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Attention and Prism Adaptation

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For both lateral displacement and rotation of the visual field, visual adaptation was reduced when subjects were required to perform a secondary cognitive task simultaneously with the primary exposure task of walking about hallways. Interference appeared to be independent of walking rate and occurred when the cognitive task was either mental imagery or mental arithmetic. A tentative model is presented which assumes that the direction of guidance between sensorimotor systems (e.g., eye–head and hand–head) is set by limited capacity higher level processes (attention) that differentiate the set of sensorimotor subsystems into guiding and guided subsets in accordance with a task's particular demand structure. Perceptual discordance and consequential adaptive recalibration of afferent functions are localized in the nonguiding system(s). If limited central-processing capacity is required to perform a secondary cognitive task simultaneously with the exposure task, directional linkage between discordant systems is degraded and adaptive recalibration reduced.

Interest in the behavioral effects of optical distortions began around the turn of the century (e.g., Helmholtz, 1925; Stratton, 1896) and reached a peak in the 1960s (e.g., Harris, 1965; Hay & Pick, 1966; Held, 1961; Kohler, 1951/1964; Rock 1966). The present nadir of such research has

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occurred not only because much of the initial curiosity about perceptual plasticity and perceptual-motor coordination was satisfied by over a decade of intense work (for a review, see Welch, 1978), but also because the theoretical precepts did not readily fit the emerging information theory and information-processing approach to human perception and performance (e.g., Broadbent, 1958; Garner, 1962; Neisser, 1967; Simon, 1968). Still, the prism adaptation paradigm offers unique opportunities for investigating perceptual and perceptual-motor learning. Adaptation to prisms involves "coordination" of perceptual and motor processes, "realignments" among perceptual and motor spaces, without fundamental changes in the nature of the separate processes and structures. Thus, the paradigm allows investigation of the natural limits (plasticity) of extant processes, without the confounding introduced when fundamentally new component processes must be acquired. The present study suggests a reapproachment between the prism-adaptation paradigm and information-processing approaches to perception and performance by attempting to apply information-processing concepts (especially attentional theory) to some of the problems in prism adaptation. The following introductory remarks are somewhat more extensive than is usual because we hope to reach the larger audience interested in adaptive systems in robotics (e.g., Raibert, 1978), artificial intelligence (e.g., Anderson, 1983; Grossberg, 1980), and physiology (e.g., Forssberg & Nashner, 1982; Robinson, 1982).

When people are required to interact with the world viewed through distorting prisms which, for example, laterally displace or rotate (tilt) the visual field in the frontal-parallel plane, they show obvious initial difficulty. For instance, in reaching for objects subjects miss the intended target and they tend to be hesitant and stumbling when walking. However, these obvious errors soon disappear, usually within a few minutes, and the person appears to have adapted to the distorted visual stimulation. Experimental tests (e.g., Hay & Pick, 1966; Redding, 1978) have demonstrated that such behavioral change is mediated, at least in part, by perceptual change in both the visual (eye–head) system and the proprioceptive system (the position sense of body parts such as the hand and arm).[1]

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[1] No preference is implied between "inflow" and "outflow" theories of proprioception. Indeed, both kinds of information may be necessary for the position sense (e.g., Goodwin, McCloskey, & Matthews, 1972; Matthews, 1977; McCloskey, 1981). Also, "proprioceptive adaptation" is used to mean adaptation outside the visual (eye–head) system, adaptation without phenomenal consequences for vision, and does not necessarily imply fundamental different mechanisms (cf. Harris, 1980). For example, there is no evidence that visual adaptation to displacement is ever anything other than change in registered eye position (e.g., Crawshaw & Craske, 1974), similar to proprioceptive change in hand position, and the difference between the two kinds of adaptation may be simply in locus. A similar

The salient methodological features of these tests are as follows: (1) Responses required by the tests are different from behavior required during exposure and thus the tests are uncontaminated by any compensatory motor learning that may have occurred during exposure. (2) Tests are performed without the prisms and there is no reason to expect contamination by any corrective rule consciously acquired during exposure. (3) The direction of change in test performance (pre- to postexposure) which would compensate for the distortion can be specified beforehand and thus adaptive change can be identified. (4) Specific tests can be constructed which involve only a single perceptual system and thus are exclusively sensitive to different loci of perceptual change. Three specific tests are commonly used in studies of adaptation to the optical transforms of displacement and rotation: tests which are sensitive to changes in the visual system, in a proprioceptive system, and to changes in both kinds of systems.

In studies of displacement adaptation, the interest is in change in egocentric direction. In visual tests, subjects remotely adjust a target to appear straight ahead of the nose in an otherwise homogeneous field. This test is logically sensitive only to change in the eye–head system and the expected (adaptive) pre- to postperformance difference is in the direction of the displacement. A proprioceptive test requires subjects to point straight ahead of their nose with vision occluded. This test is sensitive to change in proprioceptive systems (e.g., hand-to-head) and the adaptive direction is opposite to the displacement. A test for visual and/or proprioceptive adaptation requires subjects to point at a visual target with their unseen hand. This test is sensitive to any changes in the eye-to-hand systems since it involves coordination of visual and proprioceptive systems and the adaptive direction is opposite to the displacement.

In studies of tilt adaptation, the same logic is applied to construct tests of visual and proprioceptive change in egocentric orientation. In visual tests, subjects remotely adjust a short line in an otherwise homogeneous field to appear vertically aligned with the head. Proprioceptive tests require subjects to use their hand to adjust a rod to feel aligned with their head when vision is occluded. A measure of total adaptive change is obtained by requiring subjects to use their unseen hand to adjust a rod to match the orientation of a seen line.

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account of tilt adaptation is problematical since it is unclear whether the eye is capable of torsional movement of a magnitude commensurate with tilt aftereffects (for reviews, see Howard, 1982, and Howard & Templeton, 1966), and visual adaptation to tilt may be mediated by a "true" visual change in retinal local sign. Current theory does not permit a test between these two possible accounts of visual change and the present research is neutral with respect to this problem.

