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EFFERENCE AND THE CONSCIOUS EXPERIENCE OF PERCEPTION [1]

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A historical review of past attempts at formulating theories in which efference plays a role in conscious perception is presented. A testable version of such a theory is formulated, and 4 experiments are presented testing implications from this theory. In all of these experiments, conditions in which Ss must learn a new afferent-efferent association are compared with Ss whose physical activity and perceptual experience are very similar but who need not learn a new association between afferent input and relevant efferent output. In all of the experiments significant change in the visual perception of curvature was obtained in the conditions in which the new associations had to be learned. Where no new associations had to be learned, significantly less visual change occurred. The results are consistent with the theoretical position that the efference and efferent readiness activated by visual input helps determine the visual perception of contour.

Historical Introduction

Around the turn of the last century there were a few people who proposed that motor output was essential to the conscious experience of perception. Münsterberg (1899), for example, elaborated the view that incoming, afferent stimulation and outgoing motor innervation were a single, continuous nerve process with no point of separation between them. The motor dis-

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charge, he held, is necessary before any central activity corresponding to perception or consciousness takes place. Montague (1908) stated that "Perceptions are presumed to arise synchronously with the redirection in the central nervous system of afferent currents into efferent channels [p. 128]."

Ultimately, such views fell into disrepute for a variety of reasons. For one thing, these theories arose out of an attempt to understand consciousness and, with the rise of behaviorism, consciousness became less and less a proper subject for study. Thus, for example, Washburn (1916) devoted most of the introduction of her book to attacking Watson and behaviorism and to justifying that the study of consciousness is proper. But this book is one of the last attempts to state and elaborate a motor theory of consciousness.

Another reason for the decline of such theories was that they never were able to cope adequately with the facts. If the conscious experience of perception is occasioned by the motor discharge initiated by the afferent input, then one would expect all perception to be accompanied by motor movements. Münsterberg (1900) explained that we frequently do not perceive something if our attention is directed elsewhere because the appropriate motor responses are suppressed if attention is fixed on something else. He, consequently, stated that the vividness of conscious experience is a direct function of how free the motor pathway is to discharge. This view, however, seems to conflict with the fact that when a movement is well learned and occurs freely and easily, consciousness of the movement decreases. A skilled violin player, for example, is not conscious of all his movements. This led Montague (1908) to propose, contrary to Münsterberg, that consciousness is more vivid if the motor output is interfered with. Washburn (1916) attempted to reconcile all this in the statement that "consciousness accompanies a certain ratio of excitation to inhibition in a motor discharge and if the amount of excitation either sinks below a certain minimum or rises above a certain maximum, consciousness is lessened [p. 25]."

Whichever of the above hypotheses one chooses, however, one must still search for movement correlates of perception. Even if the motor discharge is interfered with somewhat, there would still be some movement. The general absence of obvious movement accompanying conscious perception led to the necessity to postulate the existence of rudimentary or tentative movements. Thus Breese (1899), in discussing the perception of speech, stated:

> The muscles of the vocal cords, throat, and respiratory organs are slightly innervated and adjusted, but the process goes no further. Sometimes, however, the enunciation is complete so far as the adjustment of the muscles of the vocal cords, throat and mouth cavities is concerned. There is a tendency to make these adjustments not only when we hear spoken words, but to make them in response to other stimuli. We are likely to utter the name of any object upon which the attention rests. . . . If, for any reason, the motor apparatus does not respond properly, there is an interruption in the conscious stream [p. 49].

The relationship between the conscious experience of perception and such motor movements, however, remained hypothetical and, to modern psychologists, implausible.

Another probable reason for the demise of these views concerning the importance of motor action for the conscious experience of perception is the unclarity concerning what explanatory power was added by the insistence that motor innervation had to exist for consciousness to exist. Up to the end of the nineteenth century there were many psychologists who accepted Helmholtz's (1962) view that there was a consciousness concerning innervation to the muscles and, as long as this view was held, motor theories of consciousness added something. James (1890), followed by Sherrington (1900), attacked this view successfully, however, and persuaded psychologists and physiologists alike that there was no conscious sense of innervation to the muscles and that afferent input via sense organs was the only input relevant to the conscious experience of perception. Thus, Münsterberg (1899) said:

> The only theory which brings in a really new factor is the theory of innervation feelings. This well-known theory claims that one special group of conscious facts, namely the feelings of effort and impulse, are not sensations and, therefore, not parallel to the sensory excitements, but are activities of consciousness and parallel to the physiological innervation of a central motor path. . . . The psychologist can show (however) that this so-called feeling of effort is merely a group of sensations like other sensations, reproduced joint and muscle sensations which precede the action. . . . If the other sensations are accompaniments of sensory excitements in the brain the feelings of impulse cannot claim an exceptional position [p. 443].

If, as became widely accepted, there was no consciousness of innervation to the muscles and all perception depended upon afferent input, then it became unclear as to the value of a theory that states that innervation to the motor system is necessary for conscious experience.

More recently, however, evidence has accumulated that, in spite of having won the argument, James (1890) and Sherrington (1900) were wrong and that the organism *does* have usable conscious information about innervation to the motor system, that is, about efferent impulses issued from the central nervous system through the motor pathways. Reviews of the issue and of the evidence may be found in Merton (1964) and in Festinger and Canon (1965). Consequently, it may be worthwhile to examine once more the possible validity of some form of theory of the conscious experience of perception which depends in whole or in part on efference activated by afferent input and to see if there are any facts which would strongly argue in the direction of some such view.

Some Observation on Perception of Limb Movement

There are some observations reported in the literature, all of them made incidentally while investigating some other problem, which seem to point in the direction of a strong effect of efference on perception. Perhaps the most interesting of these was reported by Gibson (1933) in connection with an experiment on visual adaptation to curvature. Having noted previously that if *S* wore wedge prism spectacles that made vertical straight lines appear curved, after a while *S* adapted to the curvature so that the vertical lines looked less curved, he set out to explore the mechanism of this visual adaptation. His initial hypothesis was that the adaptation occurred as a result of "conflict between vision and kinesthesis [p. 4]." That is, since the vertical lines looked curved but, if felt would feel straight, this conflict might lead to the adaptation. His *S*s, consequently, each spent about ½ hr. wearing the prism spectacles and looking at and running their fingers along vertical edges such as a meter rule.

The observation of relevance to us here is reported in the section on procedure as follows:

It was discovered, however, that in actual fact the kinaesthetic perception, in so far as it was consciously represented, did *not* conflict with the visual perception. When a visually curved edge such as a meter stick was felt, it was felt *as curved.* This was true as long as the hand was watched while running up and down the edge. If the eyes were closed or turned away, the edge of course felt straight, as it in reality was. This dominance of the visual over the kinesthetic perception was so complete that when subjects were instructed to make a strong effort to dissociate the two, *i.e.* to "feel it straight and see it curved," it was reported either difficult or impossible to do so [pp. 4–5].

This phenomenon reported by Gibson (1933) is clear and compelling and anyone who has a pair of prism spectacles can demonstrate it for himself. It has been tried in our laboratory, again and again. Wearing the spectacles and running one's hand up and down along, say, a door edge or door frame edge, the hand *feels* that it is moving in a curved path. It is not that one thinks the hand is moving in a curve because one sees a curve. The hand actually feels it is moving in a curve in spite of the fact that it actually is moving in a straight path. To say, as Gibson said, that visual perception dominates over kinesthetic perception does not explain the phenomenon. The question still remains as to how vision dominates proprioception so that the hand actually feels that the path of movement is curved.

If one thinks in terms of some theory in which efference affects perception, however, an explanation readily suggests itself. Let us imagine that the conscious perception of the path of movement of a limb is not the organization of informational input from the receptors in that limb, but is rather the organization of the efferent signals issued from the central nervous system *to* that limb. The arm would be felt to move in a curved path if the efferent signals issued through the motor pathways directed the arm to move in a curve. The fact that the arm and hand, because they are maintaining pressure on the straight edge, actually move in a straight line would then be irrelevant to the conscious experience of path of movement. The arm is felt to move as it has been directed to move.

From such a point of view one can understand the dominance of vision over proprioception in this instance. The dominance exists as it does because the visual input, perhaps because of years and years of prior learning, perhaps because of its greater precision, is heavily relied on to activate efferent instructions. If the visual input corresponds to a curve, then the efferent instructions activated by the input direct the arm to move in a curved path and the arm is felt to move that way. If this is true, one would expect to be able to observe some manifestation of the fact that the arm has been directed to move in a curved path and, indeed, one can observe indications of this. Typically, in this situation in which a person sees an actually straight edge as curved and runs his hand up and down along it, the wrist and hand twist somewhat in a manner consistent with directions to move in a curved path.

The view that the conscious perception of the movement of a limb is determined, or at least affected, by the efferent instructions issued from the central nervous system to that limb leads us to expect other observable phenomena. To take a very gross example, let us imagine that, using some drug, one paralyzed a person. We would expect that if this person tried to move, even though he actually did not move because of the paralysis, he would feel that he had moved. I know of no systematic data that have ever been collected in such a situation but an incidental observation by Campbell, Sanderson, and Laverty (1964) tends to support this expectation.

The authors report an experiment in which five *S*s were injected with succinylcholine chloride dihydrate. This is what the authors said about the action of the drug:

> The drug acts so as to break the connection between the motor neurones and the skeletal musculature. . . . During the period in which the drug is active the skeletal musculature is very nearly completely paralyzed. . . . (The drug) has no anesthetic effect. Enquiries made of subjects following the paralysis indicate that they are aware of what is going on around them. . . . [p. 628].

The drug produced a very traumatic experience for *S*s, largely because of the interruption of respiration. The average duration of this respiratory paralysis was about 100 sec. The incidental observation that is of interest to us here is the following:

> The subjects described their movements (during the paralysis) as part of a struggle to get away from the apparatus and to tear off the wires and electrodes. Though in fact their movements were small and poorly controlled the subjects were under the impression they had been making large movements [p. 632].

