. These results have been replicated by other investigators (Welch, 1969, 1971; Welch & Rhoades, 1969). Most important for the purposes of this experiment is the study by Welch & Rhoades (1969) in which it was found that the combination of error-corrective feedback and proprioceptive feedback, from a discordance between seen positions and felt positions of the limbs, produced more visuomotor adaptation than either one alone. This result would have been predicted from the "information hypothesis."

Also highly relevant for the present experiment is a study by Howard (1968). In this study, subjects were exposed to step-wise displacement of the visual image from zero to full displacement. The increments of displacement were so minute that the subjects were never allowed to make a significant pointing error. In addition, the target was transported in the direction opposite of displacement so that the image always appeared straight ahead. As a consequence, the subjects were never aware that their vision had been displaced laterally. This approach to displacement has been termed "prismatic shaping" by Howard (1968) and is similar, in many respects, to the gradual, incremental inversion in the present experiment. By using this procedure, practice effects can be separated from effects of error-corrective feedback. This is so because, if target pointing responses are made after full displacement is reached, the effect of target reaching can be observed apart from error-corrective feedback since errors are no longer occurring. Howard and colleagues (Howard, 1967, 1968; Howard, Anstis, & Lucia, 1974; Templeton, Howard, & Wilkinson, 1974) have found significant visuomotor negative afteraffects from error-corrective feedback considered separately from practice effects.

Experiment III

It is quite obvious from this and previous subsections that a number of sources of information are available to aid adaptation. However, the proportion of the variance accounted for by each source of information is unclear. As mentioned in preceding discussions, one way to determine the contribution of each source of information to visuomotor adaptation is to compare gradual, incremental inversion with immediate inversion of the visual world. Experiment III did just that and involved utilization of a three-factor mixed design with repeated measures on one factor (see Appendix B). One independent-groups variable assessed the gradual versus immediate inversion issue, and the second independent-groups variable addressed the issue of degree of movement involved. Combined, these two variables yielded the following experimental conditions: gradual inversion, active movement; gradual inversion, no movement; immediate inversion, active movement; and immediate inversion, no movement. A repeated-measures variable involved exposure to a baseline period, followed by a period of exposure to gradual or immediate inversion in order to obtain a measure of visuomotor reduction of effect, and, finally, a return to baseline for a measure of visuomotor negative aftereffect. The dependent measure used in this particular experiment consisted of speed of target pointing to visual symbols, as in Experiments I and II.

In an analysis of the experimental conditions involved in Experiment III, a number of assumptions were made. First, gradual inversion, active movement was expected to enhance speed and total amount of adaptation achieved because information from the following sources was available to subjects in this group: discrepancies between seen and felt limb positions and/or discordances between old and new reafference due to active movement, presumably "cognitive" information from the gradual inversion, and error- corrective feedback from practicing and correcting visuomotor tasks at each increment of rotation. The gradual inversion, no movement group was expected to exhibit more rapid and greater amounts of adaptation than the two immediate inversion groups due to the assumed prepotency of "cognitive" information over the other three sources of information (Webster, 1969). The immediate inversion, active movement group was expected to show superior speed and total amount of adaptation over the immediate inversion, no movement condition because all four sources of information, except cognitive, were available, whereas salient information cues were minimal or absent in the immediate inversion, no movement condition.

In addition to the theoretical importance of gradual versus immediate inversion, the issue was also considered to be important for practical reasons. Immediately after donning inverting spectacles, subjects typically report symptoms of motion sickness during body movements (e.g., see

Dolezal, 1971, 1977, 1982, pp. 109-143; Kohler, 1951, 1955, 1962, 1964; Stratton, 1896, 1897a, 1897b, 1899). In fact, any initial head movements create such extreme disorientation and nausea that it is difficult for the subject to function competently in the external surround. These symptoms appear to be very similar to those experienced during space flight. Graybiel, Miller, and Homick (1974) have reported that astronauts awakening during space flight experience extreme disorientation and motion sickness when they peer out of the capsule window at the Earth, and that during the Skylab flights, motion sickness effects lasted for 3-5 days, significantly impairing the functioning of the astronauts. It has been suggested by Dolezal (1982, p. 109) that the severe nausea and disorientation which accompanies space flight may be controlled by preadaptive wearing of inverting spectacles. This idea is based on his long-term study of adaptation to optical inversion in which the disorientation and nausea faded after approximately ten hours of prism exposure (Dolezal, 1982, p. 109). Prior to the onset of the present experiment, it was thought that a more rapid induction of visuomotor adaptation to an inverted world might possibly have implications for elimination of the disorientation and motion sickness that typically comes with space flight. Such an implication would allow preadaptive "visual weightlessness training" to proceed at a much more rapid pace.

Research Hypotheses

In summary, the following hypotheses were posed for the purposes of this investigation:

Experiment I

1. There will be no differences between and within baseline and exposure periods on speed of performance on the dependent measure task (i.e., no visuomotor adaptation will occur).

Experiment IA

1. There will be no differences within exposure periods on levels of anxiety as measured by the Likert scale.

Experiment II

1. There will be no differences between the following experimental conditions on speed of performance on the dependent measure task: active movement, passive movement with contours, passive movement without contours, and no movement (i.e., no differences with regard to visuomotor adaptation will occur between experimental conditions).

2. There will be no differences in each of the following experimental conditions between and within baseline and exposure periods: active movement, passive movement with contours, passive movement without contours, and no movement (i.e., no visuomotor adaptation will occur within any of the

experimental conditions).

Experiment III

1. Subjects in the gradual inversion, active movement condition will exhibit significantly greater and more rapid visuomotor adaptation than the gradual inversion, no movement group; the immediate inversion, active movement group; and the immediate inversion, no movement group.

2. Subjects in the gradual inversion, no movement condition will exhibit significantly greater and more rapid visuomotor adaptation than the immediate inversion, active movement condition; and the immediate inversion, no movement condition.

3. Subjects in the immediate inversion, active movement condition will exhibit significantly greater and more rapid visuomotor adaptation than will the immediate inversion, no movement condition.

CHAPTER II

METHOD

Experiment I

Subjects

The subjects for this experiment consisted of thirteen adult volunteers from the University of Nevada, Reno undergraduate and graduate population of students.

Materials

Experimental Apparatus. The apparatus consisted of an R.C.A. CKC 020 solid state color video camera mounted on a modified motorcycle helmet, with a one and one-half inch diameter Sony Watchman black and white television mounted separately behind lenses inside a rotating housing such that images picked up by the camera were presented monocularly to the right eye and rotated.

The camera was attached to the top of the helmet by a mount which allowed for adjustments of its field and axis of view to reflect that of the subject's right eye. A hole approximately 50 millimeters in diameter was made in a metal plate that covered the face portion of the modified motorcycle helmet so that subjects were able to see the television monitor.

Attached to the plate on the opposite side of the subject's face was a bearing assembly and cannister. These were assembled so that the cannister would rotate longitudinally about an axis along the line of sight for the right eye. The cannister was open on the end facing the subject, and the subject was able to look into the cannister through the hole in the faceplate. The television monitor was mounted inside the cannister in such a fashion that its screen lay perpendicular to the axis of rotation. Thus, when the subject donned the helmet and looked through the hole, the rotating television monitor was visible to the right eye with a field of view of approximately 30-degrees.

Power for the rotation was accomplished by the use of a gear assembly, the gears being driven by a cable drive attached to a motor. Camera input for the television monitor was fed into the rear of the cannister via an R.F. modulator and an arrangement of continuous coils.

The helmet, with attached elements, was bolted to a large foot locker frame that was modified so that the metal panels were removed and so that subjects were able to sit on a chair inside the locker frame with their head in the helmet. This arrangement was utilized to relieve the excessive weight and pressure of the apparatus and to control for head and body movements.

<u>Practice Display</u>. The practice display utilized for this experiment consisted of a mobile metal table located immediately in front of the locker frame and, thus, in front of the subject seated in the locker frame. The table was

covered with seamless white paper containing vertical black lines spaced at one centimeter intervals. These contours were intended to enhance the felt position of the limbs.

Test Display. The test display for this experiment was a modified Radio Shack TRS-80 Color Computer keyboard attached electronically to a standard TRS-80 Color Computer. All the keys on the keyboard were covered with black electricians' tape, with the exception of six keys, which were covered with one of six plastic visual symbols: a triangle, a rectangle, a square, a plus, a wheel, or a circle. Therefore, the only visible images on the keyboard were the six visual symbols. Each key covered by a visual symbol was correlated electronically with the same key on the Color Computer. The keyboard was also made rotatable by attaching it, with rotating washers, to a circular plastic base. The experimenter was able to control the entire display with the Color Computer.

Procedure

For Experiment I, there was one experimental session with each of the thirteen subjects. A session consisted of four periods, 10 minutes per period for a total of 40 minutes. These periods consisted of alternating baseline and exposure conditions in an ABAB repeated measures (reversal) design fashion. Baseline (A) periods consisted of an alignment between the television monitor and the video camera so that the world appeared upright. Exposure (B) periods involved rotation of the television monitor relative to the video camera at the approximate rate of 24-degrees per second because, in pilot studies, this speed of rotation proved to be rapid enough to be challenging, but not so fast as to completely impede any effective compensations in visuomotor performance.

Each of the four periods was broken down into 3 blocks of 10 pointing trials each for a total of 30 trials per period and 120 trials per session. Periods were broken down into 3 blocks of trials in order to analyze trends in performance during different phases of each period. A pointing trial took place every 20 seconds throughout the 40 minutes of the experimental session so that the occurrence of a trial was not synchronous with the period of one 360-degree rotation of the experimental apparatus. This approach effectively ensured that each pointing trial occurred at a different angle of rotation than any other trial.

The procedure for each trial was standardized across subjects throughout the experiment. A Color Basic program (see Appendix D) randomly provided the experimenter with the name of the visual symbol and the computer key to push in order to initiate a trial. The experimenter then called out the appropriate visual symbol to the subject and, immediately following, pushed the appropriate computer key which sounded an audible beep to begin the trial. The beep was intended as a signal to the subject to push the correct visual symbol as rapidly as possible. Correct responses produced a second audible beep, signalling the end of the trial. The interval between the two beeps was registered in the Color Computer as the dependent measure reaction time (R.T.).