Visual and proprioceptive adaptation should be viewed as complementary rather than opposing processes. Both kinds of adaptation usually occur, in varying amounts, and each represents a part of the total adaptive response. In both tilt and displacement adaptation, the simple sum of visual and proprioceptive measures usually equals the total amount of adaptation as measured by the eye–hand coordination test (e.g., Redding, 1978; Redding & Wallace, 1976, 1978; Templeton, Howard, & Wilkinson, 1974; Wallace, 1977; Wallace & Redding, 1979; Welch, 1974; Welch, Choe, & Heinrich, 1974; Wilkinson, 1971). Thus, adaptation seems to consist largely of local recalibration of perceptual inputs (Howard, 1971, 1982). Adaptive changes at higher levels such as the coordinative mapping of perceptual inputs onto motor systems (e.g., Hardt, Held & Steinbach, 1971) would predict greater adaptive change in eye–hand coordination than the sum of the visual and proprioceptive measures because these latter tests are insensitive to changes between systems.

Now, we come to the crux of the present problem: We know that adaptive change can occur at multiple loci, but we do not understand what determines the locus of perceptual recalibration and the relative magnitude of local changes. A perplexing variety of exposure conditions are known to produce more of one or another kind of adaptation. For example, when subjects are required to walk about hallways wearing prisms (hallway exposure) adaptation is largely visual, especially when sight of the body is restricted (e.g., Redding, 1978; Redding & Wallace, 1976), but when subjects view their stationary feet (i.e., foot exposure) adaptation is entirely visual (Craske, 1967; Craske & Crawshaw, 1974, 1978). On the other hand, if subjects are allowed a continuous view of their reaching hand while wearing prisms (concurrent exposure) adaptation tends to be more proprioceptive than visual (e.g., Harris, 1963; Kalil & Freedman, 1966), but when sight of the hand is allowed only at the end of the reaching movement (terminal exposure) adaptation tends to be more visual than proprioceptive (e.g., Uhlarik & Canon, 1971).

One explanation of the variable locus of adaptation implicates selective attention: Canon (1966, 1970, 1971) has proposed that when two spatial modalities provide discrepant information about a distal object, it is the unattended modality that becomes recalibrated. For example, Canon (1970) demonstrated that if attention was directed to one modality by instructing the subject to track with the right hand either the (prismatically displaced) visual or (pseudophonically displaced) auditory target during exposure, the conflict between visual and auditory location was resolved by recalibration of the other, unattended modality. More recently, Kelso, Cook, Olson, and Epstein (1975) found that if attention is directed to the proprioceptive modality by specifying the left hand as the target for a right-hand pointing response during prism exposure, adaptation was entirely restricted to the visual modality, but when attention was directed to visual targets only proprioceptive adaptation occurred. In a similar vein, Uhlarik and Canon (1971) argued that visual adaptation is greater in terminal exposure conditions because the subject's attention is mainly directed to the proprioceptive information from the arm during its unseen excursion. In contrast, proprioceptive adaptation is greater with concurrent exposure because attention is presumably concentrated on the available visual input. These observations can be summarized by saying that adaptation tends to occur in the unattended modality.

In this context, however, the term "attention" is purely descriptive rather than explanatory, and the essential idea is better expressed in terms of the exposure task's particular demand structure which determines the guided and guiding subsets of the total set of sensorimotor subsystems (see also Redding, 1979a). This is most clearly true of Canon's theoretical position. Perception is assumed to be based on efferent signals evoked by association with afferent stimulation (see Festinger, Burnham, Ono, & Bamber, 1967; Taylor, 1962). Adaptation occurs in the guided system ("unattended" modality) because the afference from this source is discrepant with the efference originating in the guiding system ("attended" modality). There is no such efference–afference discrepancy for the guiding modality and thus no adaptation. The Kelso et al. theoretical position can also be better interpreted in similar terms. Perception is assumed to be based on the consensual significance of simultaneous afferent sources (see also Epstein & Morgan-Paap, 1974). In the case of conflict between afferent sources, resolution is achieved by recalibration of the guided system ("subordinate" source) to agree with the guiding system ("situationally dominant" source).

It seems reasonable, therefore, to believe that the structure of the exposure task (including instructions) determines the guiding modality, whose function *must* remain unchanged for successful task performance (Redding, 1979b). Adaptation can then only occur in the modality that is not required by the exposure task (cf. Hamilton, 1964; Howard & Templeton, 1966, p. 380). Proprioceptive adaptation occurs with concurrent exposure because the available visual information is used to guide the hand to the target, but visual adaptation occurs with terminal exposure because sight of the hand is largely precluded and mainly proprioceptive information must be used to perform the reaching task. When a subject inspects his stationary foot the target location for the eye is specified by the felt location of the foot, proprioceptive information is used to guide eye movements, and adaptation is entirely visual. The selective effect of the more complex hallway exposure is more difficult to explain in these terms. However, extensive observation of subjects suggests that much behavior in this situation is under nonvisual (auditory or proprioceptive) guidance. Subjects behave as if they were walking in the dark. They do not first look at an obstacle and then avoid it. Rather, they first bump into the obstacle and then they may look at it, but more likely they will maneuver around it by "feel." There is a strong tendency to guide themselves by touching walls. Subjects engage in little spontaneous visual exploration and this little seems more to examine something first heard or touched than for purposes of visual guidance. Thus, visual exploration in hallways seems to be largely under nonvisual control, and this may explain the fact that adaptation in this exposure condition is usually visual in nature.

We will develop this directionality of guidance hypothesis more fully in our discussion, but for the moment we simply wish to establish that there is a viable alternative to the directed attention hypothesis. Current usage of the term "attention" in the prism-adaptation literature only creates an illusion of explanation and does not add any explanatory or predictive power beyond that which might be achieved by a careful delineation of the task structure specifying the direction of guidance.

The present study was designated to investigate the possibility of more substantive attentional effects in prism adaptation. Attention is conceptualized as the regulation of a limited-capacity, central-processing mechanism that comes into play when nonhabitual behavior is required (e.g., Posner & Snyder, 1975; Schneider & Shiffrin, 1977). Available processing capacity may be focused on a particular task, but when attention must be divided between simultaneous tasks, processing demands may exceed the available capacity with resultant interference. If attention is required for adaptation, having subjects perform a secondary cognitive task simultaneously with the primary exposure task should reduce the level of adaptation. Failure to obtain such an interference effect might mean that adaptation is an "automatic" process, not involving the limited-capacity mechanism. (For recent critiques of attentional theory, see Allport, 1980, and Kahneman & Treisman, 1983.)