Surely, it seems difficult to imagine any basis for this phenomenon other than that their conscious experience of movement of their limbs was based on the efferent output to those limbs.

A similar instance, not involving paralysis, was reported by Merton (1964) in connection with experiments to demonstrate that joint receptors rather than muscle receptors carry information concerning the position of a limb. He stated:

> In some recent unpublished experiments, Dr. T. Davies, Mr. A. J. M. Butt and I have used the top joint of the thumb. The advantage of this joint is that the muscles that flex and extend it both lie in the forearm and have long tendons. Hence it is possible with a pneumatic tourniquet around the wrist to make the joint and the skin of the thumb anaesthetic without any effect on the muscles.
>
> This experiment succeeds in making the top joint of the thumb show just the same properties as the eye as regards movements. After an hour to an hour and a half of aschaemia the subject becomes quite insensitive to passive movements of the joint of whatever range or rapidity. Nevertheless, active movements of the joint are made with much the same accuracy as before and, indeed, with much the same angular accuracy as eye movements in the dark. *If the movement is restrained by holding the thumb the subject believes he has moved it just the same* [pp. 393–394, italics ours].

Surely, it seems difficult to imagine any basis for these observations other than that the conscious experience of movement of the limbs, in one case, or the thumb, in the other instance, was based on the efferent output to the motor system.

The Problem of a Motor Theory of Visual Perception

We have seen that there are instances in which the perception of a motor movement seems to be based on efferent output rather than on afferent input. If the discussion were to be confined to the perception of motor movements, there does not seem to be much difficulty in specifying and maintaining an "efference" theory of perception. If, however, we wish to broaden our considerations to include visual perception, we immediately encounter difficulties. Efferent instructions issued to the muscles associated with the eye do not seem to be integral in visual perception. It is difficult to imagine what specific eye movements would be relevant to the perception of brightness and color, in the first place. But even if we ignore brightness and color and think only of the visual perception of shape, pattern, and contour, there are still problems. We do not have to move our eyes along a contour in order to perceive that contour. Even if a steady point of fixation is maintained, we are able to perceive, and distinguish between, straight lines, curved lines, squares, circles, and the like. It is true that under ordinary conditions the eyes are always moving to a small extent, but these tremors, drifts, and small saccadic corrections do not seem to be at all associated with the contour that is perceived. If efference activated by visual input is important in visual perception, something other than actual efferent output from the central nervous system to the extraocular muscles must be involved.

The few who have suggested, or attempted to formulate, a theory of visual perception in terms of efference have, of course, recognized this and have maintained that "readiness" to issue efferent instructions is the basis for visual perception. Thus, Breese (1899), trying to explain the fluctuations obtained when there is binocular rivalry, states: "consciousness arises only when the cortical centers involved are *ready* to discharge toward the periphery [p. 60, italics ours]." He does not, however, attempt to specify what he meant by such a state of readiness.

More recently, Sperry (1952) has also suggested such a view:

> If there be any objectively demonstrable fact about perception that indicates the nature of the neural process involved, it is the following: Insofar as an organism perceives a given object, it is prepared to respond with reference to it. This preparation-to-respond is absent in an organism that has failed to perceive. . . . The presence or absence of adaptive reaction potentialities of this sort, ready to discharge into motor patterns, makes the difference between perceiving and not perceiving [p. 301].

Sperry, however, is no more specific than Breese (1899) about this suggestion. He simply made statements such as ". . . the preparation for response *is* the perception [p. 301]" and ". . . perception is basically an implicit preparation to respond [p. 302]" and urges the possible value of such a theoretical approach.

Very recently, Taylor (1962) proposed a more elaborated theory based on this same kind of idea. On the basis of his evaluation of existing data he came to the conclusion that all visual perception is learned. In facing the question of exactly what it is that the person learns, and how he learns it, Taylor stated that as a result of appropriately reinforced experience the person learns the appropriate motor responses to make to precisely given constellations of stimulus input.

So far, of course, this is not a very radical suggestion. He proceeded, however, to propose that the conscious experience of visual perception is nothing more or less than these learned responses. Specifically, Taylor developed a system in which, over a large number of repeated trials with appropriate reinforcement, the person learns to make a given response, say an eye movement or a hand movement, to a given visual input, taking account almost automatically of eye, head, and body position. The result of this learning is the formation of "engrams" that may be regarded as well-learned response tendencies that are triggered off by the visual input. These engrams, when they become well established, are automatically brought into play by the appropriate stimulus input. The totality of the engrams that are activated at any moment *is*, for Taylor, the conscious experience of visual perception. In short, Taylor said that what the person "sees" are the readinesses to respond that, over many years, he has learned.

Perhaps, to be complete, one should mention a few others, who in their theoretical considerations give some role to efferent output in affecting perception but not quite in the same way. Hebb (1949), for example, attributed considerable importance to eye movements in learning to perceive contour and shape and, hence, in establishing the cell assemblies that provide the perception of, say, a triangle. Thus, by implication, efference is important in perception for Hebb but he does not spell out any of these implications. Von Holst (1954) also stressed the importance of efference for one particular type of perception. He proposed that the organism is able to distinguish between self-produced movement and externally produced movement by matching a record of the efferent instructions issued to the musculature with the resulting afferent input. Von Holst, however, showed no intention of giving efference a role in perception generally.

Von Holst's theory of "reafference" has been pursued further by Held (1961). Held proposed that, as a result of experience, there is stored somewhere in the central nervous system a set of correlations between efferent output and reafferent input. Because of the wide variety of invariant relationships that provide redundancy through experience, this collection of correlations becomes well established. In a mature organism, following any issued efference, there is an expected reafferent input that should match with what is stored in this correlator. If in any situation the reafference does not fit the expected afferent input, that is, if there is unusual reafference, then there will be some kind of perceptual or behavioral change that occurs. Held was not very explicit about how this occurs except that such experience starts changing what is stored in the correlator. What Held would say about the conscious experience of visual perception is quite unclear.

Some Data about Visual Perception

The fact that a few people over a long period of time have suggested that efferent readiness activated by afferent input is responsible for the conscious experience of visual perception may have no more status than as a curiosity. Perhaps it is more important to note that only a very few have proposed such a view. In order to decide whether or not these suggestions should be taken seriously, we should look at the data that led these persons in this direction. If the data are compelling, that is, if they are difficult to explain in other ways, then these theories should seriously be examined.

Breese (1899) was led to this view by data he collected on binocular rivalry. He presented to one eye of his *S*s a red square with five diagonal lines running from upper left to lower right. On the corresponding part of the retina of the other eye was presented a green square with five diagonal lines running from lower left to upper right. Under such circumstances, as is well known, there is fluctuation of what *S* sees—the red square and the green square alternate in conscious experience. Breese investigated some conditions that affected the length of time that one or another of the two squares was seen. He reported that an effort to pay attention to, say, the red square and keep it in consciousness was effective in increasing the amount of time it was seen only if eye movements occurred when the red field was seen and the eye was relatively still when the green field was seen. If *S* was trained not to make eye movements, effort of will had no effect on the fluctuations. Breese also found that if *S* was instructed to move his eyes along the lines of one of the squares or to count the lines of one of the squares, that square remained much longer in consciousness.

It is easy to understand why such data led Breese to adopt a theory involving efference in the conscious experience of perception. It is difficult to explain the efficacy of eye movements in other ways. If the eyes move when the red square is "seen," the same movement is occurring for both the red and green squares on their respective retinas; if the eyes are relatively still when the green square is "seen," the same relative stillness applies to each square on its respective retina. This suggested to Breese that an explanation should be sought in terms of readiness for motor activity.

Rather different considerations led Taylor (1962) to think in terms of an "efferent readiness" theory of visual perception. The reports of Kohler (1964), originally published in 1951, concerning dramatic changes in the visual perception of contour were of primary importance for Taylor. Kohler had *S*s wear spectacles containing wedge prisms for prolonged periods of time. Such wedge prisms (with bases mounted laterally), among other things, make straight vertical lines appear curved. The dramatic nature of the visual changes that can occur is illustrated by the following quote from Kohler (1964) concerning one of his *S*s:

> After ten days of continuously wearing the spectacles, all objects had straightened out and were no longer distorted. The subject then removed the spectacles. Immediately, impressions of curvature, distortions, and apparent movement set in. The subject complained: "What I experienced after I took off the spectacles was much worse than what I experienced when I first started wearing them. I felt as if I were drunk." Aftereffects continued for four days [p. 34].

In other words, after 10 days of wearing the spectacles *S*'s visual perception had completely adapted and the distortions were eliminated. Curved retinal images were then seen as straight. On taking the spectacles off, distortion, of course, appeared since now straight retinal images were seen as curved. While Kohler did not report such complete adaptation for all of his *S*s, the fact that some *S*s largely, or completely, altered the visual perception of contour is important and requires understanding. How does it happen that the same pattern of retinal stimulation that at one time is "seen" as straight comes to be "seen" as curved?

The observations that Kohler made are not isolated observations. The same phenomenon was reported by Wundt (1898), by Gibson (1933), and more recently by Pick and Hay (1965). Gibson attempted to explain the change in perception of curvature by positing a tendency toward visual "normalization." He discovered that there was some small change toward perceiving less curvature in a contour after simply staring at that contour for 5–10 min. He erroneously assumed that this "Gibson effect" accounted for the entire phenomenon. It has since been shown by Held and Rekosh (1963) and by Cohen (1963) that there is adaptation to prismatically induced curvature over and above the small magnitude involved in the "Gibson effect" and that relevant motor movements are necessary to produce this visual adaptation.