During the interim-time periods between trials, the subjects moved their arms actively in a transverse arc so that their hands were visible through the eyepiece in the apparatus. These arm movements were required under the assumption that self-produced motor activity enhances visuomotor adaptation, either due to a recorrelation between efference and "new reafference," or to increased saliency of the body position sense.

In order to eliminate memorization of the specific locations of the visual symbols on the keyboard as a subject response strategy, along with subsequent calibration of reaching movements to the memorized locations, the entire keyboard was rotated in 90-degree increments every two and one-half minutes of each exposure period (B), beginning at 90-degrees, so that an equal number of trials occurred at each of the following test display angles: 90-degrees, 180-degrees, 270-degrees, and 360-degrees. Direction of keyboard rotation was counterbalanced so that clockwise rotation occurred during the first exposure (B1) period and counterclockwise rotation during the second exposure (B2) period.

Experiment IA

Subjects

The subjects for this experiment were the same thirteen adult volunteers recruited in Experiment I from undergraduate and graduate student populations at the University of Nevada, Reno.

Materials

Materials utilized for this experiment consisted of pen and paper recordings of subjects' responses on each exposure trial to an inquiry regarding current emotional state. The emotional state of subjects was measured via a ten-point Likert anxiety scale (see Appendix C).

Procedure

For this experiment, there was one experimental session for each subject. A session consisted of the two exposure periods (B) in Experiment I. Those periods were divided up into 3 blocks of ten trials each. Therefore, a total of 60 anxiety level responses was gathered for each subject in Experiment IA.

The procedure was set up so that subjects were requested to provide a number from 1 to 10 immediately preceding each button pushing trial during the exposure periods in Experiment I. The response given by the subject was based on current levels of anxiety as measured by a ten-point Likert scale (see Appendix C).

Experiment II

Subjects

The subjects for this experiment were forty normal adult volunteers recruited from the undergraduate and graduate student populations at the University of Nevada, Reno. Subjects were assigned to experimental conditions via a block randomization procedure, with ten subjects in each of the following experimental conditions: active movement, passive movement with contours, passive movement without contours, and no movement.

Materials

Experimental Apparatus. The experimental apparatus for this experiment was identical to the one used in Experiment I.

Practice Display. The practice display was identical to the one used in the first experiment, with the following exception: a white seamless paper background covered the metal table for the passive movement without contours condition. All other conditions were presented with vertical black lines on a white seamless paper background, just as in Experiment I.

Test Display. The test display for Experiment II was identical to the one used in Experiment I.

Procedure

For each subject in each of the four experimental conditions involved in this experiment - active movement, passive movement with contours, passive movement without contours, and no movement - there was one experimental session consisting of three periods. The three periods (levels) for the repeated measures variable were arranged in an ABA repeated (reversal) design fashion. Each baseline (A) period consisted of exposure to the experimental apparatus with the video camera and television monitor aligned in an upright position. The exposure (B) period for each subject involved wearing the apparatus with the television monitor rotating relative to the video camera at a constant rate of 24-degrees per second. Each period was divided into 3 blocks of 10 trials each for a total of 30 trials per period and 90 trials per session. The rationale for dividing each period into 3 blocks of trials was the same as for Experiment I.

The sequence of events for each trial was the same as that detailed in Experiment I. However, trials during the two baseline periods (A1, A2) were administered as rapidly as possible, with no intervals separating each trial. Trials during the 15 minutes of exposure to optical rotation (B) were administered in the following fashion: the first block of trials immediately upon exposure to rotation, with no intervals between trials; the second block of trials beginning 7.5 minutes after completion of the first block with, again, no intervals separating trials; and the third block of trials beginning 7.5 minutes after completion of the second block, with no intervals between trials.

The following activities occurred in the interim time-periods between blocks of trials during exposure to rotation only: subjects in the active movement condition engaged in self-produced transverse arm movements across the contoured background with their hands in full view through the television monitor; the subjects in the passive movement with contours condition had their right arm moved for them in transverse movements across the contoured background with the hands in full view; the subjects in the passive movement without contours condition, likewise, had their arms moved in a transverse pattern against the contourless background with their hands in full view; and the subjects in the no movement condition rested their arms at their sides, but were still able to view the contoured background through the experimental apparatus.

To control for memorization response strategies, the test display (keyboard) was rotated 90-degrees after every 2 trials so that trials occurred at each of the following angles of rotation during the exposure (B) period: 0-degrees, 90-degrees, 180-degrees, 270-degrees, and 360-degrees.

Experiment III

Subjects

For this experiment, forty adult volunteers were selected from the undergraduate and graduate population of students at the University of Nevada, Reno. As with the previous experiment, a block randomization procedure was utilized for assignment of subjects to experimental conditions. The sample size for each of the following experimental conditions was ten: gradual inversion, active movement; gradual inversion, no movement; immediate inversion, active movement; and immediate inversion, no movement.

Materials

Experimental Apparatus. The experimental apparatus for Experiment III was identical to the one used in Experiments I and II.

Practice Display. The practice display for Experiment III consisted of line drawings covered by lightweight extra-thin tracing paper located on the experimental table used in Experiments I and II. The line drawings consisted of a circle filled with a grid, an equilateral triangle, an asterisk, a rectangle filled with a grid, a square with a diagonal cross inside, a cube, a figure 8, a plus, a tree, an hour glass, and an isosceles triangle.

Test Display. The test display for this particular experiment was the same as the one used in Experiments I and II.

Procedure

For each subject in each of the four experimental conditions in this study - gradual inversion, active movement; gradual inversion, no movement; immediate inversion, active movement; and immediate inversion, no movement - there was one experimental session. Each session consisted of three periods arranged in an ABA repeated measures (reversal) design fashion. Each baseline (A) period consisted of one block of 20 upright pointing trials sequentially administered, without intervals between trials (trials in the second baseline period (A2) served as a measure of visuomotor negative aftereffect). The exposure (B) period also involved one block of 20 button pushing trials which were administered after 20 minutes of exposure to gradual or immediate optical inversion. The trials in this period served as a measure of visuomotor reduction of effect, and were also administered with no intervals between trials.

During the exposure period (B), subjects in the two active movement conditions were seated at the practice display to complete tracings of line drawings for 20 minutes, while subjects in the two no movement conditions were seated with their arms at their sides and observed the experimenter tracing line drawings during the same time period. Upon donning the experimental apparatus, subjects in the immediate inversion groups were exposed to complete optical inversion of the visual world. Subjects in the gradual inversion groups were exposed to optical inversion of the visual world in the following static increments: 0-degrees, 40-degrees, 80-degrees, 100-degrees, 105-degrees, 110-degrees, 115-degrees, 120-degrees, 125-degrees, 130-degrees, 135-degrees, 140-degrees, 145-degrees, 150-degrees, 155-degrees, 160-degrees, 165-degrees, 170-degrees, 175-degrees, and 180-degrees. Exposure at each increment of inversion lasted for one minute; thus, complete optical inversion was reached in 20 minutes. The purpose behind such brief intervals of exposure to each increment of rotation was that partial visuomotor adaptation was likely to occur fairly rapidly with the immediate inversion groups and, so, any presumed advantages of gradual inversion would necessarily need to be detected very rapidly. In other words, a difference between gradual and immediate inversion in speed and completeness of visuomotor adaptation might have occurred but, unless complete optical inversion for the gradual groups was reached fairly rapidly, those differences may not have been detectable in the data.

As with Experiments I and II, memorization strategies were controlled for by rotating the keyboard during the exposure period in 90-degree increments every 5 trials so that target pointing responses occurred at 90-degrees, 180-degrees, 270-degrees, and 360-degrees.

CHAPTER III

RESULTS

Experiment I

A cursory visual inspection of the data in graphical form revealed some potentially significant changes in target pointing reaction times (R.T.'s) over the course of the experiment (see Figure 1). The initial baseline (A1) period was relatively stable over the three blocks of trials, although, as expected, the average R.T. decreased somewhat from 1.14 seconds to .74 seconds. Increasing familiarity with the experimental apparatus and trial procedures would easily account for improvements in performance from block 1 to block 3. With the onset of optical rotation in period 2, a rather sharp degradation in visuomotor performance occurred. Subject R.T.'s increased from .74 seconds to 2.44 seconds. However, over the course of exposure to rotation, performance steadily improved from an average of 2.44 seconds in block 4 to an average of 1.45 seconds in block 6. This indicated a possibly significant visuomotor reduction of effect, one measure of visuomotor adaptation. Upon returning to baseline (A2) in period 3, performance improved from 1.45 seconds in block 6 to 1.16 seconds in block 7, which would have been expected with the change from optical rotation to upright vision. However, a mean R.T. of 1.16 seconds in block 7 of period 3 was considerably slower than a mean R.T. of .74 seconds in block 3 of period 1, the previous block of trials undertaken with upright vision. Since there was no reason to expect such a strong decrement in performance from one baseline period (A1) to another (A2), unless visuomotor adaptation to optical rotation had occurred, the change in performance from block 3 to block 7 was indicative of a visuomotor negative aftereffect, a second measure of visuomotor adaptation. Further evidence for this interpretation was found in a comparison of mean R.T.'s between block 7 and block 9. If a negative aftereffect was operating in the upright period following optical rotation, it should have gradually faded with a decrease in mean R.T. over subsequent trials. This, in fact, did happen in Experiment I. Mean R.T.'s decreased from 1.16 seconds in block 7 to .64 seconds in block 9. Finally, mean R.T. in period 4 dropped from 1.96 seconds in block 10 to 1.12 in block 12, providing additional support for the reduction of effect found in period 2.