Of course, the possible nature of an interface between attentional and adaptive processes remains to be specified. For example, in our discussion we develop the idea that a limited-capacity central mechanism is involved in establishing and maintaining the direction of guidance required by the exposure task. Initially, however, we were concerned simply with determining whether adaptation is a limited-capacity process and, if so, what is the nature of the dual-task interference.

In an effort to produce the simplest, most direct test of the attentional hypothesis, we restricted the locus of perceptual change to the visual system by using the hallways exposure task which is known to produce largely visual adaptation.[2] Moreover, it was hoped that using such a highly practiced ("automated") behavior as walking would avoid the ambiguity of interpretation which could arise if the secondary task directly interfered with the exposure task (but see Experiments 3 and 4). To increase the generality of the test, we investigated both tilt and displacement adaptation. Almost certainly, these two kinds of adaptation involve separate and independent mechanisms (Redding, 1973b, 1975b), but except for parametric differences, they appear to be similar processes (Redding, 1973a, 1975a) and should be similarly affected by attentional manipulations.

GENERAL METHOD

All of the experiments employed the same kind of between-subjects design with all subjects receiving the primary (exposure) task of walking back and forth along hallways, but independent groups were subjected to the presence or absence of an optical transform (tilt or displacement) combined with the presence or absence of a secondary (cognitive) task. Adaptation to 30° clockwise (CW) tilt and 17.1° (30 diopters) rightward (R) lateral displacement was investigated in separate experiments. Exposure was right-eye monocular and only the exposed eye was tested.[3] Subjects were instructed to perform the primary task without looking at their hands or feet and no subject was observed to violate this prohibition. Moreover, sight of any part of the body was largely precluded by the reduced visual fields afforded by the prism headsets, approximately 10 and 20° for tilt and displacement, respectively. (For a more detailed description of the headsets, see Redding, 1978, and Redding & Wallace, 1976.)

The secondary task consisted of cognitive problems given verbally by the accompanying experimenter, and subjects were required to solve the problems as quickly and as accurately as possible, simultaneously with walking along the hallways. In all but Experiment 5, the secondary task was mental addition and the problem set consisted of all unordered pairs of double-digit numbers from 70 to 99, excluding identical pairs. These 435 pairs were randomly ordered prior to the experiments and were presented aloud to subjects in the form of addition questions (e.g., "95 + 79 = ?"). In Experiment 5, some subjects were given clock times, asked to imagine the face of a clock, and required to say whether the hands of the clock for the given time were closer to forming a straight line (e.g., 12:00 and 3:45) or a right angle (e.g., 9:00 and 3:35). Initially, all of the 144 times in 5-min intervals were generated and the angle between hands computed assuming 30° per 5-min interval and 2.5° of hour-hand movement per 5 min. Four clock times were found to be indeterminate and were excluded (i.e., 1:30, 4:30, 7:30, and 10:30). Half of the remaining randomly ordered 140 clock times required an "angle" response and half a "straight" response.

Four dependent measures were obtained: Visual adaptation was assessed by requiring

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[2] Experiments 1 and 2 included tests confirming this assumption, but the effects were exceedingly small and unreliable and in the interest of clarity they are not reported.

[3] Since interocular transfer of adaptation is essentially complete (e.g., Crawshaw & Craske, 1976; Foley & Miyanshi, 1969; Mack & Chitayat, 1970; Quinlan, 1970; Redding, 1973a) there is no reason to believe that monocular exposure affects the nature of adaptation, and this procedure considerably simplifies the apparatus requirements.

subjects to remotely align a visual target to their head, without prisms, and level of adaptation (LA) was expressed as the difference in degrees between pretest and post-test adjustments, with change in the adaptive direction receiving a positive sign. Primary task performance was measured by walking rate in meters per minute, and secondary task performance was measured in terms of the percentage of correctly solved problems and number of problems attempted. Heterogeneity of variance appeared early in the research and unless otherwise indicated Student's *t* statistic with corrected degrees of freedom (Weiner, 1962, p. 28) was used for all significance tests. Finally, all subjects were undergraduate volunteers with reported normal or corrected-to-normal vision (contact lenses only) and right-hand dominant. Additional details of the method are given as needed in the reports of individual experiments.

EXPERIMENTS 1 AND 2: COGNITIVE INTERFERENCE

The first two experiments constituted the basic tests for cognitive interference in tilt and displacement adaptation, respectively. If adaptation involves limited-capacity cognitive mechanisms, then a cognitive task performed simultaneously with the exposure task should produce a lower LA than that produced by the exposure task alone. The design of these experiments also included tests for the effect of the transform on primary and secondary tasks and for the effect of the cognitive task on the exposure task. Except for the different transforms, the same design was used for both experiments.

Method

Procedure. Before and after the exposure period, subjects were required to perform visual alignments which constituted tests for adaptation. In Experiment 1, subjects verbally instructed the experimenter in how to adjust a 2-cm luminous line to appear aligned with the chin-to-center-of-forehead axis in an otherwise dark field. For each test, the line was started once 25° CW and once 25° counterclockwise (CCW) from objective vertical. In Experiment 2, subjects used a switch to "move" a small red light to appear straight ahead of the nose in an otherwise dark field. This apparently moving target was produced by successively illuminating (every 0.25 s) each LED (2 mm diameter) in an arc (5 mm spacing between LED centers) with a radius of 57.2 cm from the viewing aperture, thus providing a resolution of 0.5° visual angle. For each test, the target was started once 10° to the right and once 10° to the left of objective straight ahead. In both experiments, the subject's head was constrained by a face mask mounted on the front of the test box, and two pretests and one post-test were administered. The first pretest was considered practice and LA was computed as the signed difference between the average of the two measures of the second pretest and the average of the two measures of the post-test. The adaptive, positive direction of change was in the direction of the transform (CW or R).