Taylor (1962) felt that these facts forced him to the theory he proposes in which, in our own terms, the efferent readiness activated by the afferent visual input determines the conscious experience of perception. Thus, for him, the perception of contour changes because, while wearing the prism spectacles and engaging in normal activities, *S* learns to make, and then is ready to make, different motor movements in response to the visual input. It is also possible, of course, to think of the changed perception of contour as due to a recoding of the visual input in the central nervous system. But even if one thinks of it this way, one must say that this recoding was determined somehow by the motor activity of the person while he was wearing the spectacles. Perhaps Taylor's position is simpler and more adequate.

Taylor also attempted to derive additional testable propositions from his theoretical statement and to marshall data in support of it. The relationship between his theory and his data will leave many dissatisfied, however. For example, he reasons that, if his theory is correct, the specific visual changes occurring for a person should be unique, depending upon his previous learning and the specific motor adjustments he must make while he is wearing distorting lenses. He documents this by describing his own experiences with adaptation to prismatic distortion—a set of experiences which seem consistent with what he says but are not very compelling.

The most interesting, and most theoretically relevant, data that Taylor presented concern his experiences adapting to prismatically induced curvature when the prism was mounted on a scleral contact lens rather than in a spectacle frame. He realized that if the prism was mounted on a contact lens, the eye itself must move according to the objective contour when scanning that contour and not according to the retinal image. He reasoned that, under these circumstances, adaptation to the curvature distortion should occur as a result of eye movements alone. The *S* would learn quickly to make a different set of motor movements with his eye in response to a given visual input. Specifically, the input to the retina which used to activate "engrams" to move the eye over a curved path would, after some experience with the contact lens, activate engrams to move the eye over a straight path. Once this happened, the perception should have changed since it is based on the evoked "engram" and *S* would see the contour as straight in spite of the curved retinal image. Taylor reported that, indeed, with a prism mounted on a contact lens he adapted to the curvature quickly and completely by just looking back and forth along a contour.

Some data do exist, then, that encourage, even if they do not compel, a theory of visual perception in which the efferent readiness activated by the visual input determines the conscious experience of perception. These data that we have discussed were concerned with the question of "what a person sees." If, however, the conscious experience of visual perception is determined by efference and efferent readiness, we might expect to find some relevant data addressed to the question of "whether or not a person sees." The kind of theory we are discussing here would imply that if, somehow, a situation were created in which the person completely stopped being ready to react to visual input, there might be a cessation of the conscious experience of visual perception. There are two situations that have been used in experiments on visual perception that might produce such a state of affairs, namely, stabilized retinal images and ganzfelds. A close examination of the data reported from such experiments may be useful.

With suitable optical arrangements, a pattern of retinal stimulation can be maintained at a given location on the retina in spite of any eye movements that occur. These images have been called stopped or stabilized retinal images. The experimental findings are that when a retinal image is stopped, contours and shapes tend to disappear. The interpretation of these findings has been in terms of fatigue or satiation of neural mechanisms due to the constant stimulation of the same nerve endings on the retina. The conclusion has been that the ordinary small nystagmic eye movements are essential in maintaining visual perception.

One may also look at the situation produced by a stopped retinal image in another way. There has been a complete destruction of the usual correlation between eye movements and movement of the image across the retina—no matter what eye movements occur, the retinal position remains unchanged. We might well imagine that in such a situation, where movement of the eyes is completely irrelevant to position of retinal stimulation, the person might soon cease responding, or even being ready to respond, to the visual input. Why should the person continue to be ready to make motor movements when these motor movements are useless and irrelevant? From this point of view we might also expect the disappearance of contour and shape with a stopped retinal image as soon as the person stops being ready to react to the input. Furthermore, from this point of view one might expect to observe the same kinds of disappearance of contour even if the stabilized image were not *stopped* on the retina. That is, the stabilized image could be moved, by *E,* across the retina while maintaining the complete lack of correlation between position on the retina and eye movements. Since, from this viewpoint, the important factor would be the cessation of reactivity due to the total lack of correlation between eye movement and movement across the retina, we would still expect the disappearance.

Along these lines an interesting observation is reported by Campbell and Robson (1961). They studied stabilized images produced by making visible the shadows of the retinal capillaries, a very precise way of producing a stabilized image. They reported as follows:

> New findings are that a stabilized shadow of the retinal capillaries disappears in a few seconds and does not reappear even in flickering light. The capillary shadow can be seen for a much longer period if moved across the retina at certain amplitudes and frequencies but, even so, these moving shadows also ultimately disappear and never reappear again spontaneously. Similar observations have been made using the central details of the shadow of the macular pigment [p. 12P].

Clearly, these observations cannot be explained entirely in terms of fatigue or satiation of neural mechanisms. They do fit what we would expect from our conjectures about the importance of efferent readiness in visual perception.

There is another known situation in which persons experience the cessation of visual perception. This occurs sometimes if a person's total visual field is a "ganzfeld," that is, a completely homogeneous, structureless field of vision. Typically, when viewing a "ganzfeld," *O* perceives a fog or mist of light and does not perceive any surface. Cohen (1960) reported that about one-third of *S*s in his study also experience "blank out," that is, "complete disappearance of the sense of vision for short periods of time." It is conceivable that, in the absence of any structure in the visual field that the person can use for fixation, the person occasionally stops responding altogether to the visual input. We will not pursue the speculation further. We will leave it at this except for one piece of data that is interesting with respect to this speculation. Tepas (1962) found that there was a significant absence of saccadic eye movements just prior to the onset of a "blank out." The absence of saccadic eye movements continued during the blank out and the end of the blank-out period coincided with the resumption of such eye movements.

Some Theoretical Specifications

If one is to take seriously a theory proposing that the conscious experience of visual perception is determined by efferent readiness activated by afferent visual input, it is necessary to specify some of the characteristics that such a theory must have to fit the known data. It is also necessary to specify something about what "efferent readiness" is, how it is developed, how it is activated, and what particular efferent readinesses affect visual perception.

The published literature discussed above suggests that the visual perception of contour can be altered. If we wish to say that this visual perception is determined by efferent readiness, then we must postulate that the efferent readiness appropriate to a given visual input must, to at least some extent, be learned and modifiable. This would make it likely that visual perception of contour and shape must be learned, or at least in part. We might imagine that the visual experience of a newborn infant has no sharp contours or definite shapes but consists entirely of fuzzy blotches of brightness and color differentials. Perhaps more than this is innately built into the organism but we need not concern ourselves with the problem. Even if only this much is built in, mature visual perception based on efferent readiness can easily develop.

There is a precise and invariant relationship that always holds between the magnitude and direction of an eye movement and the magnitude and direction of movement across the retina of any point of stimulation on the retina. Thus, of course, the basis exists for being able to learn the appropriate efferent instructions to issue to move a point of stimulation from one part of the retina to any other part. To learn this, however, would mean to learn an almost countless number of efferent sets of instructions and the human organism almost certainly does not learn all of this. The part of the retina that is of the greatest interest is the fovea. We can imagine a tendency in our newborn infant to examine, in detail, parts of the visual field in which the brightness or the color changes. When such parts of the visual field fall on the fovea, the detail is best and so the organism learns to direct the eye so as to bring points of peripheral stimulation to the fovea. This, of course, is a much more restricted and manageable set of efferent instructions to learn. Most adult organisms have never learned to, and cannot, execute eye movements to bring a point of stimulation from 20 degrees to the right of the fovea, for example, to a point 10 degrees below the fovea. Thus, for example, Fender (1964) reported that "subjects find it almost impossible to track a moving target while maintaining fixation a few degrees away from it [p. 315]."

It is, then, a manageable set of efferent instructions that the organism learns to issue for eye movements. Considering that the saccadic fixating eye movement in the adult is not a completely accurate movement—errors up to half a degree are not unusual—the amount to be learned is manageable indeed. Thus, we can imagine the input to the retina coded as if the retina were calibrated in terms of distance and direction from the fovea. The organism learns the appropriate efferent instructions to be issued from the central nervous system to direct the eye to move so as to bring any point of stimulation on to the fovea. After a considerable amount of learning has gone on, these sets of efferent instructions can be viewed as becoming "preprogrammed" and as being automatically activated by brightness or color differentials stimulating the retina. We do not mean the term "activated" in the sense of efference actually being sent from the central nervous system through the motor neurones; we mean to use the term in the sense that these preprogrammed sets of efferent instructions are brought into a state of immediate readiness for use. Thus, those efferent instructions which if issued would bring areas of brightness differential onto the fovea, are ready for immediate use.

Although the idea of efferent instructions held in readiness for use is not a new one, as we have seen, it is still a rather vague one. Some attempt at clarification would perhaps be helpful. Without trying to speculate about the exact physiological mechanisms and arrangements, it seems plausible to imagine that the physical system is limited in the number of sets of stored preprogrammed instructions that can be "immediately" sent out through the motor pathways. Thus, out of the very large number of sets of efferent instructions that the organism has learned, only some are held in readiness for immediate use. Without intending any precise analogy, we could imagine a jukebox which, at the push of the appropriate button, will immediately play any of a hundred different phonograph records. The owner of the jukebox could also have many thousands of other records available but, obviously, they cannot be played immediately. The owner could, however, with a little bit of work, change the entire set, or part of the set, of the hundred records that are immediately available for playing. One might think of these hundred records as being "ready for immediate use."

If we are to think of the conscious experience of visual perception as being determined by these preprogrammed sets of efferent instructions that are activated into readiness by the afferent input, then it is necessary to specify something about the level of generality or specificity of the efferent signals that are issued from the central nervous system. If, using an efference readiness theory of visual perception, we are to be able to have a person perceive a given shape or contour as the same no matter what the eye position is when viewing it, it seems necessary to specify that the efferent instructions issued from the central nervous system must be general in nature, that is, relatively far removed from the final signal that causes the exact muscle twitch. Thus, the efferent signal from the central nervous system could be concerned only with direction and magnitude of deviation from the fovea, and final computation to effectuate the actual muscle contractions could take account of afferent information at more peripheral levels. This is not an unlikely state of affairs. For example, Merton (1964) said: "Hughlings Jackson (no reference given) showed that, in the code used by the motor cortex, the orders sent out represent instructions to perform movements, not instructions to individual muscles to contract [p. 399]."