Despite the fact that these changes in visuomotor performance were consistent with an interpretation of visuomotor adaptation, the question remained as to whether these shifts in performance were statistically significant. Since the null hypothesis (Ho) was formulated for this particular experiment, the use of planned comparisons between experimental means would have been inappropriate. Therefore, a one-way (Treatments X Subjects) analysis of variance with repeated measures was performed on the statistical data as recommended by Drew (1980, p. 281) for parametric data of more than two nonindependent means (see Table 1). From this analysis, statistically significant differences across treatment blocks were detected in the data ($F=33.7$; $df=11, 133$; $p<.001$). Therefore, post-hoc comparisons, utilizing the Tukey HSD (honestly significant difference) test, were employed to determine which treatment blocks differed significantly from one another (see Table 2). This particular post-hoc analysis was used because no assumptions of independence regarding trial means was required for its use (Hays, 1981, p. 434). The following pairwise statistical comparisons were found to be significant, where M=mean and b=block: Mb3 with Mb4 for a measure of exposure effects ($p<.01$), Mb4 with Mb6 for a measure of visuomotor reduction of effect ($p<.01$), Mb7 with Mb3 for a measure of visuomotor negative aftereffect ($p<.05$), Mb7 with Mb9 for an additional measure of visuomotor negative aftereffect ($p<.01$), and Mb10 with Mb12 for a measure of the replicability of the visuomotor reduction of effect ($p<.01$).

A word here on the rationale for comparing Mb7 with Mb3 and Mb7 with Mb9 for a measure of visuomotor negative aftereffect is appropriate at this time. First, since the period of exposure to optical rotation was so brief (ten minutes) and since optical rotation was such a dramatic distortion of visual sensation and perception, it would have been inappropriate to expect performance, following optical rotation, to become worse than what it was at the end of the exposure period. Ten minutes was simply not a sufficiently long enough period of exposure to optical rotation to expect this strong a negative aftereffect. Second, there was no logical reason to expect performance to become temporarily worse, following a return to baseline, than what it was in the final block of the previous baseline period, unless some amount of visuomotor adaptation to optical rotation had occurred. For these reasons, it seemed reasonable to make the above-mentioned comparisons for the visuomotor negative aftereffect measure.

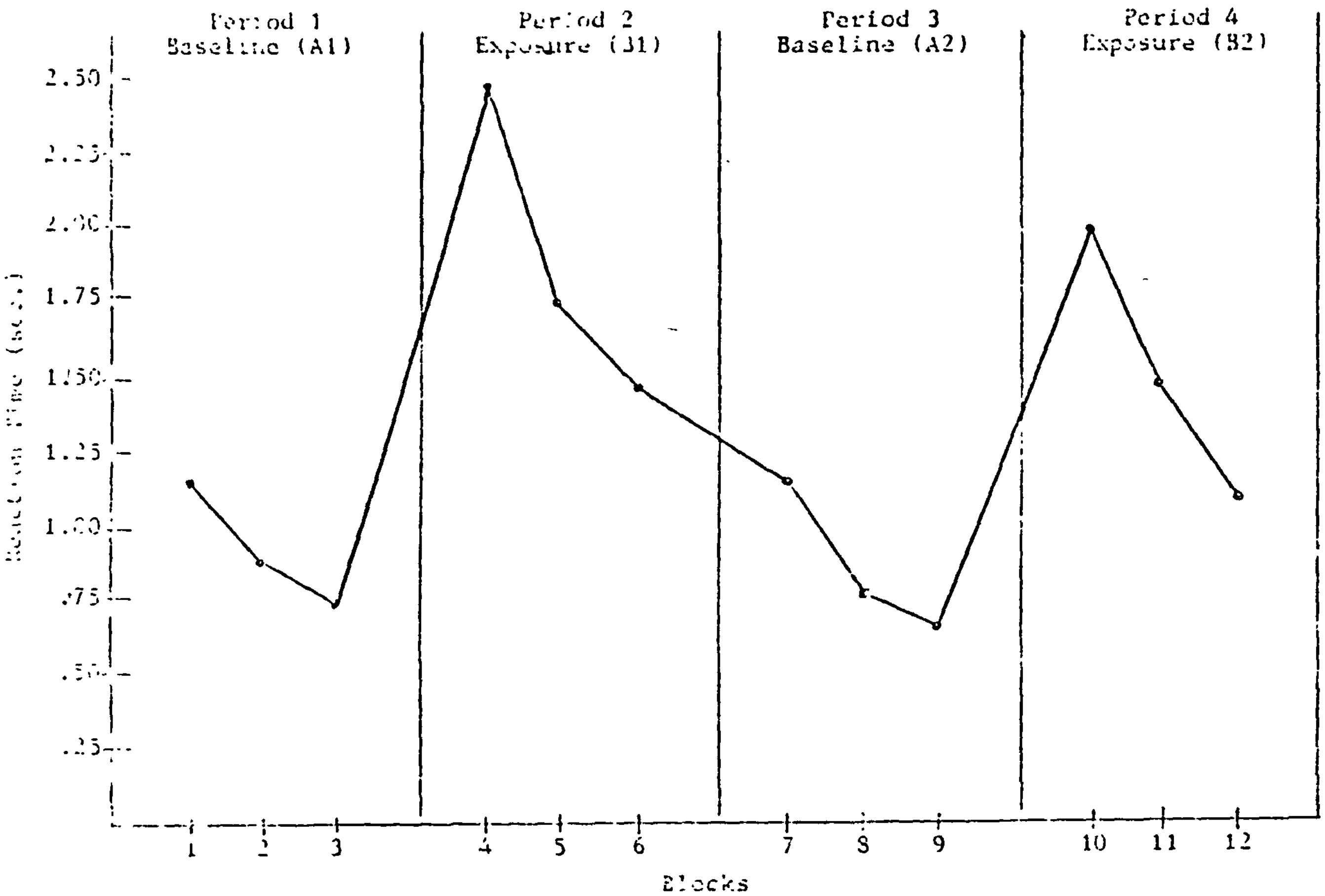

Figure 1. A graph of block means for all subjects across periods in experiment I.

Table 1

Experiment I Summary Table for Treatments X Subjects Analysis of Variance, Showing Source of Variation, Sum of Squared Deviations (SS), Degrees of Freedom (df), Means of Squared Deviations (MS), F ratio (F), and Significance level (p)

Source	SS	df	MS	F	p
Total	62.72	156	-	-	-
Subjects	8.08	12	-	-	-
Treatments	41.45	11	3.77	33.7	<.001
Error	13.19	133	.10	-	-

Table 2

Experiment I Summary Table for Tukey HSD
Post-Hoc Comparisons for Block Means,
Where M=mean and b= block

Comparison	1st Mean	2nd Mean	R.T. Diff.	p
1-Mb3 with Mb4	.74	2.44	-1.70	<.01
2-Mb4 with Mb6	2.44	1.45	.99	<.01
3-Mb7 with Mb3	1.16	.74	.42	<.05
4-Mb7 with Mb9	1.16	.64	.52	<.01
5-Mb10 with Mb12	1.96	1.12	.84	<.01

Experiment IA

Since the data in this experiment were not ordinal in nature and, therefore, did not meet the assumptions required for parametric data, the nonparametric Friedman two-way analysis of variance by ranks was computed. In this analysis, one variable is considered to be subjects, thus the term two-way analysis of variance (Drew, 1980, p. 281; Spence, Cotton, Underwood, & Duncan, 1976, p. 241). The results of this analysis proved to be statistically significant ($Xr=22.71$; $df=5$; $p<.01$). However, since the experiment was concerned with changes from block 4 to block 6 of period 2 and block 10 to block 12 of period 4, the Wilcoxan signed-ranks test for two matched samples was computed on the statistical data. For comparisons between blocks 4 and 6 and also between blocks 10 and 12, the results proved to be statistically significant ($T=0$; $Ns-r=13$; $p<.01$). This indicated that over the course of exposure to optical rotation, in both period 2 and period 4, a significant reduction in anxiety levels occurred (see Table 3 for mean values in each block).

Table 3

Experiment IA Summary Table for Subject Means Across Blocks on Likert Scale

Block 4	Block 5	Block 6	Block 10	Block 11	Block 12
6.28	4.19	2.76	4.72	2.94	1.95

Experiment II

Again, a brief visual inspection of the data in Experiment II revealed a similar, perhaps even more pronounced trend toward visuomotor adaptation among all four experimental conditions than in Experiment I (see Figure 2). However, differences between experimental conditions were not evident until blocks 5 and 6 of period 2 and block 7 of period 3. In these blocks, mean R.T.'s for the active movement and passive movement with contours conditions were much the same; i.e., a strong visuomotor reduction of effect and visuomotor negative aftereffect were apparent for both conditions. However, in blocks 5 and 6 of period 2, a divergence in R.T.'s occurred between the active movement and passive movement with contours conditions and the other two experimental conditions. The reduction of effect measure for the no movement condition was particularly weak in contrast to the active movement and passive movement with contours conditions. In block 7 of period 3, the first upright period following exposure to optical rotation, mean R.T.'s for the passive movement without contours and no movement conditions tended to converge even more than in blocks 5 and 6 of period 2, with the measure of visuomotor negative aftereffect being weaker for both groups than for the active movement and passive movement with contours conditions.

Although some possible effects were detectable from a visual inspection of the data only, statistical analyses were performed in order the assess the significance of these differences. Once again, as with Experiment I, the null hypothesis was formulated for this particular experiment, making the use of planned comparisons between experimental condition means inappropriate. Therefore, a two-way mixed analysis of variance with repeated measures on one factor was computed on the derived data (see Table 4). This analysis yielded a statistically significant main effect for blocks ($F=266.2$; $df=8, 288$; $p<.001$) and a significant interaction for blocks X experimental conditions ($F=2.0$; $df=24, 288$; $p<.005$). Further analyses utilizing the Tukey HSD test for post-hoc pairwise comparisons was undertaken to determine where the significant differences were located for the main effect of blocks (see Table 5). In each experimental condition, the following pairwise comparisons were made, where M=mean and b=block: Mb3 with Mb4 for a measure of exposure effectiveness, Mb4 with Mb6 for a measure of visuomotor reduction of effect, Mb7 with Mb3 for a measure of visuomotor negative aftereffect, and Mb7 with Mb9 for an additional confirmatory measure of visuomotor negative aftereffect. In each of these comparisons for all four experimental conditions, statistical significance was obtained at the $p<.01$ level. This indicated that, regardless of experimental condition, statistically significant visuomotor adaptation, as measured by the visuomotor reduction of effect and the visuomotor negative aftereffect, was present.