Following the pretests, subjects were fitted with a headset containing prisms set either to transform the visual field or leave it untransformed. Each subject then walked back and forth along a 59-m-long L-shaped hallway for 10 min and the total distance traveled was recorded. Also during hallway exploration, subjects were either required to perform mental arithmetic problems set by the experimenter or no problems were given and verbal interaction with the experimenter was minimized. Performance on each problem was recorded. Following the exposure period, subjects returned to the test room for the post-test. At no time after the headset was first in place were the subjects allowed to view the normal world, except in the dark test box.

Design. All subjects received hallway exposure and pretests and post-tests. In each experiment, factorial combination of transform or no transform, problems or no problems, and order of starting positions in tests produced eight groups of six subjects each, and subjects were alternately assigned to one of these groups as they appeared in the laboratory.

Results and Discussion

Experiment 1: Tilt adaptation. The results for the first experiment are shown in Table 1A. Tilt adaptation was reduced by requiring subjects to perform mental addition compared to no arithmetic, $t(15) = 2.25$, $p < .025$, but not so much as to equal the zero LA obtained with arithmetic but no tilt, $t(20) = 4.09$, $p < .001$. Mental arithmetic reduced walking rate both in the presence of tilt, $t(22) = 5.04$, $p < .001$, and without tilt, $t(22) = 3.89$, $p < .001$, but tilt did not have a significant effect on walking rate either in the presence of arithmetic, $t(22) = 2.06$, or without arithmetic, $t(21) = 0.22$, although there was a tendency for tilt to combine with arithmetic to reduce walking rate. There was also a nonsignificant tendency for tilt to reduce the percentage of problems solved correctly, $t(21) = 2.00$, and the number of problems attempted, $t(21) = 1.13$. Thus, both tilt adaptation and the primary exposure task suffered interference from the cognitive task.

Experiment 2: Displacement adaptation. The results of Experiment 2 are shown in Table 1B. If we consider only the differences in LA and ignore for the moment the substantial negative values, the pattern of results is similar to the first experiment. Displacement adaptation was reduced by mental arithmetic compared to no arithmetic, $t(22) = 1.73$, $p < .05$, so much so as not to be significantly greater than that obtained with arithmetic and no displacement, $t(20) = 0.85$. However, adaptation for the displacement and arithmetic group was still greater than that obtained with no displacement and no arithmetic, $t(20) = 2.13$, $p < .025$. Mental arithmetic reduced walking rate both in the presence of displacement, $t(20) = 5.62$, $p < .001$, and without displacement, $t(21) = 3.56$, $p < .005$, and displacement reduced walking rate in the presence of arithmetic, $t(21) = 2.12$, $p < .025$, but not without arithmetic, $t(22) = 0.16$. Subjects receiving displacement tended to solve slightly more problems correctly, but again the difference was not significant, two tailed $t(22) = 0.66$, and neither was the difference in number of problems attempted significant, $t(22) = 1.22$. Thus, as in Experiment 1, adaptation and the primary task both suffered interference from the cognitive task, but in addition displacement seems to have had a further significant interference effect on walking rate.

TABLE 1
Results for Optical Tilt (A, Experiment 1) and Optical Displacement (B, Experiment 2)

	A. Tilt			
	30°		0°	
Measure	No arithmetic	Arithmetic	Arithmetic	No arithmetic
Level of adaptation	4.71	2.21	.00	−.21
	(2.25)	(.95)	(.71)	(.64)
Walking rate	49.3	31.4	38.3	50.0
	(5.5)	(5.6)	(4.9)	(4.5)
Percentage correct	—	76.2	84.3	—
		(7.1)	(5.4)	
Number of problems	—	51.3	59.0	—
		(9.7)	(11.4)	
	B. Displacement			
	17.1°		0°	
Measure	No arithmetic	Arithmetic	Arithmetic	No arithmetic
Level of adaptation	1.46	−.94	−2.46	−3.63
	(2.05)	(2.25)	(3.22)	(1.61)
Walking rate	56.8	31.0	39.9	58.8
	(8.2)	(5.9)	(7.1)	(9.3)
Percentage correct	—	82.2	79.6	—
		(6.2)	(6.0)	
Number of problems	—	61.7	51.2	—
		(16.5)	(9.4)	

Note. Mean level of adaptation (degrees), walking rate (m/min), number of problems attempted, and percentage correct (where problems were received) for four independent groups receiving combinations of arithmetic problems or no problems with the presence, or in the absence, of an optical distortion. The 95% confidence limits for each mean are shown in parentheses.

Although it does not compromise the aforementioned conclusions about interference effects, the negative (leftward) bias is puzzling. One possibility is that this bias may be due to the effects of deviation (phoria) of the occluded eye on visual location. Ono and Weber (1981) have demonstrated that errors in visual location with monocular viewing are correlated with the kind and degree of individual subjects' phoria in the occluded eye and that such phoria-induced error can be reduced in the same way as people adapt to prism-induced error. Since most people are exophoric (temporal deviation) for a stimulus at reaching distances similar to those used in the present tests (see also Ono & Gonda, 1978), the occluded left eye may have produced, on the average, a leftward phoric displacement which would have reduced the rightward prism displacement. Thus, the effective displacement may have been considerably less than the actual prism displacement, with consequential small amounts of prism adaptation. The leftward shift found with no prism displacement may reflect adaptation to the phoric displacement. Phoric displacement is an uncontrolled variable and may have contributed to large variability in the present experiment; however, there is no reason to believe it was seriously confounded with the arithmetic task. Thus, it seems reasonable to conclude that adaptation does suffer interference from the arithmetic task. There is even the suggestion that adaptation to phoric displacement may be subject to similar interference effects since the leftward shifts in visual location without prism displacement were numerically greater when the arithmetic task was not required. Unfortunately, this difference was not significant, two tailed $t(16) = 0.71$, and no definite conclusions can be drawn.

EXPERIMENTS 3 AND 4: WALKING RATE CONTROLS

The first two experiments demonstrated cognitive interference with displacement and tilt adaptation, but the nature of such interference remains uncertain. The cognitive task might interfere peripherally with information pickup rather than centrally with information processing. For example, since LA and walking rate tended to be positively correlated, reduced adaptation might have arisen because the arithmetic task decreased walking and experience with the distorted world rather than because the task preempted the central processing capacity necessary for adaptive recalibration. Experiments 3 and 4 were designed to test this hypothesis for tilt and displacement adaptation, respectively. The strategy in these experiments was to attempt to equate walking rates by differential instructions to arithmetic and no arithmetic groups, and then to see if interference remained. Also, Experiment 4 employed a test apparatus which had previously been found not to introduce a negative bias in displacement adaptation (e.g., see Redding & Wallace, 1976).