One might be tempted to say that the conscious experience of visual perception of contour and shape (and similar arguments could be made for perception of distance and depth) was determined by readiness to issue efferent instructions to the extraocular muscles. However, it is clear that this cannot be the whole story. The data show clearly that fairly large changes in the visual perception of curvature occur if wedge prism spectacles are worn for long periods of time. Pick and Hay (1964), for example, found an average of 30% adaptation to curvature in eight *S*s who wore such spectacles all their waking hours for 42 days. But if *S* wears prism spectacles, no change in the efference or efferent readiness activated by the visual input should occur with respect to the extraocular muscles. The eye, under these conditions, must move with respect to the retinal contour, not with respect to the objective contour. However, head movements, arm movements, and all other body movements must, in order to be effective, correspond to the objective contour and so, efference and efferent readiness concerning these motor movements that are activated by the visual input must change. If we are to explain these adaptations to curvature in terms of an efferent readiness theory, then, it is necessary to say that the conscious experience of visual perception is determined by the total efferent readiness activated by the visual input, not just the efference relevant to the eyes.

Perhaps this represents sufficient specification of an "efference readiness theory" to permit submitting the theory to experimental test. Before proceeding to examine this question, however, it is necessary to consider an alternative interpretation of the data on which we have relied in the discussion. Harris (1965) proposed that the visual system and visual perception are probably not changeable and that the changes that occur when adapting to distorting spectacles are proprioceptive changes, that is, the end result of the adaptation is a change in the felt position of some part of the body. He stated,

> Vision seems to be largely inflexible, whereas the position sense is remarkably labile . . . proprioceptive perception of parts of the body (and therefore of the location of touched objects) develops with the help of *innate visual perception* . . . [italics ours, pp. 441–442].

Harris presented data to show that such changes in "felt position" do indeed occur as a result of adaptation to displacement of the visual field. He also presented a highly ingenious analysis in terms of changes in "felt position" to explain adaptation to spectacles that invert or reverse the visual field. With regard to curvature, Harris implied (although he retracted the implication partly in a footnote) that the same end result is achieved rather than any change in visual perception. He said,

> So perhaps adaptation to curvature also involves altered registration of eye movements without any change in scanning behavior. After adapting, the subject may feel that his eyes are moving in a straight line when they are actually tracing out a curve [p. 428].

On examination, however, this suggestion seems strange and even rather inconsistent with the position taken by Harris. First of all, if *S* is wearing prism spectacles, what could conceivably lead to a change in felt position of the eyes? The eye movements necessary to scan a contour would be precisely consistent with vision (retinal input) which is "largely inflexible" and "innate." After moving about in the environment an *S* might be expected to recalibrate the felt position of other parts of the body but *not* of the eyes. Second, Harris seemed to be making a very curious suggestion. He was apparently suggesting that the visual perception of a contour such as curvature is determined by how *S* feels his eyes are moving when he scans this contour. It becomes unclear what Harris meant by visual perception. Did he suggest that with steady fixation contours cannot be perceived, or did he suggest some notion of efferent readiness similar to ours?

Possible Experimental Tests

If the conscious experience of visual perception of contour is, indeed, determined by the efferent readiness activated by the visual input, there is a definite empirical implication that can be tested experimentally. If, without changing anything about the pattern of retinal stimulation, one could alter the particular preprogrammed sets of efferent instructions that were activated and held in readiness for immediate use, one would expect to produce a change in visual perception.

It is clear that, by using prism spectacles that produce a curved retinal input when looking at a straight line, one could induce a person to learn, say, to make a straight arm movement in response to a curved retinal image. It is also possible, as Taylor (1962) pointed out, that by using prisms mounted on contact lenses one could induce a person to make a straight eye movement in response to a curved retinal image. The problem is how to do these experiments with appropriate controls and appropriate comparison conditions so that alternative interpretations of the data can be ruled out. Since a major class of possible alternative interpretations of such changes in visual perception would be based on the idea that the change occurs because of conflicting information obtained from retinal input and from feedback from the muscles and joints, it would seem to be desirable to control for these factors. In other words, we would want different experimental conditions in which retinal input was identical and feedback from muscles and joints was identical but the efference issued from the central nervous system was different.

Theoretically, of course, it is possible to have quite different general efference issued ending in exactly the same muscle contractions. To use an analogy, instructions could be issued to a computer to divide 28 by 4 or to find the fifth prime number. As a result of these two very different instructions, the machine ends up doing the identical thing, namely, it prints the number 7. Operationally, it does not seem easy to do but perhaps one may approach such a situation. For example, if an *S* wearing prism spectacles looks at a straight edge that appears curved and is instructed to run his finger along the edge, pressing on the edge, the finger will actually move in a straight line, of course, and feedback from the skeletal joint receptors will provide this information. There is no necessity, however, for efference from the central nervous system to concern itself with the exact contour involved. If, however, *S* had to learn to make an accurate sweeping motion with his finger that corresponded to the contour without any edge to press on, it seems more likely that the efference from the central nervous system would have to concern itself with contour. In both conditions, however, the feedback from the limb would be very similar. Only in the latter conditions would we expect *S* to develop the new efferent readiness to move his arm in a straight path when the retinal input is curved and, hence, only in that condition would we expect change in visual perception.

Four experiments have been designed to provide such tests of the theory that the conscious experience of visual perception is determined by efferent readiness activated by the visual input. They all used, for this purpose, the empirical vehicle of adaptation to prismatically induced curvature.

Experiment I

In this preliminary experiment an attempt was made to create two experimental conditions similar with respect to the active movements that occur and the proprioceptive feedback but different with respect to whether or not *S* learns a new afferent-efferent association. One-half of the *S*s were required to learn to move a stylus in a continuous movement along a path between two brass rods. Since the path between the rods either was objectively straight and appeared curved or else was objectively curved and appeared straight, *S*s needed to learn a new, unitary, afferent-efferent association in order to perform the continuous tracking motion without error, i.e., without striking one of the rods. The remaining *S*s were not asked to learn a continuous tracking motion. Rather, they were asked to move the stylus, as slowly as they wished, between the rods with the paramount objective of never touching a rod. Thus, one-half the *S*s were asked to learn a new, unitary, skilled movement; the remaining *S*s were not.

Method

Subjects.—The *S*s in this experiment were freshmen or sophomore female students at either Stanford University or Foothill College. All were right handed and did not wear spectacles. Each was paid $4.00 for participating in the experiment. Only females were used in the study because preliminary work had indicated that males tended to become more frustrated at the boring nature of the task and tended to lose interest and motivation. The *S*s were run, assigned to experimental conditions at random, until 10 usable *S*s in each condition were obtained. During the course of conducting the experiment, the data from 12 *S*s were discarded for the following reasons: (*a*) Three *S*s because of difficulties with the biteboard during the session; (*b*) Two *S*s because of disregarding the instructions; (*c*) Seven *S*s because of highly inaccurate or suspicious initial settings with the prisms.

Apparatus.—The main piece of apparatus was a white formica board, 40 in. wide × 26 in. high. The board was held vertically in a wooden frame and rested on a table. Down the middle of the board ran two parallel vertical brass rods. The rods were slightly less than ⅛ in. in diameter and were mounted ½ in. apart between centers. The ends of the rods ran through holes at the top and bottom of the board. The ends of the rods were free to slip back and forth through these holes. The midpoints of the rods were rigidly attached to a horizontal center strip in the board which had an identical surface set flush with the surface of the rest of the board. A knob was mounted in the frame below the board and to the right of center. By turning this knob, *S* could move the center strip back and forth and thus adjust the rods to various desired degrees of curvature. On the back of the board was a pointer which ran along a centimeter scale. The pointer measured the horizontal deviation of the midpoints of the rods from true straight. A biteboard was mounted on the table directly in front of the center of the board so that the distance from *S*'s eyes to the board was approximately 40 cm.

During most of the experimental session *S* wore goggles with 25-diopter prisms mounted with their bases left. While wearing the goggles and biting on the biteboard, the vertical extent of vision on the board was about 37 cm. For measurements involving the naked eye, *S*s wore a similar pair of goggles with plate glass in them. For each *S*, the height of the chair and of the biteboard was adjusted so that her eyes were at the same height as the horizontal center strip on the board.

Procedure.—Before any goggles were put on *S*, she was shown how, by turning the knob, the curvature of the lines could be changed. She was told that periodically she would be asked to adjust the lines so that they were straight. She was also told that she would spend part of the session moving a stylus down between the two rods using her right hand and was shown that if the stylus touched either rod a buzzer would sound. The type of stylus stroke was then explained to *S*, the specific instruction depending on the experimental condition.

In the condition designed to encourage learning a new afferent-efferent association (Learning condition) *S* was told to make a smooth, fast, sweeping motion with the stylus between the two rods. She was told to try to learn to avoid hitting the rods but not to be concerned about hitting them at the beginning. She was not to slow her motion down in order to avoid hitting the rods but to continue a smooth, rapid motion and gradually improve her performance. The smoothness and rapidity of the stylus stroke and the objective of learning to make the stroke better were emphasized.

In the condition designed to minimize the learning of a new afferent-efferent association (Accuracy condition) *S* was told to make a slow, very careful movement of the stylus between the rods so that she would not hit either rod. She was told to move slowly enough to be sure she was accurate. The importance of going slowly and never hitting the rods was stressed.