In addition to the foregoing comparisons, analyses were performed to determine on which particular blocks of trials the four experimental conditions differed as indicated by the significant blocks X conditions interaction (see Table 6). Simple F tests were computed to analyze overall differences between experimental conditions on each block of trials as outlined in Bruning and Kintz (1977, pp. 141-142). As would be expected from a randomized block assignment procedure, non-significant F tests were obtained between conditions on blocks 1 through 3 of period 1, block 4 of period 2, and blocks 8 and 9 of period 3. These results would have been expected because the experimental conditions did not differ on these blocks. However, statistically significant differences were apparent on blocks 5 and 6 of period 2 ($F=4.29$; $df=3, 324$; $p<.005$; $F=15.29$; $df= 3, 324$; $p<.01$) and statistical significance was barely missed on block 7 of period 3. Because significance was obtained on blocks 5 and 6 of period 2 and barely missed on block 7 of period 3, the Tukey HSD test was employed to ascertain which specific experimental condition means differed on each of these three blocks (see Table 7). These analyses yielded the following significant comparisons: M1b5 with M3b5 ($p<.01$), M1b5 with M4b5 ($p<.01$), M2b5 with M3b5 ($p<.01$), M2b5 with M4b5 ($p<.01$), M3b5 with M4b5 ($p<.01$), M1b6 with M3b6 ($p<.01$), M1b6 with M4b6 ($p<.01$), M2b6 with M3b6 ($p<.01$), M2b6 with M4b6 ($p<.01$), M1b7 with M3b7 ($p<.05$), M1b7 with M4b7 ($p<.01$), M2b7 with M3b7 ($p<.01$), M2b7 with M4b7 ($p<.01$). Generally, these results support no differences between the active movement and passive movement with contours conditions and no differences between the passive movement without contours and no movement conditions. However, measures of visuomotor reduction of effect and visuomotor negative aftereffect were significantly stronger for the active movement and passive movement with contours conditions than for the passive without contours and no movement conditions.

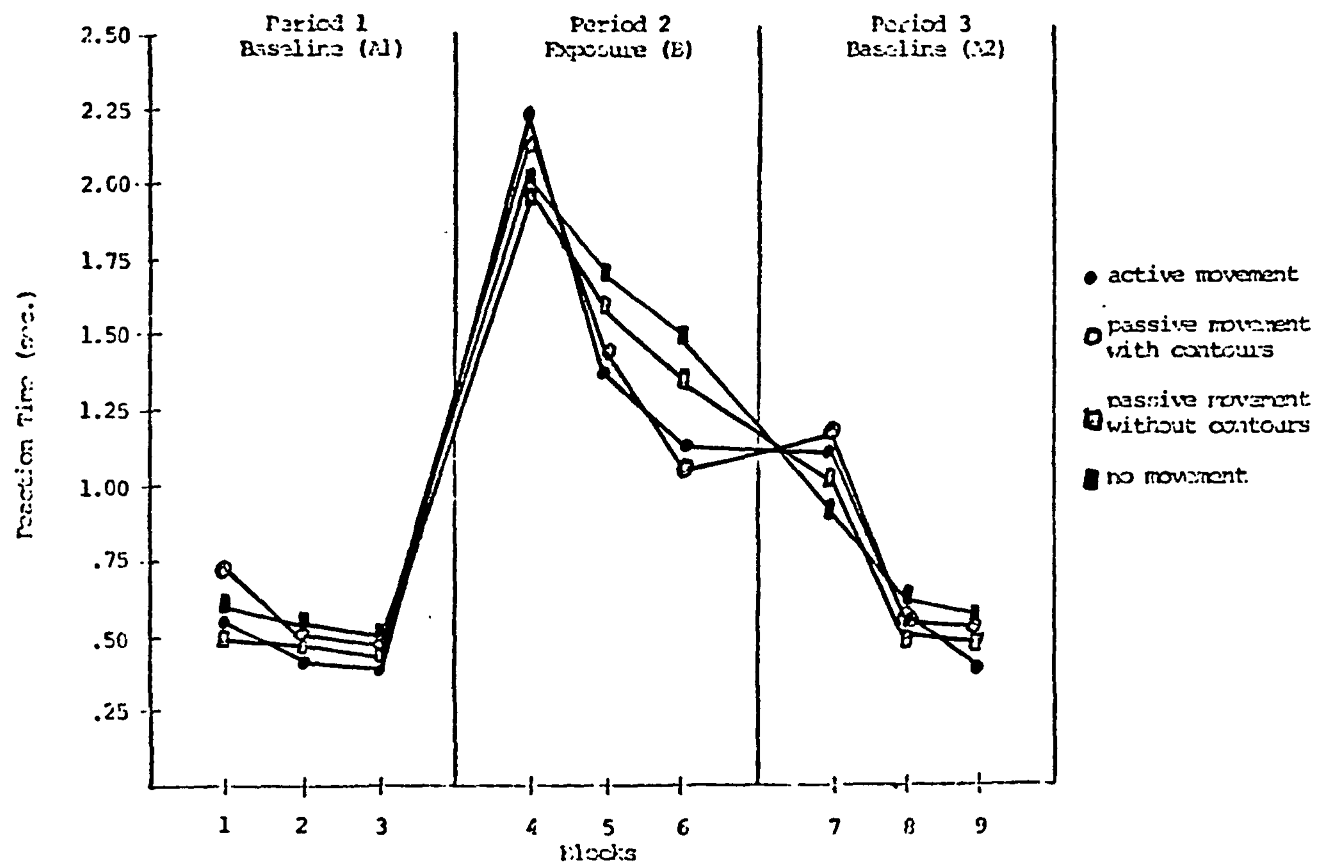

Figure 2. A graph of block means for all experimental conditions across periods in Experiment II

Table 4

Experiment II Summary Table for Two-Way Mixed Analysis of Variance With Repeated Measures on One Factor, Showing Source of Variation, Sum of Squared Deviations (SS), Degrees of Freedom (df), Means of Squared Deviations (MS), F Ratios (F), and Significance Levels (p)

Source	SS	df	MS	F	p
Total	132.92	359	-	-	-
Between Subjects	9.04	39	-	-	-
Conditions	.27	3	.09	.38	ns
Error b	8.77	36	.24	-	-
Within Subjects	123.88	320	-	-	-
Blocks	106.48	8	13.31	266.2	<.001
Blocks X Conditions	2.48	24	.10	2.0	<.005
Error w	14.92	288	.05	-	-

Table 5

Experiment II Summary Table for Tukey HSD Post-Hoc Comparisons for Significant Main Effect of Blocks, Where M1=mean of active movement, M2=mean of passive movement with contours, M3=mean of passive movement without contours, M4= mean of no movement and b=block

Comparison	1st Mean	2nd Mean	R.T. Diff.	*p*
1-M1b3 with M1b4	.40	2.22	-1.82	<.01
2-M1b4 with M1b6	2.22	1.14	1.08	<.01
3-M1b7 with M1b3	1.13	.40	.73	<.01
4-M1b7 with M1b9	1.13	.42	.71	<.01
5-M2b3 with M2b4	.48	2.13	-1.65	<.01
6-M2b4 with M2b6	2.13	1.07	1.06	<.01
7-M2b7 with M2b3	1.17	.48	.69	<.01
8-M2b7 with M2b9	1.17	.51	.66	<.01
9-M3b3 with M3b4	.43	1.99	-1.56	<.01
10-M3b4 with M3b6	1.99	1.33	.66	<.01
11-M3b7 with M3b3	1.01	.43	.58	<.01
12-M3b7 with M3b9	1.01	.50	.51	<.01
13-M4b3 with M4b4	.49	2.03	-1.54	<.01
14-M4b4 with M4b6	2.03	1.44	.59	<.01
15-M4b7 with M4b3	.91	.49	.42	<.01
16-M4b7 with M4b9	.91	.56	.35	<.01

Table 6

Experiment II Summary Table for Simple F Tests of Significance for Overall Block Means, Showing Source of Variation, Sum of Squared Deviations (SS), Degrees of Freedom (df), Means of Squared Deviations, (MS), F ratios (F), and Significance Levels (p)

Source	SS Conditions	df	MS	F	p
Block 1	.20	3, 324	.07	1.00	ns
Block 2	.09	3, 324	.03	.43	ns
Block 3	.05	3, 324	.02	.29	ns
Block 4	.32	3, 324	.11	1.57	ns
Block 5	.90	3, 324	.30	4.29	<.005
Block 6	3.20	3, 324	1.07	15.29	<.001
Block 7	.41	3, 324	.14	2.00	ns
Block 8	.03	3, 324	.01	.14	ns
Block 9	.10	3, 324	.03	.43	ns

Table 7

Experiment II Summary Table for Tukey HSD Post-Hoc Comparisons for Significant Blocks X Conditions Interaction; M1=mean of active movement, M2= mean of passive movement with contours, M3= mean of passive movement without contours, M4=mean of no movement and b=block

Comparison	1st Mean	2nd Mean	R.T. Diff.	*p*
1-M1b5 with M2b5	1.39	1.41	-.02	ns
2-M1b5 with M3b5	1.39	1.56	-.17	<.01
3-M1b5 with M4b5	1.39	1.71	-.32	<.01
4-M2b5 with M3b5	1.41	1.56	-.15	<.01
5-M2b5 with M4b5	1.56	1.71	-.15	<.01
6-M3b5 with M4b5	1.56	1.71	-.15	<.01
7-M1b6 with M2b6	1.14	1.07	.07	ns
8-M1b6 with M3b6	1.14	1.33	-.19	<.01
9-M1b6 with M4b6	1.14	1.44	-.30	<.01
10-M2b6 with M3b6	1.07	1.33	-.26	<.01
11-M2b6 with M4b6	1.07	1.44	-.37	<.01
12-M3b6 with M4b6	1.33	1.44	-.11	ns
13-M1b7 with M2b7	1.13	1.17	-.04	ns
14-M1b7 with M3b7	1.13	1.01	.12	<.05
15-M1b7 with M4b7	1.13	.91	.22	<.05
16-M2b7 with M3b7	1.17	1.01	.16	<.01
17-M2b7 with M4b7	1.17	.91	.26	<.01
18-M3b7 with M4b7	1.01	.91	.10	ns

Experiment III

In the present experiment, a brief visual examination of the graphed data provided an absolute and a relative measure of visuomotor negative aftereffect to optical inversion, but only a relative measure of reduction of effect (see Figure 3). This was so because no performance measures were taken at the beginning of the exposure period to compare later performance to optical inversion with. Given these limitations, it appeared that differences between block 1 mean R.T.'s and block 3 mean R.T.'s may have been significant for all four experimental conditions, indicating possible visuomotor negative aftereffects. Relative visual comparisons between experimental condition means indicated that the strongest visuomotor reduction of effect occurred for gradual inversion, active movement; this was followed by gradual inversion, no movement; immediate inversion, active movement; and, finally, immediate inversion, no movement. Mean R.T.'s for the visuomotor negative aftereffect measure were similar to those for the measure of reduction of effect. However, the positions of the gradual inversion, no movement condition and the immediate inversion, active movement condition were reversed.