Method

In each experiment, all subjects received a transform (tilt or displacement). Factorial combination of problems or no problems with order of starting positions in test produced four groups of seven subjects each in Experiment 3 and eight subjects each in Experiment 4. Subjects receiving problems were instructed to walk as fast as possible, while subjects who did not receive problems were told to walk slowly. In Experiment 4, all tests were conducted on an open table in a room completely dark except for the test target. Subjects verbally instructed the Experimenter in adjusting a luminous dot (0.25 cm diameter) to appear straight ahead of the nose. The target dot was at eye level and moved along an arc at a constant distance (1.22 m) from the subject. In all other respects the method was similar to that of the first two experiments.

Results and Discussion

Experiment 3: Tilt adaptation. Results for Experiment 3 are shown in Table 2A. Walking rate instructions were successful in equating performance on the exposure task, two tailed $t(24) = 0.23$, and performance on the problems was comparable to that in the previous experiments. Nevertheless, substantial interference with adaptation remained, $t(19) = 3.94$, $p < .001$. These results exclude the possibility that interference with tilt adaptation arises indirectly from gross differences in exploratory behavior and support the idea that the cognitive task directly interferes with the adaptation process.

Experiment 4: Displacement adaptation. Table 2B shows similar results for Experiment 4. Interference with displacement adaptation remained, $t(28) = 1.89$, $p < .05$, even though there was no significant difference in walking rate between groups, two tailed $t(28) = 1.22$. Thus, for both kinds of adaptation, interference from the cognitive task cannot be attributed to gross differences in exploratory behavior.[4]

The negative bias found in Experiment 2 was absent in Experiment 4. Adaptation for the arithmetic group was still greater than zero (95 percent confidence limits). The reason for this difference between experiments remains uncertain, but one possibility is that it was due to the different distances to the test target. On the average, people tend to be more esophoric (nasal deviation) with greater viewing distances (Ono & Gonda, 1978). Thus, in the present experiment the direction of phoric displacement and adaptation would have been the same as that for prism displacement and adaptation. Still, there is no reason to believe that individual phorias were confounded with the cognitive task.

EXPERIMENT 5: IMAGERY CONTROL

Another "peripheral" hypothesis is that mental arithmetic interferes with the perceptual processing of information rather than with the central regulation of processing. More specifically, it may be that mental imagery involves some of the same mechanisms as does perception (e.g., Segal & Fusella, 1970), and introspection suggests that the mental arithmetic task involves a certain amount of mental imagery (see also Luria, 1970). Therefore, mental arithmetic might partially preempt the perceptual mechanisms providing input to the adaptation process, rather than diverting central control from perceptual processing. Experiment 5 was designed to provide a test of this hypothesis for tilt adaptation. The pre-

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[4] Further evidence that level of adaptation is independent of walking rate comes from examination of the correlation between these two variables for each of the eight groups receiving an optical transform in the first four experiments. Spearman rank correlation coefficients (Siegel, 1956) ranged from $-.29$ to $.43$, but none were significantly different from zero ($p < .05$) and the average coefficient was effectively zero ($-.08$).

TABLE 2
Results for 30° Optical Tilt (A, Experiment 3) and 17.1° Optical Displacement (B, Experiment 4)

	A. Tilt		B. Displacement	
Measure	No arithmetic	Arithmetic	No arithmetic	Arithmetic
Level of adaptation	3.80 (1.43)	1.64 (.72)	4.64 (.97)	3.16 (1.20)
Walking rate	45.7 (3.3)	47.3 (4.7)	42.2 (6.1)	46.8 (4.6)
Percentage correct	—	79.4 (8.5)	—	77.1 (4.2)
Number of problems	—	50.5 (8.8)	—	58.9 (7.9)

Note. Mean level of adaptation (degrees), walking rate (m/min), number of problems attempted, and percentage correct (where problems were received) for two independent groups receiving arithmetic problems or no problems in the presence of an optical distortion. The 95% confidence limits for each mean are shown in parentheses.

viously described clock task was introduced in this experiment. Since this clock task clearly involves a large imagery component, one could reasonably expect greater interference from this task if interference were due to the mental imagery component of mental arithmetic. Also, a new apparatus which gave the subject remote control over the test line was introduced in this experiment.

Method

All subjects received optical tilt, and factorial combination of arithmetic problems, imagery (clock) problems, or no problems with order of starting positions in test produced six groups of 12 subjects each. As in Experiments 3 and 4, subjects receiving problems were told to walk rapidly, while subjects not receiving problems were told to walk slowly. Movement of the test line was motorized and subjects were provided with a switch for remote control of the line. In all other respects the method was similar to that of the previous experiments.

Results and Discussion

The results of Experiment 5 appear in Table 3. First, it must be noted that despite differential walking rate instructions, performance on the exposure task and LA tended to covary. However, only the largest difference in walking rate between arithmetic and no-arithmetic groups was significant, two tailed $t(45) = 2.02$, $p < .05$, and interference with adaptation persisted in the face of the small and nonsignificant difference in walking rate between arithmetic and imagery groups, two tailed $t(46) = 0.83$. Thus, differences in walking rate remain an unlikely cause of interference with adaptation.