It was intended that, in the Learning condition, *S*s would have to learn to make a straight arm movement when the retinal input was curved or a curved arm movement when the retinal input was straight. To the extent that they learned this, a new efferent readiness would be activated by the visual input. It was also intended that, in the Accuracy condition, *S*s would respond primarily to the local deviation of the stylus from the rod and would never learn anything new about efferent instructions to the arm relevant to the contour. In order to keep the amount of experience constant for *S*s in the different experimental conditions, each was instructed that a bell would sound every 12 sec. At this signal she was to insert the stylus between the two rods at the top of her visual field and make the downward stroke, ending near the bottom of her visual field. Thus, each *S* had exactly the same number of stylus strokes and the same time spent looking at the lines.

After telling *S* that, from this point on, she was to have her eyes open only while biting on the biteboard, she was asked to shut her eyes and *E* put the plain glass goggles on her.

The *E* then moved the rods a few centimeters to the left of where they would look approximately straight and *S* was asked to turn the knob so as to make the lines straight. The setting was recorded to the nearest ½ mm. He then moved the rods off in the opposite direction and another setting was made. This was continued until four measurements were obtained. The *S* then closed her eyes and the plain glass goggles were replaced by prism goggles. Initial settings of straight with the prism goggles were obtained in a similar manner.

The *S* closed her eyes again while *E* set the lines at the proper position. If *S* was in an "apparently straight" condition, the rods were positioned at the average of the settings of "straight" that *S* had just made wearing the prism goggles. If *S* was in an "apparently curved" condition, the rods were positioned at the average of the settings of straight that *S* had made wearing the plain glass goggles.

The *S* was then asked, with her eyes shut, to run her fingers up and down the two rods until she could tell whether they were straight or curved and, if they were curved, in which direction. The purpose of this was to provide some information to *S* that might help in the performance of the task. This aspect of the procedure was probably unnecessary. It was omitted in Exp. II reported below.

The *S* then opened her eyes, took the stylus in her hand, and after *E* quickly reviewed the stroking instructions and started the bell, began the actual practice. There were five stroking periods each intended to be 10 min. long. Some of the periods for *S*s in the Accuracy conditions were longer since, if they skipped some of the bell rings, the period was extended so that there would be 50 strokes in each period. The stroking periods were separated by rest periods of 3 min. during which *S* leaned back with eyes closed.

During the stroking periods, *E* observed the speed of *S*'s strokes. If *S* in a Learning condition stroked too slowly (more than 1 sec. per stroke), she was reminded to go faster. The *S*s in the Accuracy conditions were reminded to slow down if they went too fast (less than 4 sec. per stroke). The *S*s in the Accuracy conditions were also reminded to be careful if they hit the rods, telling them to go slowly enough so that it would not happen.

Following the fifth 10-min. stroking period, while *S* rested, the board was washed to remove the slight traces left by the stylus. The *S* then spent 2 min. stroking and immediately afterwards the final settings of straight while wearing the prism goggles were made. The rods were then returned to the stroking position for that *S* and she stroked for another 2 min. With *S*'s eyes shut, *E* removed the prism goggles and put the plain glass goggles in their place. He quickly washed the board off again and had *S* open her eyes and make the final settings looking through plain glass.

Results

Initial straight settings.—Table 1 presents, for each of the four experimental conditions the average initial setting of straight with the naked eye (plain glass goggles) and with the prism goggles. It also presents the average change from the beginning to the end of the experimental session for each of these measures.

There are only minor variations among the four experimental conditions on the initial measurements. The average setting of straight with the naked eye is very close to objectively straight (between 9.90 and 9.95 on our measurement scale). The average setting of straight with the prisms varies slightly around 4.40; in other words, the prisms produced a curvature of about 5.5 cm. displacement of the middle of the line. Analysis of variance on the initial measurements revealed that none of the differences among experimental conditions even approached statistical significance.

Change from initial to final measurements.—These showed systematic differences in line with what one would expect on the basis of an efferent readiness theory. Although the effects were small, they were reasonably consistent. On both the measures of adaptation (changes measured with prisms in place) and aftereffects (changes measured with the naked eye) the Learning condition yielded more changes in visual perception than the comparable Accuracy condition. Neither of these quite reached conventional levels of acceptable significance.

We can increase the reliability of our measure of change of visual perception, however, by simply averaging for each *S* the adaptation and aftereffect measured. An analysis of variance on this combined index yielded $F(1, 36) = 6.46$, $p < .05$. Thus, we may conclude that the Learning conditions produced more change than the Accuracy conditions.

The differences between the apparently straight and apparently curved conditions were, of course, highly significant in all cases. This difference was due to the operation of the "Gibson effect" in the Apparently curved conditions and its absence in the Apparently straight conditions. It is clear, however, that the difference between the Learning and the Accuracy conditions existed independently of the Gibson effect.

Discussion

The data were consistent with the implications from an efferent readiness theory of visual perception of contour. In the condition intended to force *S* to

TABLE 1

Initial Measurements and Changes (in Centimeters) in the Perception of a Straight Line (Exp. I)

	Experimental Cond.			
	Apparently Straight		Apparently Curved	
	Learning	Accuracy	Learning	Accuracy
Initial with Prisms	4.55	4.34	4.29	4.39
Change with Prisms	+.28	+.10	+1.59	+1.31
Initial with Naked Eye	9.92	9.96	9.90	9.96
Change with Naked Eye	+.18	+.02	+.86	+.65

learn a new afferent-efferent association significantly more change in the visual perception of curvature was obtained than in the condition intended to make such learning unlikely. Whether or not the Learning and Accuracy conditions really had their intended effect is, of course, not directly answerable from the data. All one can say is that the results obtained are in line with the predictions made from the theory and from intuitive notions as to the effects of the experimental manipulations.

The magnitude of the effect created by the experimental manipulation is, clearly, very small, being about 2 mm. between the Learning and Accuracy condition. It is, of course, unclear as to whether this magnitude of change of visual perception is, or is not, disappointing. Considering that visual perception is very likely heavily dependent upon efferent readiness concerning the extraocular muscles, and there was certainly no change in these afferent-efferent associations, and considering that the only other movement involved at all was that of the arm, one might not expect a very large change in visual perception.

The data have relevance to Held's (1961) theory concerning the importance of reafference. Both the Learning and the Accuracy conditions are, in Held's sense, active movement conditions. In both conditions the afference, and hence the reafference, would be unusual and from Held's theory one would expect perceptual change equally for both. It seems clear from the data, however, that Held's distinction between active and passive movement was too gross. Distinctions have to be made concerning the specific nature of the efference.

Experiment II

The attempt was made in the design of the previous experiment to keep the proprioceptive input from the arm the same in both Learning and Accuracy conditions so as to rule out possible interpretations of the visual changes as having been due to recoding of visual input based on information obtained from proprioceptive input. For this reason there were two rods spaced closely together so that, since the stylus was confined between the two rods in all conditions, the informational input from muscle and joint receptors would, of necessity, be similar for the two conditions. However, *E*s were obviously not successful in making the proprioceptive input identical in these experimental conditions since, at a minimum, the rate of input was systematically different. In the Learning conditions the hand moved quickly while in the Accuracy conditions the hand moved slowly. Perhaps the rate of informational input is important. In this experiment, consequently, a theoretical replication with quite different instructions to *S* was attempted so that the rate of input, as well as the specific proprioceptive information, would be held constant.

Method

Subjects.—Sixty-two females, 22 freshmen or sophomores from Stanford University and 40 junior and senior high-school students, participated in the experiment. All *S*s were naive about the experiment and were paid $3.00 for participating. The *S*s were randomly assigned to one of four experimental conditions with the restriction that the ratio of college to high-school *S*s be kept nearly equal. The data from two *S*s were discarded—one because she did not follow the instructions and the other because the apparatus failed during the experiment.

Apparatus.—The apparatus for the experiment was identical to that used in Exp. I except for a few minor changes. A sturdier biteboard was constructed; movable clips were attached to the rods at the top and bottom of *S*'s visual field so as to be sure that the stylus movement was always entirely within the visual field. The *S*s were seated so that the distance between their eyes and the rods was about 48 cm., approximately 8 cm. farther away than in Exp. I.

The experiment was conducted monocularly throughout so that we would also be able to measure interocular transfer. For this reason three sets of goggles instead of two were used. One set contained a 25-diopter prism mounted base left in front of the right eye, the left eye being occluded; the other two sets had plain glass, one in front of the right eye, the other in front of the left eye. The other eye was always occluded. There were two viewing conditions, one in which *S* viewed an objectively straight, apparently curved line; the other in which she viewed an objectively curved, apparently straight line. There were two movement conditions, one in which we attempted to maximize the learning of a new afferent-efferent association and one in which we attempted to minimize such learning while holding other variables constant. The instructions to *S*s in the Learning condition emphasized the learning of a smooth, fast, sweeping motion of the stylus between the rods. The *E* demonstrated the stroke and the buzzer sound resulting when a rod was touched by the stylus. The *S* was told that touching the rods was to be accepted at first, that the important aspect of the task was to learn the smooth stroking motion required to move the stylus between the rods. In the Contact condition *S*s were instructed to learn a smooth, stroking motion while maintaining pressure on one rod. The *S*s in both conditions were encouraged to rest when this was needed and to proceed at the task at a self-determined pace.

Instructions were also given concerning how to set the line so that it was straight and to keep the eyes closed any time *S* was not biting on the biteboard. Measurements were made in the same way as in Exp. I with the addition that separate measurements were taken for each naked eye at the beginning and end of the experiment.

During the experimental period *E* recorded the number of strokes made and the cumulative time on and off the biteboard. He also recorded any verbal reports given by *S* while she was leaning back and resting. If *S* was not following instructions, she was corrected at once. When the time on the biteboard had accumulated to 10 min., 20 min., and 30 min., *E* reminded *S* of what she was supposed to be doing; e.g., "You're doing fine, but let me remind you that the important thing is that you make firm contact with one of the rods," or "You're doing fine, but let me remind you that you're supposed to be trying to learn to make a fast, smooth, sweeping stroke."