In terms of statistical analysis, a three-way mixed analysis of variance with repeated measures on one factor was computed for the data (see Table 8). In this analysis, a main effect for blocks, an interaction for blocks X speed of inversion, and an interaction for blocks X degree of arm movement were all found to be statistically significant ($F=152.29$; $df=2, 72$; $p<.001$; $F=11.43$; $df=2, 72$; $p<.001$; $F=13.29$; $df=2, 72$; $p<.001$). However, only specific nonorthogonal planned comparisons, formulated in the Research Hypotheses subsection of the Introductory Section, were of interest in this experiment (see Table 9). Consequently, one-tailed Bonferroni t-tests were computed as recommended by Kirk (1968, p. 86) and Keppel (1982, pp. 146-150). Computational procedures for the test were derived from Bruning and Kintz (1977, pp. 113-116). Using these computational procedures, the following planned comparisons between experimental condition means were found to be statistically significant, where M1=the mean of the gradual inversion, active movement condition; M2=the mean of the gradual inversion, no movement condition; M3=the mean of the immediate inversion, active movement condition; M4=the mean of the immediate inversion, no movement condition; and b=block (see Table 12): M1b2 < M2b2 ($p<.01$), M1b2 < M3b2 ($p<.01$), M1b2 < M4b2 ($p<.01$), M2b2 < M3b2 ($p<.05$), M2b2 < M4b2 ($p<.01$), M3b2 < M4b2 ($p<.01$), M1b3 > M2b3 ($p<.01$), M1b3 > M3b3 ($p<.05$), M1b3 > M4b3 ($p<.01$), M2b3 > M4b3 ($p<.01$), M3b3 > M4b3 ($p<.01$). The only one-tailed t-test that did not turn out to be statistically significant was the comparison of M2b3 with M3b3. Originally, in the Research Hypotheses subsection, it was predicted that M2b3 would be greater than M3b3; i.e., the visuomotor negative aftereffect of the gradual inversion, no movement condition would be significantly stronger than the visuomotor negative aftereffect for the immediate inversion, active movement condition. However, just the opposite occurred. Overall, the results tended to support the research hypotheses discussed previously for this experiment, with the exception noted above.

In addition to the foregoing analysis, it was also of interest to ascertain whether significant adaptation to optical inversion was occurring in each of the four experimental conditions, exclusive of relative comparisons between groups. For the purposes of this analysis, the Tukey HSD test for post-hoc comparisons was utilized (see Table 10). The following comparisons between block means proved to be statistically significant: M1b1 with M1b3 ($p<.01$), M2b1 with M2b2 ($p<.01$), M3b1 with M3b3 ($p<.01$), and M4b1 with M4b3 ($p<.01$). These results indicated that a significant visuomotor negative aftereffect was present in each of the four experimental conditions.

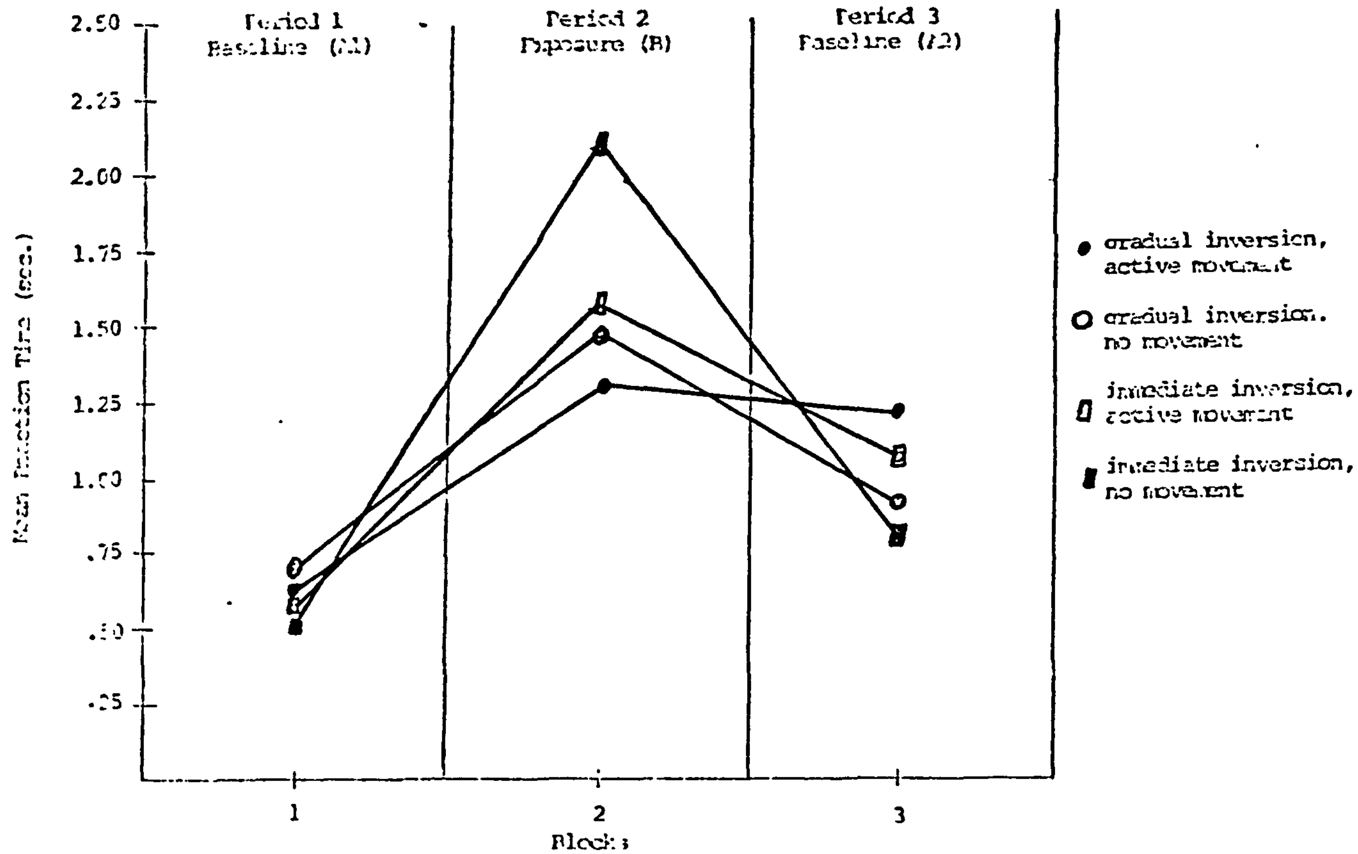

Figure 3. Graph of mean reaction times in experiment III for each experimental condition across blocks.

Table 8

Experiment III Summary Table for Three-Way Mixed Analysis of Variance With Repeated Measures on One Factor, Showing Source of Variation, Sum of Squared Deviations (SS), Degrees of Freedom (df), Means of Squared Deviations (MS), F ratios (F), and Significance Levels (p)

Source	SS	df	MS	F	p
Total	34.07	119	-	-	-
Between Subjects	3.86	39	-	-	-
Inversion (I/G)	.21	1	.21	2.10	ns
Movement (A/N.M.)	.05	1	.05	.50	ns
Inver. X Move.	.03	1	.03	.30	ns
Error b	3.57	36	.10	-	-
Within Subjects	30.21	80	-	-	-
Blocks	21.32	2	10.66	152.29	<.001
Blocks X I.	1.59	2	.80	11.43	<.001
Blocks X M	1.85	2	.93	13.29	<.001
Blocks X I X M	.06	2	.03	.43	ns
Error w	5.39	72	.07	-	-

Table 9

Experiment III Summary Table for Bonferonni t-test Non-Orthogonal Planned Comparisons, where M1=mean of gradual inversion, active movement; M2=mean of gradual inversion, no movement; M3=mean of immediate inversion, active movement, M4= mean of immediate inversion, no movement and b=block

Comparison	1st Mean	<>	2nd Mean	R.T. Diff.	*p*
1-M1b2<M2b2	1.31	<	1.48	-.17	<.01
2-M1b2<M3b2	1.31	<	1.60	-.29	<.01
3-M1b2<M4b2	1.31	<	2.13	-.82	<.01
4-M2b2<M3b2	1.48	<	1.60	-.12	<.05
5-M2b2<M4b2	1.48	<	2.13	-.65	<.01
6-M3b2<M4b2	1.60	<	2.13	-.53	<.01
7-M1b3>M2b3	1.22	>	.99	.23	<.01
8-M1b3>M3b3	1.22	>	1.10	.12	<.05
9-M1b3>M4b3	1.22	>	.82	.40	<.01
10-M2b3>M3b3	.99	<	1.10	.11	ns
11-M2b3>M4b3	.99	>	.82	.17	<.01
12-M3b3>M4b3	1.10	>	.82	.28	<.01

Table 10

Experiment III Summary Table for Tukey HSD Post-Hoc Comparisons for Significant Main Effect of Blocks, where M1=mean of gradual inversion, active movement, M2=mean of gradual inversion, no movement, M3=mean of immediate inversion, active movement, M4=mean of immediate inversion, no movement and b=block

Comparison	1st Mean	2nd Mean	R.T. Diff.	*p*
1-M1b1 with M1b3	.61	1.22	-.61	<.01
2-M2b1 with M2b3	.67	.99	-.32	<.01
3-M3b1 with M3b3	.57	1.10	-.53	<.01
4-M4b1 with M4b3	.56	.82	-.26	<.01

CHAPTER IV

DISCUSSION

Experiments I & II

General Conclusions

The results of Experiment I indicate that human subjects are capable of adapting, in some sense, to a dynamically rotating visual world. This is so because a statistically significant visuomotor reduction of effect and visuomotor negative aftereffect were present for the subjects in this experiment. Generally, both measures are thought to be essential for inferences of visuomotor adaptation, with the visuomotor negative aftereffect considered to be the more important measure (Welch, 1978, pp. 6-7). The possibility exists, however, that the significant reduction of effect in Experiment I was due simply to practice effects, but this explanation is highly unlikely given the presence of a visuomotor negative aftereffect with no plausible explanations available to account for its significance. This explanation of the reduction of effect also lacks credence due to the replication of the reduction of effect from period 2 to period 4. Certainly, if subjects had merely become competent at target pointing to visual symbols from practicing the performance task over and over again, a greater carryover of these effects would be expected from period 2 to period 4. Yet the data clearly indicate that upon return to rotation in period 4, subject reaction times rise dramatically to a point not far below the initial reaction times to rotation in period 2. This indicates that a temporary adaptive compensation to the visual distortion took place.