Compared with LA for the no-problems group, interference appeared for both the arithmetic group, $t(44) = 2.27$, $p < .025$, and the imagery group, $t(38) = 2.03$, $p < .025$. More importantly, since LA was not significantly different for arithmetic and imagery groups, two tailed $t(43) = 0.43$, interference was not greater and, indeed, was numerically less for

TABLE 3
Results for Experiment 5

Measure	Tilt No problems	 Arithmetic problems	 Imagery problems
Level of adaptation	3.61	1.97	2.22
	(1.16)	(.96)	(.73)
Walking rate	46.1	41.0	43.9
	(4.0)	(3.4)	(3.8)
Percentage correct	—	76.9	71.6
		(5.8)	(2.8)
Number of problems	—	52.4	88.7
		(7.0)	(8.6)

Note. Mean level of adaptation (degrees), walking rate (m/min), number of problems attempted, and percentage correct (where problems were received) for three independent groups receiving arithmetic, imagery, or no problems in the presence of 30° optical tilt. The 95% confidence limits for each mean are shown in parentheses.

the imagery task. This small reversal in magnitude of interference from that predicted by the peripheral hypothesis occurred even though the imagery task was slightly, but not significantly, more difficult than the arithmetic task in terms of percentage correct, two tailed $t(33) = 1.69$, and produced far more "interruptions" of primary processing in terms of number of problems attempted, two tailed $t(44) = 6.79$, $p < .001$.[5] Thus, mental imagery failed to produce more interference than mental arithmetic despite the fact that imagery problems were at least as difficult as arithmetic problems. These results support the conclusion that interference with adaptation arises not from the peripheral effect of imagery but rather from the demand on central processing capacity.

EXPERIMENT 6: EXPOSURE TIME

The fact that some adaptation occurred in the preceding experiments even in the presence of a cognitive task suggests that the secondary task slows but does not preempt the adaptation process. The last experiment was designed to test this hypothesis by measuring adaptation as a function of exposure time for groups receiving or not receiving arithmetic problems during the hallway exposure to optical displacement.

Experiment 6 also employed a test apparatus and procedure which provided a test for another hypothesis about the negative bias in Experiment 2. The absence of a bias in Experiment 4 suggests that it arose from exophoria at short viewing distances, but it is also possible that the

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[5] Reports from subjects suggested that the difficulty of the clock problems was not fully appreciated. For example, many subjects failed to consider the small movements of the hour hand in making their judgments. In a student project at Illinois State University, Edward Coleman and Susan Carlisle replicated Experiment 5, attempting to make certain that the subjects understood and appreciated the difficulty of the problems. Results were essentially the same, except that the imagery task produced a significantly smaller percentage correct (73.0) than did the arithmetic task (82.6), two tailed $t(37) = 3.12$, $p < .01$.

bias arose from exophoric adaptation *during* the visual location tests, especially the post-tests. Wallace has shown that prism adaptation can occur under conditions where the subject directly controls the alignment of a target to straight ahead in an otherwise dark field (Wallace, Melamed, & Cohen, 1973; Wallace, Melamed, & Kaplan, 1973). Under these conditions, the prismatically displaced target is the only available stimulus that the subject can relate to his own egocentric localization, presumably the target becomes an extension of the subject's hand that is controlling its position, and the situation is a kind of terminal exposure condition. To test this hypothesis, the pretest and post-test target in the present experiment was presented at a short viewing distance, but in a homogeneously lighted field and the subject only indirectly controlled target movement by verbal instructions to the experimenter. These conditions should eliminate any tendency for the localization tests to be treated as a condition of terminal exposure to exophoric displacement and the negative bias should not appear.

Method

All subjects received optical displacement, and factorial combination of arithmetic problems or no problems with order of starting positions in test produced four groups of eight subjects each. As in the previous three experiments, subjects receiving problems were told to walk rapidly, while subjects not receiving problems were told to walk slowly. The test apparatus was similar to that used by Wallace and Redding (1979). Subjects viewed a vertical target (0.2 × 8 cm at a viewing distance of 60 cm) moving laterally across their visual field at eye level and against an illuminated but homogeneous background. When the experimenter moved this target, the subjects simply indicated when the target appeared to be straight ahead of their nose. Before the first 5-min exposure period and after each of the five successive 5-min exposures, a total of 10 test trials were given, 5 with the target starting at randomly determined positions in the left half of the subject's visual field and 5 starting with the target randomly positioned in the right half of the visual field. The average of the 10 pretest measures was taken as the baseline for evaluating change in visual location as measured by the average of the post-test values following each exposure period. In most other respects, the method was similar to that of the previous experiments.[6]

Results and Discussion

The heterogeneity of variance problems did not appear in this experiment and the data were evaluated using analysis of variance. Separate analyses were performed on the data from each of the four dependent variables. Order of starting positions was considered a control variable and the data were combined over this variable. Duncan's multiple range test (Kirk, 1968) was used to evaluate pairwise differences between exposures ($p < .05$).

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[6] Experiment 6 was conducted at Cleveland State University with a different subject population and a different exposure environment. The hallway had only a single short (9.1-m) segment, but was about the same width (1.7 m) as that used in the other experiments.

The results for Experiment 6 are illustrated in Table 4. Mental arithmetic interfered with adaptation, $F(1,30) = 40.46$, $p < .001$, and LA increased over successive exposures, $F(4,120) = 134.21$, $p < .001$, but more slowly for the arithmetic group, $F(4,120) = 7.36$, $p < .001$. The differences in LA between successive pairs of exposures were significant in all instances except the smallest increase between 15 and 20 min for the arithmetic group. The arithmetic group walked more rapidly than did the group not receiving problems, $F(1,30) = 141.35$, $p < .001$, but there was no change in walking rate for either group over successive exposures, $F(4,120) = 1.29$. Performance on the problems increased with successive exposures for percentage correct, $F(4,60) = 5.35$, $p < .001$, and for the number of problems attempted, $F(4,60) = 2.95$, $p < .05$, but the only significant increases were between the first and third exposures for percentage correct and between first and second exposures for number of problems.[7]

Thus, mental arithmetic interfered with adaptation even when walking rate was much greater for the arithmetic group, and adaptation continued to increase after walking rate was constant and after arithmetic performance has reached its maximum in the second exposure period. The main effect of the secondary task seems to be to slow down the adaptive process. These observations are consistent with a central processing mechanism which allocates resources in a graded fashion.

The absence of a negative bias in these data supports the idea that such a bias can arise from exophoric displacement and adaptation during the location tests, but does not preclude the possibility of contributions from exophoric effects during exposure. A critical factor determining the appearance of a negative bias seems to be whether the subject or the experimenter controls test target movement, but viewing distance and illumination of the field may also be important.