When *S* had been on the biteboard for 40 min., she was asked to close her eyes and to lean back. At this point *E* removed from the board any traces left by the stylus. The *S* was then asked to work for a little while longer. After *S* had stayed on the biteboard for 45 sec., she was instructed to remain on the biteboard but to close her eyes. Any traces of the stylus were again removed and the final measurements of straight were taken.

At this point *E* informed *S* that the experiment was over, but that he would like to ask a few questions. The *S* was asked how the board looked, whether she noticed any changes in the curvature of the rods, and how her eyes felt during the experiment.

Results

Table 2 presents the data for each experimental condition. As in Exp. I, the differences among the four conditions in the initial measurements were very small. In all four experimental conditions, the average settings of straight were slightly under 10.0 on the measurement scale with the right naked eye. With the left naked eye they were a shade over 10.0. This difference was significant; 52 *S*s showed a higher mean setting with the left naked eye than with the right naked eye; 7 *S*s showed a difference in the other direction; and for 1 *S* the average settings were equal. This difference was undoubtedly due to the slightly different angle of view between the two eyes. The average setting of straight with the prism spectacles was 4.96, a curvature represented by about 5 cm. displacement of the rods from the middle of the board.

The data on changes from initial to final measurements were very similar to those obtained in Exp. I. In the Learning conditions, where one would expect some learning of new efferent instructions activated by the visual input, greater change in visual perception was obtained than in the Contact conditions. An analysis of variance on the changes of the settings of straight with prisms yielded $F\ (1, 56) = 8.92$, $p < .01$, for the difference between the Learning and Contact conditions. A

TABLE 2

INITIAL MEASUREMENTS AND CHANGES (IN CENTIMETERS) IN THE PERCEPTION OF A STRAIGHT LINE (EXP. II)

	Experimental Cond.			
	Apparently Straight		Apparently Curved	
	Learning	Contact	Learning	Contact
Initial with Prism (right eye)	5.02	4.86	4.94	5.01
Change	+.23	+.15	+1.20	+.88
Initial with Right Naked Eye	9.77	9.72	9.74	9.83
Change	+.32	+.20	+.91	+.68
Initial with Left Naked Eye	10.04	10.03	10.09	10.10
Change	+.14	+.05	+.35	+.20

similar analysis of variance on the changes from initial to final measurements for the right naked eye (the eye that wore the prism) showed the Learning and Contact conditions to be significant also, F (1, 56) = 5.47, $p <$ .05. The combined index of adaptation and aftereffect that was used in Exp. I was, of course, highly significant, F = 15.57.

The results for transfer from the right naked eye to the left naked eye were less clear. In all of the experimental conditions there was some transfer to the left naked eye and the amount of change in the left eye was greater in the Learning conditions than in the comparable Contact conditions. The difference between the Learning and Contact conditions was not statistically significant, however, $F = 2.82$. The measurements on the left eye were always taken after the measurements on the right eye in this study. It is impossible to assess the effect of the time delay on the results.

Similar to the results of Exp. I, there was a highly significant difference on all measurements between the conditions in which an apparently straight or apparently curved line was viewed. This Gibson effect clearly was independent of the changes of primary interest.

Discussion

The results of Exp. II completely supported the results, and the interpretation of the results, from Exp. I. In spite of the fact that quite different instructions were used to create conditions that would minimize the learning of new afferent-efferent associations, the results came out in the same way. In Exp. I *E*s depended on an instruction to go very slowly and to avoid ever hitting the rods. It was intended that this would force *S* to concentrate on the local deviation of the stylus from the rod and that she would, therefore, not learn new efference to issue in response to the visual input. In Exp. II *E*s depended, for the same purpose, on an instruction to maintain pressure and contact with one rod during the whole stroke. It was hoped that, since the movement of the arm would thus be guided by the actual rod, *S* need not, and would not, learn a new afferent-efferent association. The results of the two experiments support the interpretation that visual perceptual change occurs if one changes the efferent readiness activated by the visual input.

In both experiments the actual arm movement, and hence the actual proprioceptive feedback from the arm movement, was nearly identical for the Learning conditions and the comparable nonlearning conditions. In Exp. I it was possible to argue that, since the rate of proprioceptive input was different (fast vs. slow movements), perhaps this affected the results. In Exp. II this difference did not exist. The rate of movement was similar in all experimental conditions—if anything, the movement was faster in the Contact conditions. Table 3 shows the number of strokes made on the average by *S*s in each experimental condition in the 40 min. of actual stroking. None of the differences are statistically significant but it is clear that the difference that does exist is in the direction of more strokes per unit time in the Contact conditions. Hence, it is no longer plausible to suppose that the rate of proprioceptive input affects the results.

It is worth pointing out that while the two different kinds of nonlearning conditions did probably reduce the extent to which *S*s learned new afferent-efferent associations, we cannot be sure that these conditions prevented such learning altogether. The data from the Contact conditions in Exp. II provide some basis for assessing whether some learning did occur. One might expect that if learning occurred in these Contact conditions, it would probably depend on amount of experience to a greater extent that it would in the Learning conditions. In the Contact conditions those who made very many strokes might be more likely to have learned some new efference. To examine this possibility we computed the correlations, within each experimental condition, between the number of strokes made and the combined index of adaptation and aftereffect for the right naked eye. These correlations are presented in Table 3. There is no significant correlation at all for the two Learning conditions but significant (at the 5% level) correlation for each of the Contact conditions. It seems, then, that some *S*s in the Contact conditions did learn. If such learning could have been entirely prevented, the difference between conditions would, presumably, have been larger.

Experiment III

Experiments I and II, while supportive of the theory, have in common a possible confounding factor. In the Learning conditions there were frequent error signals that were absent in the nonlearning conditions. The third experiment was designed to eliminate this possibly confounding factor while testing the theory again under very different empirical conditions.

Two general methodological changes were made in the third study: (*a*) Adaptation resulting from a change in efferent readiness and the adaptation resulting from the "Gibson normalization effect" were experimentally separated by allowing normalization to develop prior to the introduction of arm and hand movements; and (*b*) measurements of adaptation were made after short periods of activity to make it possible to study the course of adaptation throughout the experimental session.

Method

Subjects.—All *S*s were males, either high-school seniors or college students. All had

TABLE 3

Number of Strokes and its Correlation with the Combined Index of Perceptual Change

	Experimental Cond.			
	Apparently Straight		Apparently Curved	
	Learning	Contact	Learning	Contact
Number of Strokes	624.00	689.93	585.33	626.73
r between Adapt + Aftereffect and Number of Strokes	−.172	+.525	+.022	+.500

good, uncorrected vision sufficient for an unrestricted driver's license or had vision fully corrected by contact lenses. A total of 73 *S*s participated in the study but only data from 54 (9 in each condition) were used in the analysis. Sixteen of the discarded *S*s made very inaccurate level settings during initial measures with prism goggles. One *S* was unable to make settings within time limits, and two *S*s used background cues as a basis for their settings after the shooting period.

Procedures.—The technique used in this study to provide *S*s with an opportunity to make arm and hand movements discrepant with their visual input employed a shooting gallery. The *S*s "shot" a pistol emitting a continuous light ray at a target that moved back and forth on a track. While engaging in this activity, they wore prism spectacles. When the light ray hit the center of the target, a photocell and relay mechanism activated a buzzer. In one experimental condition the light was visible; in the other an infrared filter was placed over the barrel of the pistol.

No adaptation to the prism induced curvature was expected in the visible light condition. The efference issued in this condition need not be made in response to the path of the target's movement or the contour of the track but rather to the discrepancy between the seen position of the light ray and the target's position, speed, and direction of movement. In essence, these *S*s could act as servomechanisms as they performed a simple tracking task. Yet their arms and hands would move in a path consistent with the distal contour and be discrepant with the perceived proximal contour.

Ideally, *S*s shooting with the invisible infrared light would have been forced to issue efference activated only by the perceived contour of the target's path. Guided by the information from the buzzer when on target, they would have to learn a new set of efferent responses to the distorted perception. Therefore, they would be expected to adapt to the prism induced curvature. Pretesting with this manipulation, however, rapidly led to the conclusion that it was almost impossible to hit the target; hitting occurred rarely and seemingly by chance. Consequently, *S*s were permitted to aim while shooting with the infrared light. With aiming they were able to hit the target, although still with some difficulty, and make the required arm and hand movements. Although aiming was not necessary for *S*s shooting with the visible light, they were also told to aim in order to equate this factor.

The two conditions involving infrared and visible light were combined with two conditions of viewing an apparently straight or apparently curved line, resulting in a 2 × 2 design. After these four initial groups were run, two supplementary groups of *S*s were added to clarify the findings and interpretations of the results. The *S*s in the Aim-only condition shot with the infrared light and were allowed to aim but received no information as to when they hit the target. The *S*s in the other supplementary condition also shot with the infrared light and received no information. In addition, they were not allowed to view their arms, hands, or the barrel of the pistol. This No-information group was designed to determine whether there were any factors in the experimental situation which would result in a change in contour perception if *S*s neither made discrepant efferent responses nor received any atypical visual reafference. The *S*s in these two supplementary groups viewed only an apparently straight contour.

Apparatus.—As indicated above, the experimental apparatus consisted of a prism to produce a curvature transformation of the visual world and a shooting gallery to give *S*s a means of engaging in activity with the distorted world. In addition, there was a method for measuring adaptation to curvature.