Another possible explanation for the results of Experiment I is that subjects merely waited until the apparatus was in an upright or nearly upright position to make a response. However, the relatively short R.T.'s, as compared with the 15 seconds required to make a complete 360-degree rotation, mitigate against this explanation. The slowest average response time in any exposure block was 2.44 seconds, far too short of an interval to accurately account for the results in terms of the subject response strategy of waiting for the apparatus to rotate to an upright or nearly upright position. Furthermore, since the speed of rotation was not synchronous with the interval between performance measurements, it is impossible to account for the results by claiming that the apparatus was always nearing an upright position or actually in an upright position when a performance measurement was taken.

An additional explanation for the obtained results might possibly rely on the claim that subjects memorized the approximate locations of the visual symbols on the keyboard (test display) and then calibrated reaching movements to those locations while ignoring the visual input provided by optical rotation of the apparatus. However, as discussed previously, the entire test display was rotated at standardized increments so that subjects were forced to process the visual input in order to make a motor response.

Finally, it is possible to speculate that true visuomotor adaptation did not occur because the performance measure was one of speed of response and not degree of pointing accuracy, thereby allowing subjects to make compensatory shifts in reaching movements during a motor response after initially reaching in an improper direction. According to this interpretation of the data, the reduction of effect found to optical rotation may have been simply due to the subjects increasing competence at modifying motor responses when feedback was received during the course of those actions. However, although this may be a partial explanation of the results, it is inadequate as the only explanation. This is so because it fails to account for the strong visuomotor negative aftereffect that was found among subjects. If the reduction of effect was due only to midstream motor compensations, why should this continue into an upright phase when, presumably, visual input was relatively normal? Based on the significant visuomotor negative aftereffect for this experiment, it appears that some type of short-term calibration of motor ouput occurred to the distorted visual input of optical rotation. Other possibilities may have played a role as well and these will be examined shortly.

Overall, it appears safe to assume that a form of adaptation to optical rotation was shown by the data in Experiment I. This finding of increased visuomotor plasticity would appear to extend the findings of Stratton (1896, 1897a, 1897b, 1899), Ewert (1930), Peterson and Peterson (1938), Snyder and Pronko (1953), Erismann (1947), Kohler (1951, 1955, 1962, 1964), Kottenhoff (1957), Kruger (1939), Taylor (1962), and Dolezal (1971, 1977, 1982) in which visuomotor adaptation to static optical inversion was demonstrated. Put another way, this experiment indicates that human visuomotor plasticity and adaptability extend to dynamic transpositions of the visual world, as well as static ones.

Although the results of Experiment I support the notion that humans are able to adapt to dynamic visual distortions, they do not explain what underlying mechanisms may be responsible for these instances of adaptation. The results of Experiment II did, however, provide some insight into this question, as well as the question of what type of adaptation was apparent during exposure to optical rotation.

As will be recalled from previous theoretical discussions, contrasting active movement and passive movement with contours is considered to be an acceptable way of distinguishing between the "reafference hypothesis" of Held and the "proprioceptive change hypothesis" (Melamed et al., 1973; Wallace, 1975). This is thought to be true because, according to the "reafference hypothesis," only active motor ouputs call up old reafferent signals for comparison with new reafferent signals so that adaptive compensations in motor activity can be made and then correlated with the "new reafference." In contrast, the "proprioceptive change hypothesis" asserts that anything that makes the felt position of the limbs more salient will enhance adaptation since adaptation, according to this hypothesis, is simply the recalibration of the felt positions of the limbs with the seen positions. Theoretically, then, this viewpoint claims that visuomotor adaptation is due to the enhancement of the body position sense, regardless of how that enhancement is accomplished.

A test of these two hypotheses in Experiment II provided strong support for the "proprioceptive change hypothesis." Comparisons of the means for the active movement condition and the passive movement with contours condition indicated that no statistically significant differences existed between the two groups on measures of visuomotor reduction of effect and visuomotor negative aftereffect. This finding must be interpreted to mean that passive movement, which stimulates the felt position of the limb when contours are present in the background as a comparison, can produce total amounts of visuomotor adaptation equivalent to the visuomotor adaptation produced by active movement. Since no superiority was found for the active movement group, the visuomotor adaptation evident in this condition can be easily accounted for by reference to the increased salience of the felt position of the limbs that naturally occurs during active movement. In general, then, these findings tend to support the studies of Kravitz and Wallach (1966), Mather and Lackner (1975, 1981), Melamed et al. (1973), Moulden (1971), Wallace (1975, 1980), Wallace and Fisher (1979, 1982, 1984), Wallace and Garrett (1973, 1975), and Wallace and Hoyenga (1981). In these studies, the "proprioceptive change hypothesis" proved to be superior to the "reafference hypothesis" as an explanatory mechanism for cases of visuomotor adaptation to optical displacement of vision.

However, despite the lack of significant differences between the active movement and passive movement with contours conditions, this does not preclude the possibility that the "reafference hypothesis" played some role in the visuomotor adaptation found with optical rotation in Experiments I and II. In other words, the possibility exists that different explanations are required to adequately account for visuomotor adaptation with different types of motor activity. Since there is, at present, no means of observing the neural correlates of visuomotor adaptation, it would seem that no plausible way of resolving this quandary exists. In the absence of an effective approach for addressing this problem, it is reasonable to conclude that the "proprioceptive change hypothesis" adequately accounted for the lack of significant differences between the active movement and passive movement with contours conditions. The strength of this interpretation was given added impetus by the finding of statistically significant superiority on the visuomotor reduction of effect measure and on the visuomotor negative aftereffect measure for the passive movement with contours condition over the passive movement without contours condition and the no movement condition. Presumably, felt limb positions were not enhanced in the passive movement without contours condition to the extent that they were in the passive movement with contours condition due to the absence of identifiable contours for locating the felt positions relative to the background. This was likely true to an even larger extent in the no movement condition since the subjects in the passive movement without contours condition exhibited significantly greater visuomotor adaptation than did the subjects in the no movement condition.

Despite the apparent superiority of the "proprioceptive change hypothesis," any simplistic theoretical interpretation of the results in Experiment II would be risky at the least and foolish in the extreme. As can be gleaned from the results of this experiment, significant adaptation was found in all four experimental conditions for both the visuomotor reduction of effect measure and the visuomotor negative aftereffect measure. This was true even-though subjects in the no movement condition received limited motor feedback. In fact, the only motor feedback available to the subjects in the no movement condition was that provided during the actual performance of target pointing responses. The finding of statistically significant visuomotor adaptation to optical rotation in all four experimental conditions indicates a very distinct possibility that a form of cognitive adaptation occurred, whereby subjects learned to predict where to reach given the locus of the apparatus in the 360-degree rotation and became so proficient at doing so that this carried over into the next upright period, manifesting as a visuomotor negative aftereffect. According to this interpretation of the results, the recalibration of felt positions of the limbs with their seen positions would have increased the total amount of visuomotor adaptation exhibited to optical rotation by building upon and adding to the foundation level of cognitive adaptation demonstrated by subjects. This hypothesis is consonant with the findings of Experiment II. This is so because the greatest amounts of adaptation were exhibited in the active movement and passive movement with contours conditions where the level of proprioceptive feedback was greatest, followed by the passive movement without contours condition where proprioceptive feedback was minimal, and the no movement condition where proprioceptive feedback was virtually nonexistent. Future research efforts will need to address the issue of cognitive adaptation to optical rotational transformations in considerably more detail than was done in the present investigation.

Implications for Future Research

Significant visuomotor adaptation to a dynamically rotating visual world has important implications for future research activities in the areas of perceptual modifications and perceptual adaptation. Numerous followup studies to Experiments I and II would be appropriate. In particular, the issue of cognitive adaptation needs additional clarification. One worthwhile approach might be to examine transfer of training from visuomotor tasks, in a rotating visual world, to cognitive tasks such as identifying angles, or motorically rotating an object to the perceived upright in the absence of orienting background cues, or mentally rotating letters or shapes to an upright position. With regard to mental transformations of physical stimuli, a rich and controversial literature exists (for reviews, see Kosslyn, 1978, 1980; Morris & Hampson, 1983; Shepard & Cooper, 1982; Shepard & Podgorny, 1979). In order to completely understand the role of cognition in visuomotor adaptation to optical rotational transformations, it is absolutely essential that the relationship between mental transformations and cognitive adaptation be elucidated in greater detail. Also, it is important to examine the role of other cognitive forms of information in visuomotor adaptation, such as verbal feedback.