GENERAL DISCUSSION

These experiments clearly indicate cognitive involvement in the adaptability of spatial behavior and are consistent with evidence showing "higher level" involvement even in reflexive behavior (e.g., Barr,

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[7] It is interesting to compare these results with those of a previous experiment where a more passive exposure procedure was inadvertantly used. Because of a communication failure in this earlier experiment, the Experimenter placed her arm about the waist of the subjects and consequently constrained their movement in the hall. The total amount of adaptation was lower than in Experiment 6 and failed to increase over successive tests even though the total exposure time (40 min) was greater, but the difference in adaptation between arithmetic (1.55) and no-arithmetic (3.73) groups was about the same. These results suggest that attentional effects are independent of the effects of active vs passive movement. Possibly, the amount of available attentional capacity determines the extent to which a subject exercises the amount of active guidance allowed by the structure of the exposure task.

TABLE 4
Results for Experiment 6

		Exposure time (min)					
Group	Measure	5	10	15	20	25	Mean
No arithmetic	Level of adaptation	2.85 (.56)	3.46 (.53)	4.19 (.63)	5.12 (.79)	5.91 (.90)	4.31 (.65)
	Walking rate	48.9 (1.9)	49.7 (2.3)	49.8 (2.0)	49.0 (1.8)	49.9 (1.7)	49.4 (1.5)
Arithmetic	Level of adaptation	1.28 (.29)	1.72 (.26)	2.34 (.29)	2.62 (.30)	3.28 (.39)	2.25 (.24)
	Walking rate	68.8 (4.7)	66.4 (3.5)	68.1 (2.3)	68.1 (3.8)	66.6 (3.0)	67.6 (2.9)
	Percentage correct	74.1 (7.3)	78.6 (5.2)	81.5 (5.5)	83.1 (5.2)	83.4 (5.6)	80.1 (4.9)
	Number of problems	29.2 (3.4)	31.7 (4.2)	31.5 (4.4)	32.2 (3.7)	31.8 (3.8)	31.3 (3.7)

Note. Mean level of adaptation (degrees) and walking rate (m/min) as a function of exposure time for two independent groups receiving arithmetic or no problems in the presence of 17.1 optical displacement. Percentage correct and number of problems attempted are also shown for the group receiving problems. The 95% confidence limits for each mean are shown in parentheses.

Schultheis, & Robinson, 1976). Moreover, the present results suggest that in prism adaptation such cognitive effects occur in the central regulation of processing rather than in peripheral processing of information from the environment. Prism adaptation requires central processing capacity and is retarded when such limited capacity is diverted to a secondary task. In this sense "attention" is involved in prism adaptation.

We conceive of the perceptual-motor system as composed of a number of separate sensorimotor subsystems, each of which can function independently, but which can also be coordinated by central planning functions. That is, each subsystem has its own efferent and afferent structures and is capable of autonomous function in limited situations, but when two (or more) systems must work together coordinative linkages must be activated. We would further argue that for some well-structured and highly habitual tasks linkage activation is "automatic," but highly variable or unusual tasks require central processing capacity to establish and maintain appropriate linkage between systems. Moreover, these connections between systems are assumed to be unidirectional linkages. That is, a given system cannot simultaneously be guiding and guided by another system. (This directional linkage assumption is critically important for the following discussion of the variable locus of adaptation.) Thus, central processing capacity (i.e., attention) is required for establishing and maintaining the directional linkages between systems required for nonhabitual tasks.

Figure 1 illustrates the idea of coordinative linkage between the visual system (i.e., eye–head) and a proprioceptive system (e.g., hand–

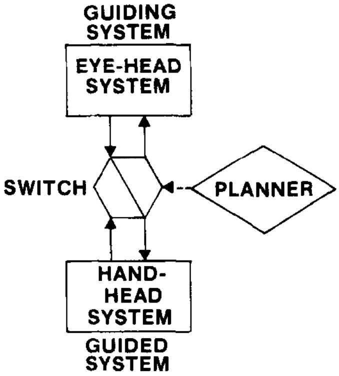

FIG. 1. A model for directional guidance between the visual (eye–head) system and a proprioceptive (e.g., hand–head) system. Solid arrows represent the flow of informational commands between systems and the broken arrow indicates higher level setting of the direction of guidance between the two systems. Note that the "switch" is shown set for visual guidance of the hand. See text for additional explanation.

shoulder or foot–hip). A directional switch set by a central planner determines guided and guiding systems. Each sensorimotor system is assumed to be "grounded" on the trunk such that control signals passed between systems can be read directly as positions in body-centric space. Thus, a position sense code represents the combined inputs from all distal-to-proximal articulations (e.g., fingers, wrist, elbow, and shoulder or eye orbit and neck). Similarly, sensory codes (e.g., visual or tactile) are assumed to "take into account" effector position.

It is important to realize that Fig. 1 is an extreme simplification. Actually, in even the simplest situations it is likely that there are multiple target attributes (e.g., location, orientation, size, and shape) with distributed control along parallel channels, each channel guiding a different aspect of the response of the guided system (cf. Arbib, 1981; Jeannerod & Biguer, 1982). This potentially large processing load can be reduced by automation which removes a switch from planner control such that the task-relevant switch settings are situationally preselected and the required behavior runs off without planner intervention.

To summarize: Sensorimotor systems may function independently or they can be linked by the operation of a higher level planner which responds to overall task structure. Habitual tasks may be performed automatically, but for unusual tasks, requiring continuous feedback monitoring, higher level planning functions must be exercised to establish and maintain appropriate linkage between systems. When a secondary task requiring central processing capacity is imposed, directional linkage may deteriorate and performance may suffer.

The modular "design" of the perceptual-motor system enables strategic flexibility in response to changing and novel task demands. Moreover, the frequent exchange of information in the form of guidance signals between subsystems assures that they are kept in a state of cross calibration with each other. That is, when two systems come to be out of body-centric registration with each other (because of growth, pathology, or natural "drift," e.g., Held & Blossom, 1961; Robinson, 1976), command signals from the guiding system will produce a discordance between expected and achieved postions,[8] prompting a recalibration of afferent functions in the guided system. Note that the recalibration occurs in the guided system regardless of the actual source of the misalignment; however, the frequent alternations in directional guidance required by everyday task demands assures that veridical realignment of systems will be achieved.