A 30° wedge prism of optical plastic, 4 in. long and 1¾ in. in height, was used to produce curvature. It was mounted base upwards in welder's goggles with the front of the prism flush with the outside of the goggles. The field of view through the prism goggles was 86° wide and 48° high. Similar goggles with a plain piece of glass were used when *S*s viewed the same size visual field without any distortion. The shooting-gallery component of the apparatus consisted of a 9-ft. horizontal track across which a target box moved at a rate of 1.5 ft/sec. The reversal and reacceleration of the target box were virtually instantaneous. The actual target was a 1 × 1 cm. photocell which was sensitive to both visible and infrared light. It was mounted in the middle of the target box; a series of concentric red and white rings surrounded the photocell and enhanced its target-like appearance. When the photocell was activated by light, a relay closed, starting a buzzer and clock. The buzzer signaled *S*s that they were on target. The clock provided a record of the amount of time spent on the target.

The *S*s shot at the photocell with a pistol emitting a continuous collimated ray of light approximately 1 in. in diameter. The infrared filter used in the invisible light conditions, inserted in front of the barrel of the pistol, effectively blocked visible light under the illumination conditions used in the study.

The track on which the target ran could be bent into a smooth curve. The track itself was attached to an aluminum bar 9 ft. long, 3 in. wide, and ¼ in. thick. The bar was held at a constant height at both ends by supports and forced up or down by pressure at the middle. A threaded rod affixed with a bracket to the center of the bar was raised or lowered by a motor and pulley arrangement. The position of the bar was measured by a cord running from the threaded rod along the length of a meter stick placed at the front of the table where *E* sat. The position of an indicator on this cord accurately reflected the position of the middle of the bar.

It was impossible to set the bar to appear perfectly straight with or without the prisms. Since it was supported only at the ends and middle, the bar sagged slightly at the ¼ and ¾ points, and curvature produced by bending the bar did not exactly compensate for the curvature induced by the prism. When set to appear approximately straight, the ¼ and ¾ points looked slightly elevated. Consequently, *S*s were always told to set the bar to appear level, with the middle of the bar placed at the same height as the two ends. The *S*s had no difficulty in doing this either with the naked eye or the prism goggles.

The *S*s sat at a table directly in front of the middle of the track with their eyes 64 in. from the bar. From this position the target movement subtended a visual angle of 78°. While making settings, viewing the bar and target, or shooting, *S*'s head was held fixed by a biteboard attached to this table. When *S*s wore the nondistorting goggles, the biteboard was parallel to the surface of the table, and the bar appeared in the center of the field of view. When wearing the prism goggles, the biteboard was angled 15° downward to compensate for the prism displacement effect and make the bar still appear in the approximate center of the field of view.

Black cloth draped irregularly over, behind, and to the sides of the bar blocked *S*'s view of the walls and ceilings of the experimental room and prevented him from realizing that the goggles produced curvature. The threaded rod and motor and pulley arrangement were also hidden by a piece of black cloth to prevent *S*s from using the position of the bar relative to the motor and pulleys as a guide for their settings. In the no-information condition a shield prevented *S*s from seeing their arms, hands, or the pistol.

The *S*s were given first a demonstration of the use of the shooting gallery and the method of setting the bar to appear level. They were allowed to shoot briefly and thus became aware of the operation of the buzzer and time clock. At this time they were told how to hold the pistol and urged to do as well as they could when shooting. The *S*s in the two supplementary groups were told that they would be unable to tell when they were on target since the buzzer would be disconnected and a "soundproof cover" placed over the relay and time clock to mask the clicking of these instruments. In actuality, these instruments were disconnected to insure that *S*s would receive no indication when they were on target.

Initial measurements of straight with the plain glass goggles and then with the prism goggles were made. Each measurement consisted of six settings made by *S* from alternate displacements of the bar by *E* to positions approximately 8 cm. above and below an apparently level position.

The average of the initial setting made with the plain glass goggles indicated *S*'s preexperimental perception of level. After the initial settings with the prism goggles were made, *E* either set the bar to the average of the initial measurements made with the plain glass goggles for *S*s in the apparently curved viewing conditions or to the average of the measurements made with the prism goggles for *S*s in the apparently straight viewing conditions.

All *S*s then viewed the target moving back and forth across the track for a period of 8 min. to allow time for the Gibson effect to develop for *S*s viewing the apparently curved bar. Following this viewing period all *S*s made another series of settings. It was assumed that 8 min. was long enough to achieve complete adaptation due to "normalization" and that subsequent changes in the settings in the apparently curved viewing conditions would reflect adaptation resulting from a change in efference.

There followed five 8-min. shooting periods separated by rest periods of 5 min. Immediately after each shooting period *S*s made a series of settings. A final setting with the plain glass goggles followed shortly after the last settings with prisms.

At the end of the experiment, which lasted for approximately 2 hr., *S*s were questioned about their impression of the goggles they wore, and the method they used to set the bar to appear level. All were paid $3.00 for their time.

Results

The six experimental groups were approximately equal on the initial measurements. The average magnitude of the measured prism-induced curvature is about 20.5 cm. for all of them. The measurements made after the initial nonshooting viewing period may be expected to reflect the Gibson effect for the apparently curved conditions. Those *S*s who viewed the target moving back and forth along an apparently curved path changed an average of 1.42 cm. in the direction of adaptation. The change for *S*s in the apparently straight viewing conditions was −.10 cm. The difference between the two viewing conditions was highly significant, $t(34) = 5.39$, $p < .001$.

The data used to test the major hypotheses were the differences between settings of apparently straight following the shooting periods and the settings which followed the initial nonshooting viewing period. This computation presumably removed the Gibson effect from the comparison between the apparently straight and apparently curved experimental conditions. The adaptation data for each shooting period are shown in Table 4. A negative sign indicates a change opposite to the adaptive direction, i.e., more perceived curvature.

Examination of the data in this table shows that the average amount of adaptation appears to vary nonsystematically from period to period. An analysis of variance of the increase in adaptation from the first two to the last two shooting periods produced no significant differences. The analysis of the data is, hence, presented using the most reliable single measure reflecting the effects of the experimental manipulations, namely, the average amount of adaptation for all five periods. The mean adaptation for the two infrared conditions was .27 cm.; for the two visible light conditions it was −.38 cm. These means were significantly different, $F\ (1, 32) = 14.19$, $p < .001$; and both were significantly different from zero by *t* test. There was no difference in the average magnitude of adaptation between the two apparently straight and the two apparently curved conditions. For the two apparently straight groups combined the adaptation was .02 cm.; for the two apparently curved groups combined it was −.14 cm. Apparently the initial nonshooting viewing period did eliminate the Gibson effect.

TABLE 4

MEAN ADAPTATION AFTER EACH SHOOTING PERIOD (IN CENTIMETERS)

Period	Experimental Cond.					
	Apparently Curved		Apparently Straight		Supplementary Groups	
	Infrared	Visible Light	Infrared	Visible Light	Aim Only	No Information
1	.32	−.59	.17	−.32	.36	−.20
2	.09	−.36	.25	−.07	.07	−.19
3	.03	−.59	.43	−.14	.05	−.62
4	.20	−.48	.49	−.45	.14	−.10
5	.28	−.29	.40	−.57	.07	−.07
Avg.	.19	−.46	.35	−.31	.14	−.24

The *S*s shooting with the visible light were on target an average of 49% of the total shooting time. Those shooting with the infrared light were on target only 18% of the time. This difference reflects the difficulty of hitting the target with the infrared light. The major question of interest concerning the performance data is the relative increase for the two shooting conditions. It was expected that *S*s shooting with the infrared light would improve over periods as they learned the correct arm and hand movements. Those shooting with the visible light were expected to improve very little. Their task was one which could be mastered rapidly. An index of relative improvement, the difference between the average hit time for the last two periods and the average for the first two periods divided by the sum of these two averages, was computed for each *S*. The difference between indexes for the shooting conditions was significant, F (1, 32) = 11.55, $p < .01$. The *S*s shooting with the infrared light showed more relative improvement. There was no significant difference between those who viewed apparently straight or apparently curved lines. There was, however, a significant interaction, F (1, 32) = 5.39, $p < .05$. In the apparently straight conditions there was a large difference between the shooting conditions; in the apparently curved conditions there was little difference.

It was expected that there would be significant positive correlations between the relative increase in performance and the amount of visual adaptation for *S*s in the infrared conditions. As these *S*s learned to issue appropriate efference they would be expected to both improve in performance and to visually adapt. The correlations between these two measures in the visible light conditions were expected to be negligible; improvement in performance was not expected to be associated with visual change since the efference issued in this condition was not associated with the perception of contour. None of these correlations, however, approaches statistical significance for any of the four groups.

The difference between the final and initial settings of straight with the plain glass goggles indicates the extent to which any visual adaptation persisted for "naked eye" measurements. As would be expected from the Gibson normalization phenomenon, there was a significantly larger aftereffect, F (1, 32) = 5.55, $p < .05$, for *S*s who viewed an apparently curved line (.65 cm.) than for *S*s who viewed an apparently straight line (−.02 cm.). The aftereffect data, unlike the adaptation data, include the normalization effect since they were computed from the initial settings of straight with the plain glass goggles that were made before the nonshooting viewing period. The difference between the shooting conditions, although in the expected direction, was not significant. The average aftereffect for *S*s in the infrared condition is .50 cm.; for *S*s in the visible light condition it was .13 cm. There was no interaction of the shooting and viewing conditions.

As was mentioned, two additional, apparently straight groups were run to clarify the findings and interpretations of the basic experiment. The Aim-only group was designed to test the conditions necessary for visual adaptation; the No-information group was designed to determine the changes resulting from prolonged viewing of the target and bar. The results of these two groups were analyzed by a one-way analysis of variance in conjunction with the results from the infrared and visible light apparently straight groups.

The average visual adaptation for each of these groups is also presented in Table 4. Using the average adaptation for all five periods, the four apparently straight groups differ significantly, $F\ (3, 32) = 3.54$, $p < .05$. The infrared group is significantly different from both the visible light group, $t(32) = 2.81$, $p < .01$, and the No-information group, $t(32) = 2.51$, $p < .02$. None of the other internal comparisons is significant. There is no significant difference in the aftereffect data between these four groups.