In addition to the foregoing, a number of additional issues need to be examined. To begin with, it would be of theoretical significance to establish the upper limits of human visuomotor plasticity to a dynamically rotating visual world. For example, what would the upper limit to speed of rotation be in which subjects could at least partially adapt? In Experiments I and II, the speed of rotation was selected to be a reasonable 360-degrees of rotation every 15 seconds. This rate of rotation should be increased in future experiments to examine the limits of plasticity to optical rotation. A related issue that needs to be addressed is the length of exposure to optical rotation; i.e., would periods of exposure longer than the relatively short periods in Experiments I and II produce significantly greater visuomotor adaptation? Given the large amounts of visuomotor adaptation reported from long-term studies of exposure to optical inversion, it seems reasonable to expect greater adaptation to optical rotation with increased exposure lengths. However, symptoms of possible motion sickness would necessarily need to be monitored very closely.

An additional question worth looking at relates to one of the issues examined in Experiment III; that is, would gradual increases in the speed of rotation produce more rapid and greater amounts of visuomotor adaptation? Preliminary data from Experiment III indicated that this does occur with optical inversion. Therefore, it is extremely likely that similar results would be obtained for other visual distortions, such as optical rotation. This finding would, of course, support an "information hypothesis" of visuomotor adaptation to optical distortions because of the increased information about the nature of the distortion that is conveyed through shaping.

Other salient issues of importance that need to be investigated is the role of head and body movements, and the role of ambulation in visuomotor adaptation to an optically rotating world. Experiments I and II were conducted so that head movements were completely eliminated and body movements were limited to the arm. However, given the findings of increased adaptation with active movement and passive movement with contours in Experiment II, it is likely that free ambulation, with the apparatus in place, would increase the proprioceptive feedback and, thus, the total amount of visuomotor adaptation. In the beginning, however, head and body movements would probably prove to be more confusing, complicating the task of functioning competently in the visual surround.

Finally, anecdotal reports of perceptual illusions, such as the feeling that the body was rotating relative to the external environment, could conceivably be investigated using the experimental apparatus in the present study. It would be possible to isolate personality variables associated with this illusion, and to seek explanations for the illusion, both neural and psychological.

Practical Implications

The present research has many practical implications for the aerospace industry. For example, the finding that subjects have the ability to adapt, in a visuomotor sense, to an optically rotating world is one that has great significance for the space program since one of the major problems astronauts encounter during space flight is visual disorientation (Graybiel et al., 1974). The findings of Experiments I and II suggest that subjects can be trained to become "super perceivers" so that they can function competently in a wide variety of distorted environments. A program to train pilots and astronauts to be more flexible perceivers could, quite possibly, involve exposing them to an optically rotating world similar to the one experienced during space flight where the capsule is rotating relative to the astronauts. Furthermore, if a relationship is found between cognitive adaptation and mental transformations of physical objects, training in an optically rotating world could be utilized to train more flexible abstract mathematical abilities or map reading abilities requiring mental visualizations and manipulations of geometric forms and shapes.

In addition, an optically rotating world could be used to study the role of the visual system in motion sickness. As mentioned previously, vertigo and nausea are major problems experienced by astronauts during space flight (Graybiel et al., 1974). Dolezal (1982, pp. 308-313) has suggested that "visual weightlessness training" to an optically inverted world would reduce some of the symptoms of motion sickness. If this is true, it is highly likely that exposure to an optically rotating visual world would also serve to preadapt subjects to some of the symptoms of motion sickness. Evidence for this assumption can be found from Dolezal's (1971, 1977, 1982, p. 109) study of adaptation to long-term wearing of inverting prisms in which the nausea, vertigo, and general visual disorientation that accompanied optical inversion faded within approximately ten hours. It was also found in this study that the visual system is capable of exerting an "override" over vestibularly controlled compensatory eye movements, and that the peripheral visual system appears to control orientation in the immediate visual surround (Dolezal, 1982, p. 308).

Experiment IA

General Conclusions

The statistically significant Wilcoxan signed-ranks test for comparisons between blocks 4 and 6 and blocks 10 and 12 indicated that a significant reduction in anxiety levels occurred over the course of exposure to optical rotation. As will be recalled, this result would have been expected if the model of adaptation proposed by Welch is accurate (Welch, 1978, pp. 279-286). This is so, because anxiety level is a likely overt manifestation of the "aversive drive state" which triggers visuomotor adaptation. According to Welch, the aversive nature of the drive state is reduced over the course of exposure by habituation to the "registered discrepancy." Therefore, if anxiety level is an appropriate measure of the "aversive drive state," anxiety levels should have decreased with habituation to the "registered discrepancy" in the nervous system. This, in fact, did occur in Experiment IA.

Implications for Future Research

An attempt should be made in future research to obtain a parametric measure of anxiety so that correlations between visuomotor adaptation and anxiety levels can be made. This is important, because the model of adaptation, as proposed by Welch, hypothesizes that when habituation to the "registered discrepancy" is complete, the "aversive drive state" shuts down and, as a consequence, visuomotor adaptation ceases. By correlating anxiety levels with visuomotor adaptation, it would be possible to test the prediction that the "adaptive process" ceases when the "aversive drive state" is no longer present. Presumably, anxiety levels would be at their lowest level when visuomotor adaptation stops, if the model of adaptation is correct.

Practical Implications

The results of Experiment IA have implications for preadapting astronauts and pilots to visual disorientation and other symptoms of motion sickness. It appears that keeping anxiety levels high is conducive to an enhanced "aversive drive state" and, thus, visuomotor adaptation. Therefore, when the aversiveness of the optical distortion, as measured by anxiety levels, begins to wane, additional increments of the optical distortion should be introduced in order to create an additional "registered discrepancy," thereby, reactivating the "aversive drive state" (see Ebenholtz, 1969; Ebenholtz & Mayer, 1968, and Experiment III of the present investigation for more information on this topic). By using this procedure, the fullest possible preadaptation to visual disorientation and motion sickness could be achieved for pilots and astronauts undergoing training for air flight or space flight.

Experiment III

General Conclusions

The results of Experiment III generally supported the major assumption of the "information hypothesis," that any salient form of information about the nature of the optical distortion will aid performatory adaptation. This was true because the speed and total amount of visuomotor adaptation exhibited in the four experimental conditions was generally dependent on the amount of information available regarding the nature of the optical distortion. When exceptions to this rule occurred, they were due to the saliency of a particular item of information; i.e., some forms of information were hypothesized to be of greater value in providing information about the optical distortion. The significant superiority of the gradual inversion, active movement condition over the other three experimental conditions, on both measures of visuomotor adaptation, supported the position of the "information hypothesis" since more forms of information were thought to be present in this condition than in any other. A type of cognitive information from observing the gradual inversion was hypothesized to be available to both gradual inversion groups, and error-corrective feedback was present for both active movement conditions, as was proprioceptive and/or reafferent information.

Support for Webster's (1969) assertion that cognitive information alone can produce statistically significant performatory adaptation was demonstrated by the significantly greater reduction of effect shown by the gradual inversion, no movement condition as contrasted with the two immediate inversion groups. Hypothetically, only cognitive information was available to the gradual inversion, no movement condition, whereas proprioceptive and/or reafferent feedback, and error-corrective feedback were available to the immediate inversion, active movement condition. None of these forms of information, at least as presently defined, was present in the immediate inversion, no movement condition. However, despite a prediction of prepotency for cognitive information over the other three sources of information, the gradual inversion, no movement group had a weaker visuomotor negative aftereffect than did the immediate inversion, active movement condition, although the statistical significance of this difference was impossible to determine due to the uni-directional hypotheses examined in this experiment. This finding indicates the possibility that error-corrective feedback, and proprioceptive and/or reafferent information may be more useful for establishing a true recalibration between motor output and the distorted visual input than is cognitive information. Therefore, cognitive information may only be prepotent over the other three sources of information for making the type of cognitive compensations required with a reduction of effect measure. Evidence for this hypothesis can be found in Experiment II and in the present experiment where the no movement conditions exhibited visuomotor negative aftereffects that were significantly weaker than for any other experimental conditions. The no movement conditions, of course, did not have the type of cognitive information hypothesized to be present in Experiment III, but any information that may have been available for these groups must certainly have been cognitive in nature.

In summary, then, for the reduction of effect measure, the two gradual inversion groups exhibited significantly greater amounts and speed of visuomotor adaptation than the two immediate inversion groups, with the gradual inversion, active movement condition being the strongest. These results were thought to indicate support for the major assumption of the "information hypothesis" view of visuomotor adaptation (Welch, 1978, p. 24) and the research findings of other investigators (Uhlarik, 1973; Webster, 1969). With regard to the measure of visuomotor negative aftereffect, the two active movement conditions showed greater and more rapid visuomotor adaptation than did the two no movement conditions with, again, visuomotor adaptation being more rapid and complete in the gradual inversion, active movement condition. This was thought to be a result of the greater opportunity for visuomotor recalibration provided by the enhanced proprioceptive feedback and error-corrective feedback from active movement. This finding supports the research efforts of several previous investigators (Coren, 1966; Kravitz & Wallach, 1966; Mather & Lackner, 1975, 1981; Melamed et al., 1973; Moulden, 1971; Wallace, 1975, 1980; Wallace & Fisher, 1979, 1982, 1984; Wallace & Garrett, 1973, 1975; Wallace & Hoyenga, 1981; Welch, 1969, 1971; Welch & Rhoades, 1969).

Implications for Future Research

Of paramount importance for future investigations of perceptual adaptation is the issue, again, of the role of cognition in visuomotor adaptation. As with Experiment II, the results of this experiment indicated that a form of cognitive adaptation does occur to optical distortions. This was obvious from the significant visuomotor adaptation found in the two no movement conditions and, especially, from the strength of the visuomotor reduction of effect found with gradual inversion, no movement. Since the only form of apparent information available with no movement was cognitive, this information must be adequate alone to produce visuomotor adaptation. A real question arises as to why a significant visuomotor negative aftereffect occurred with no movement. Obviously, proprioceptive and error-corrective feedback enhances visuomotor adaptation for both the visuomotor reduction of effect measure and the visuomotor negative aftereffect measure, but particularly so for the visuomotor negative aftereffect measure. Still, it is not immediately obvious why a negative aftereffect was present when only cognitive information was available regarding the nature of the visual distortion. In the present investigation, the significant visuomotor negative aftereffect present in the no movement conditions might possibly have been due to a rapid recalibration of distorted visual input with motor ouput during performance of target pointing taken at the end of the exposure period and immediately following. One means by which this possible explanation could be examined in future research would be to contrast the visuomotor negative aftereffect measures for an experimental condition in which a reduction of effect measure is taken, with an experimental condition in which no reduction of effect measure is taken. Presumably, a strong visuomotor negative aftereffect would not be present in the absence of a reduction of effect measure, if the aforementioned explanation is

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correct. This would be true because no opportunity to recalibrate input and output during performance of the the dependent measure task would be available. This potential experiment would help elucidate the role of cognition in visuomotor adaptation by providing evidence, either positive or negative, regarding the presence of a visuomotor negative aftereffect with cognitive information only.