It is this natural adaptive capacity of the perceptual-motor system which is revealed so clearly by prism-adaptation studies. Placing a prism in front of the eye creates a misalignment between the visual system and other sensorimotor systems (e.g., auditory and proprioceptive). The locus of adaptive recalibration depends upon the direction of guidance between anomalous and nonanomalous systems. If the task structure permits alternation in the direction of guidance, adaptation will occur in multiple systems, but the simple sum of local changes will equal the total adaptive change in linked systems (e.g., Redding, 1978). Thus, the direction(s) of guidance specified by task structure determines the relative magnitude of local adaptive changes. For instance, when the subject reaches to where he is looking (i.e., visual guidance), adaptation will be localized in the hand–head system, but when she looks to where her hand is (i.e., proprioceptive guidance), adaptation will occur in the eye–head system. When the exposure task involves both directions of guidance (at different times), both kinds of adaptation will occur, the relative magnitude being determined by the proportion of activity spent under each direction of guidance.

The total amount of adaptation depends upon the ability of the subject to establish and maintain the prescribed linkages. A secondary task (imposed either explicitly or implicitly) may weaken linkage between discordant systems. Consequently, performance on the exposure task may suffer and adaptive recalibration will be reduced. A vigilance decrement and failure to maintain linkage between discordant systems over the ex-

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[8] The term "position" is most readily interpreted to mean the perceptual dimension of location and its sensorimotor correspondents, however, a more generic meaning is also intended, including dimensions of orientation, size, and shape. Of course, not all such spatial channels are represented equally well in all sensorimotor systems (e.g., in the auditory system).

posure period may partly account for the limited nature of prism adaptation (Redding, 1981).

Note that the total amount of adaptation can be affected by task structure as well as attentional factors. If the exposure task can be performed without bringing the anomalous system into direct conflict with normal systems (e.g., the intersensory bias paradigm; for a review, see Welch & Warren, 1980), little or no adaptive recalibration will occur. The effectiveness of active over passive movement conditions in producing adaptation (Held & Hein, 1958; for a review, see Welch, 1978) is probably due to the increased likelihood and strength of a directional link between anomalous and normal systems when active movement is required. Thus, attention and task structure are, in principle at least, separable factors.

The concept of distributed processing along parallel and independent channels helps to account for our ability to adapt simultaneously to different optical transforms (Redding, 1973b, 1975b), but it also raises a problem of experimental control; namely, it becomes difficult to be certain that performance of the exposure task requires those channels which are distorted by the prism. The directionality of guidance model of hallway adaptation shown in Fig. 2 illustrates this problem. Visual control of locomotion (i.e., the eye–foot linkage) may not be affected by the prism. There is good evidence (e.g., Fitch, Tuller, & Turvey, 1982; Lee & Thomson, 1982) that walking is automatically guided by optical flow patterns on which the optical transforms used have little effect (beyond that which might be removed by postural adjustments of the head). Consequently, walking during prism exposure may be performed in the normal automatic manner, not requiring central processing capacity, and would not suffer interference from the secondary cognitive task. However, the continuous nature of optical flow is such that accurate loco-

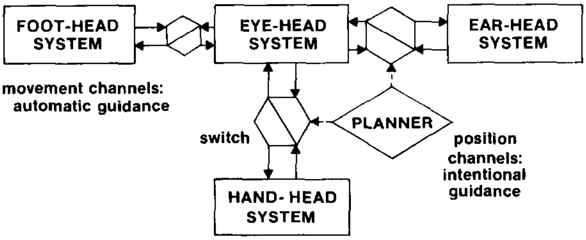

FIG. 2. Directionality of guidance model for hall exposure. Locomotion is automatically guided by undistorted optical flow while intentional guidance, involving discordant positional channels, is subject to interference from cognitive tasks with consequentially less adaptation. Direction linkages between sensorimotor systems are shown set in a manner that would produce visual adaptation, but some tasks would require reversed linkage, producing auditory or proprioceptive adaptation. See text for additional discussion.

motion can be maintained with occasional visual responses to auditory or proprioceptive stimuli. That is, subjects can occasionally direct their eyes to look at, for example, another person speaking (i.e., the ear–eye linkage) or an obstacle they have just bumped into (i.e., the hand–eye linkage). On these occasions, the visual system is the guided system and local recalibration occurs in the eye–head system (i.e., visual adaptation). Such directional linkage of visual and nonvisual systems requires central-processing capacity and when such capacity is not available because it has been allocated to mental arithmetic, intersystem linkage is weakened and adaptation is reduced. Thus, the model predicts visual adaptation under conditions which afford visual exploration responses to nonvisual stimuli (e.g., viewable sound sources), but no adaptation of any kind when only optical flow is available (e.g., walking toward a fixated visual target). Preliminary results from our ongoing research are consistent with these predictions, but much work remains to be done before we can claim a thorough test of the model. For the present we only wish to emphasize the heuristic value of the general model and its ability to provide a theoretically based evaluation of ecologically valid versus experimentally controlled designs.

Finally, we wish to suggest how the model might be extended to account for other manipulations which have been shown to affect the locus of adaptation, particularly those studies which have involved more than a single linkage between two systems (i.e., Canon, 1970; Kelso et al., 1975). In these studies, the instructionally designated target (visual, proprioceptive, or auditory) specifies the guiding system (eye–head, left hand–head, or ear–head) which is linked, in parallel, with both the response system (right hand–head) and the other nonguiding system (eye–head, left hand–head, or ear–head). That is, we assume that if a system is receiving situational input, it will also receive intersystem positional information, even when it is not directly guided in the sense that a response is required. For instance, in the Canon study when subjects tracked the auditory target with their right hand, information about the location of the target may have produced discordance in and recalibration of the nonguiding visual system. Similarly, in the Kelso et al. study when subjects pointed at the visual target, information about target location may have produced discordance and adaptation in the proprioceptive (left hand–head) system. Note that this account entails an intermodality identity assumption (Welch & Warren, 1980): In the absence of strong evidence to the contrary, the perceptual-motor system may assume that coincidental stimuli arise from the same source. The statistical validity of this assumption constrains the problem of mapping multiple stimuli onto a single noetic space and would allow the system to deal separately only with nonsimultaneous stimuli. The perceptual-motor system may, therefore, take coincidental stimuli as an occasion for cross-checking the calibration of its various subsystems.

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