One additional issue worth examining would be the gradual incremental degrees of inversion that produce the most rapid and complete rates of visuomotor adaptation. Perhaps, even smaller increments than those used in the present experiment would result in more rapid and complete visuomotor adaptation. Concomitant with this issue is the question of the most conducive lengths of exposure time to each angular increment of rotation. In experiment III, exposure time to each increment was limited to one minute. Longer or shorter exposure periods would likely alter the resulting levels of visuomotor adaptation. In addition, it would be of theoretical significance to determine the role of external reinforcements in the shaping of visuomotor adaptation to an optically inverted world. Perhaps, positive reinforcements would produce more rapid rates of visuomotor adaptation than the types of feedback that are normally present in gradual optical inversion. Finally, the positive results for gradual optical inversion over immediate inversion suggest the possibility of gradually shaping visuomotor adaptation to other types of visual rearrangements, such as optical displacement, optical curvature, optical minification, optical magnification, etc.

Practical Implications

All of the practical implications discussed for Experiments I and II also apply for Experiment III. It is especially important to point out that more rapid rates of adaptation to optical inversion would, very likely, speed up the preadaptation process involved in "visual weightlessness training." In addition, visuomotor adaptation to optical inversion also has practical implications for military and airline pilots, since disorienting roll and spin maneuvers are frequently performed by these individuals. In these situations, the pilot's functioning can be seriously impaired. Training under conditions of optical inversion could potentially reduce the disorientation produced in these aerial maneuvers.

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APPENDICES

APPENDIX A: DEFINITIONS OF KEY TERMS

For the purposes of this investigation, the terms will be defined in the following manner:

Concurrent Display

A type of constrained exposure to an optical distortion, where a target may or may nor be present, that involves an uninterrupted view of the moving hand. If a target is provided, arm movements are usually transverse, whereas, if a target is not present, arm movements are usually sagittal in nature (Welch, 1978, p. 16).

Incremental Inversion

One-hundred and eighty degree reinversion of the retinal image accomplished in static, predetermined increments of rotation.

Optical Inversion

One-hundred and eighty degree reinversion of the retinal image, usually accomplished with double convex lenses or amici roof prisms. Put another way, optical inversion refers to left-right reversal and up-down reversal of the retinal image (Dolezal, 1982, p. 19).

Optical Reversal

Left-right horizontal transposition of the retinal image or up-down vertical transposition of the retinal image accomplished via right-angle prisms or mirrors (Dolezal, 1982, p. 19).

Optical Rotation

Dynamic 360-degree circular movement of the retinal image around the Z-axis, accomplished via rotation of a miniature television monitor relative to a video camera.

Optical Rotational Transformations

In the context of this investigation, optical rotational transformations refer to optical rotation.

Perceptual Adaptation

"A semi-permanent change of perception that serves to reduce or eliminate a registered discrepancy between or within sensory modalities" (Welch, 1978, p. 8). "If perceptual adaptation were complete, the world would appear precisely as it did before it was viewed through the distorting device" (Rock, 1966, p. 1).

Perceptual Modifications

The production of discordances between or within sensorimotor systems via some distorting device, optical if in the visual modality (Welch, 1978, p. 8).

Perceptuomotor Adaptation

"A semi-permanent change of perceptuomotor coordination that serves to reduce or eliminate a registered discrepancy between or within sensory modalities or that serves to reduce the errors in behavior induced by this discrepancy" (Welch, 1978, p. 8).

Performatory Adaptation

In the context of this investigation, performatory adaptation is equivalent to perceptuomotor adaptation (Dolezal, 1982).

Proprioception

"The class of sensory information arising from vestibular and kinesthetic stimulation" (Schiffmann, 1982, p. 455). In this investigation, proprioception and body position sense refer the the same sensory stimulation and are meant to be limited to kinesthetic stimulation.

Reafference

"Neural feedback that is dependent on voluntary movement" (Schiffmann, 1982, p. 456). In the visual modality, reafference refers to retinal stimulation from the observation of body movements.

Sensory Rearrangements

In this study, sensory rearrangements refer more broadly to modifications of sensation and perception. This is so because sensory distortions or rearrangements will always have some effect on perception. Therefore, sensory rearrangements and perceptual modifications will be viewed as equivalent.

Terminal Display

A type of constrained exposure to an optical distortion, where a target may or may not be present, that involves viewing the moving hand only at the terminus of an action. If a target is provided, arm movements are usually sagittal, whereas, if a target is not present, arm movements are usually transverse in nature (Welch, 1978, p. 16).

Visual Transpositions

Theoretically, visual transpositions include all optical distortions of the retinal image, but in this investigation, they include only optical inversion, reversal, and rotation.

Visuomotor Adaptation

Visuomotor adaptation refers to the same thing as perceptuomotor adaptation, but only in the visual modality.

Visuomotor Negative Aftereffect

A type of visuomotor adaptation that is due to errors in motor activity (usually reaching) in the direction opposite to the one created by the perceptual distortion after the optical distortion is discontinued (Welch, 1978, p. 7). In the case of optical rotation, a visuomotor negative aftereffect is far more complex and could, theoretically, refer to a form of visuomotor confusion extending beyond simply reaching in the wrong direction for a target.

Visuomotor Reduction of Effect

Visuomotor adaptation via a lessening or reduction of the registered discrepancy during the exposure period. Operationally seen as a reduction in the number of motor errors made on the performance task during exposure to the perceptual distortion.

APPENDIX B: DESIGN SUMMARY

Experiment	Factor	Levels
I	Type of Exposure	Upright, Rotating
IA	Level of Anxiety	Anxious, Neutral, Calm
II	Type of Exposure	Upright, Rotating
II	Type of Arm Movement	Active, Passive with Contours, Passive Without Contours, No Movement
III	Type of Exposure	Upright, Inverted
III	Speed of Inversion	Gradual, Immediate
III	Type of Arm Movement	Active, No Movement

APPENDIX C: LIKERT SCALE

1 and 2=Very Calm

3 and 4=Somewhat Calm

5 and 6=Neutral Feelings

7 and 8=Somewhat Anxious

9 and 10=Very Anxious

APPENDIX D: "ROTATOR PROGRAM"

```
100 REM**********INITIALIZATION**********

110 BN="X": REM NUMBER OF BLOCKS

120 TN="Y": REM NUMBER OF TRIALS

130 ID=10:  REM INTERTRIAL DELAY DELAY

140 BD=5:   REM BELL DELAY

145 DIM RA$(6)

150 RA$(1)= "5 WHEEL"

160 RA$(2)= "8 SQUARE"

170 RA$(3)= "G TRIANGLE"

180 RA$(4)= "L PLUS"

190 RA$(5)= "C RECTANGLE"

200 RA$(6)= "M CIRCLE"

210 REM**********DIM**********

220 DIM L$(TN,BN)

230 DIM E(TN,BN)

240 DIM S(TN,BN)

250 DIM A$(TN,BN)
```

```
260 DIM B$(TN,BN)

280 REM**********MAIN PROGRAM**********

290 INPUT "GROUP ID"; GN$

300 INPUT "SUBJECT ID"; SN$

305 INPUT "EXPERIMENTER ID"; EN$

310 FOR IZ= 1 TO BN

320 FOR I= 1 to TN

330 CLS

340 PRINT,I

350 L$(I,IZ)=RA$(RND(6))

360 PRINT L$(I,IZ)

365 Z$=INKEY$

366 IF Z$="A" THEN GOTO 370

367 GOTO 365

370 TIMER=0

380 A$(I,IZ)=INKEY$

390 IF A$(I,IZ)="" GOTO 380

400 E(I,IZ)=TIMER
```

```
410 TE=TIMER

420 IF TIMER< TE+BD GOTO 420

430 SOUND 100, 5

440 TIMER=0

450 B$(I,IZ)=INKEY$

470 IF B$(I,IZ)=A$(I,IZ) GOTO 490

480 GOTO 450

490 S(I,IZ)=TIMER

500 SOUND 200, 10

530 ET=ET+E(I,IZ)

540 ST=ST+S(I,IZ)

550 NEXT I

560 BET(IZ)=ET: ET=0

570 BST(IZ)=ST: ST=0

580 NEXT IZ

590 REM**********PRINTING INSTRUCTIONS**********

600 PRINT #-2, "GROUP ID", GN$

610 PRINT #-2, "SUBJECT ID", SN$
```

```
615 PRINT #-2, "EXPERIMENTER ID", EN$

620 FOR IZ=1 to BN

630 PRINT #-2, "BLOCK", IZ

640 FOR I=1 to TN

650 PRINT #-2, "TARGET", L$(I,IZ)

660 PRINT #-2, "EXP RT", E(I,IZ)

670 PRINT #-2, "SUB RT", S(I,IZ)

680 NEXT I

690 PRINT #-2, "EXPERIMENTER TOTAL FOR THIS BLOCK",
BET(IZ)

700 MET=BET(IZ)/TN

710 PRINT #-2, "MEAN EXPERIMENTER TOTAL FOR THIS
BLOCK", MET

720 PRINT #-2, "SUBJECT TOTAL FOR THIS BLOCK", BST(IZ)

730 MST=BST(IZ)/TN

740 PRINT #-2, "MEAN SUBJECT TOTAL FOR THIS BLOCK", MST

750 NEXT IZ

755 INPUT "DO YOU NEED ANOTHER PRINTOUT"; PO$

756 IF PO$="YES" GOTO 600
```

```
757 IF PO$="NO" GOTO 760

760 END
```