Discussion

The results continued to support a theory emphasizing the role of efferent readiness in determining the perception of contour. Those *S*s who had to learn to issue a new set of efferent responses to the perceived contour of the target's movement adapted to the curvature transformation significantly more than those *S*s who made approximately the same motor movements and had the same visual input but responded only to the discrepancy between the position of a visible spot of light and the target. Both the rate and path of the arm and hand movements were similar in these two conditions, but the responses of the *S*s shooting with the visible light more closely approximated the actual contour. These *S*s were on target almost three times as long as those shooting with the infrared light. The proprioceptive input from the hand and arm is, hence, clearly not the basis for visual adaptation.

The results further demonstrate that not all active or self-produced movement results in adaptation to curvature as Held's (1961) theory suggests. Instead, these results support the hypothesis that the important variable is whether or not the active movements are learned, so that the efferent readiness will be activated by a pattern of retinal stimulation. Atypical visual reafference is assumed to have occurred in both the visible light and infrared conditions, yet visual adaptation was obtained in only one condition. It can be argued that the necessity to aim, and the consequent attention paid to the position of the arm and hand in the infrared condition, resulted in more salient or usable atypical visual reafference than that which occurred from merely seeing the arm and hand in the visible light condition. The Aim-only condition was designed to clarify the distinction between adaptation resulting from a change in efferent readiness and adaptation resulting from a change in the correlation between self-produced movement and visual reafference. Since there was no buzzer to guide the arm movements made by *S*s in the Aim-only condition, more attention to the position of the hand would be expected in this condition than in the infrared condition with the buzzer feedback. Therefore, the Aim-only condition might result in maximum adaptation if this attention factor were critical. This group, however, showed no more visual adaptation than the apparently straight, infrared group, indicating that special attention to the hand and arm was not critical.

The negative adaptation found in the visible light condition was unexpected. The No-information group was run to test one obvious explanation. It was possible that continued viewing through prism spectacles resulted, in this situation, in increased perception of curvature. The average change for *S*s in the No-information condition is −.24 cm.; for *S*s in the visible light apparently straight group it is −.31 cm. These figures are very close and it appears that this shift does occur simply as a consequence of continued viewing in this situation.

Two of the findings were not in accord with the theoretical expectations, namely, the lack of significant differences between the shooting conditions in aftereffect and the lack of correlation between visual adaptation and performance improvement in the infrared conditions. Rapid decay of unstable adaptation may account for the lack of significant differences in aftereffect between the two shooting conditions, since about 5 min. elapsed between the end of the final shooting period and the beginning of the aftereffect measurements. The lack of expected correlation may be explained by the relative unreliability of the measurements and the fact that the correlations are each based on only nine *S*s.

Experiment IV

If the efferent readiness that is activated by visual afferent input is important in determining the visual perception of contour, one might well expect that efferent readiness with respect to the extraocular muscles would be of particular importance. Considering the invariant relation that exists between eye movement and movement of stimulation across the retina, and considering the vast amount of experience that an individual has in establishing this relationship between input and output, it would not be surprising to find that efferent readiness relevant to eye movements was more intimately involved in visual perception than, for example, efferent readiness relevant to arm movements.

If this reasoning is correct, we would obtain, as we have obtained, only small amounts of change in visual perception of curvature when *S*s wear prism spectacles. Such spectacles produce a complex situation in which there is inconsistency between eye movements and other body movements that are evoked by the contour. If *S* engages in normal activity while wearing such spectacles, head movements, arm movements, and other body movements relevant to contour must conform to the objective shape. Thus, to the extent that these movements are in response to retinal input, *S* must learn new efference to associate with the visual input. He learns that he must move his head or his arm in a curved path in response to a straight pattern of retinal stimulation. These new afferent-efferent associations would presumably account for the observed change in the visual perception of curvature in the preceding experiments.

There is, however, one major hindrance to change of visual perception. During the entire experience with the prism spectacles, the relationship between retinal input and efferent output to the extraocular muscles remains unchanged. The eyes, in order to achieve or maintain fixation, must move in conformity to the retinal image and *not* to the objective contour. Hence, to the extent that efferent readiness relevant to eye movements is important, this would interfere with and retard any change of visual perception when prisms are worn in spectacles.

If a situation could be arranged in which the movements of the eye had to conform to the objective contour rather than the retinal contour while wearing prisms, change of visual perception might occur much more quickly and dramatically. This situation can, indeed, be achieved by putting the prism on a contact lens rather than in a spectacle frame, as was realized by Taylor (1962) who arranged to have a scleral contact lens manufactured for his own right eye with a prism on it. He reported that, after he found the proper procedure for scanning contours to make adaptation rate maximal, his adaptation to curvature distortion was complete after only a short period of scanning.

There are reasons for not placing complete reliance upon this report. Taylor reported no data concerning the amount of curvature distortion produced by the prism on his contact lens other than to say that "... the distortion was less than I had hoped for [p. 227]." However, it is likely that the curvature distortion produced by Taylor's contact lens was very small. Because a prism on a contact lens is curved to conform to the curvature of the cornea, there is much less curvature distortion obtained than from a prism with a plane surface. For example, in the experimental work presented here 30-diopter prisms were used on contact lenses. The amount of curvature distortion produced was about comparable to what one would obtain from a prism with a plane surface of 4–8 diopters. Taylor's prism of not quite 12 diopters probably produced very little curvature distortion.

Nonetheless, the theoretical issue raised by Taylor appears important. If the efferent readiness relevant to eye movements is especially important, we should be able to find large and rapid changes in visual perception from wearing a prism on a contact lens even if the only movement in which the person engages are eye movements. It was, consequently, decided to replicate Taylor's study under more controlled conditions, using several *S*s who were completely naive as to what was happening and using prisms of large enough power to be sure that the curvature distortion would be clear and unmistakable.

Method

Subjects.—Three Stanford University students, two male and one female, were paid to serve in the experiment. They were told that the study would involve wearing a scleral contact lens for which they would have to be individually fitted. None realized that the contact lens produced curvature distortion.

Apparatus.—The lenses were manufactured by the Parsons Optical Laboratories of San Francisco, California. They succeeded in producing 30-diopter prisms on the contact lenses. The surfaces of the lenses were, of course, smoothed and rounded; none of the *S*s complained of any pain, none of them had any difficulty blinking or closing their eyes during rest periods. The lens and prism were cast in one piece out of optical plastic and then ground. Each *S* wore the prism in the right eye, which was also the dominant eye, with the base of the prism down. None of the *S*s had completely clear, sharp vision through the prism. There was some slight blurring.

The manufacture of the prisms was not easy and did not proceed without mishap. For the first *S*, it was thought that the contact lens would be stable with the prism base oriented laterally. It was manufactured in this way but, when the lens was first inserted into the eye, it immediately rotated so that the base of the prism was down. It was, however, stable in this position and that is how *S* wore it in the experiment. A serious error was made in the manufacture of the lens for the second *S* so that it did not fit at all. Fortunately, it was discovered that the lens manufactured for the first *S* fit the second one perfectly, also base downward, and so the first two *S*s actually used the same lens. No problems were encountered in manufacturing or fitting the lens for the third *S*.

The experimental apparatus was the same one used in the first two experiments, except that it was positioned on its side so that the rods were horizontal rather than vertical. This was done because the prisms, mounted base down, produced curvature of horizontal straight lines.

Procedure.—For the experimental sessions *S*s were seated in front of the apparatus with the head in a biteboard so that the right eye was directly in front of the center of the lines. When in the experimental situation, *S* saw only the two brass rods, the white background, and a small portion of the side of the frame of the apparatus.

Several experimental sessions were conducted with each *S*, each session lasting for approximately 90 min. At the beginning of each session *S*, with the left eye occluded and head on the biteboard, was asked to turn the knob on the apparatus so as to see the horizontal lines straight with his naked right eye. Four such settings were taken. On two of these measurements *E* displaced the line upwards from apparently straight before asking *S* to make the setting. On the other two measurements the lines were displaced downward from apparently straight. For a few of the last sessions with the second *S* and for all of the sessions with the third *S*, such initial measurements were also taken for the naked left eye with the right eye occluded.

The *S* then inserted the contact lens into his right eye and, again with his head in the biteboard, was asked to make four settings of the lines using the same procedure. Care was taken by *E*, moving the lines back and forth before *S* opened his eyes, to prevent *S* realizing that there was any curvature distortion. The subsequent procedure differed somewhat from *S* to *S*. The following aspects of the procedure were common to all three *S*s.

After these measurements, the lines were set by *E*, while *S*'s eyes were closed, either so that they were objectively straight, corresponding to the average of the settings *S* had made with his naked right eye, or apparently straight, corresponding to the average of the settings *S* had made with the contact lens in the eye. In each session *S* was then asked to simply look back and forth along the line. He did this usually for 5 min., was then once more asked to set the line so that it was straight, and was then given a 2-min. rest period during which he closed his eye and removed his head from the biteboard. The *E* reset the lines to the same position before the next period of looking back and forth along the lines. After a number of such periods, usually 8–10, the contact lens was removed and final measurements using the naked eye were taken.

The first few sessions for each *S* were conducted with the lines set so that they looked straight to *S*. Later sessions for each *S* were conducted with the line set objectively straight, so that they looked curved. The final session for each *S* was conducted with the line objectively straight, but with *S* looking monocularly through a prism in a spectacle rather than wearing the contact lens. This was done to get some information as to the magnitude of adaptation one might expect simply from the Gibson effect (Gibson, 1933) under these circumstances. The details of the procedure for each *S* follow.

*S*1

Session I. Lines set apparently straight. Ten periods of scanning the lines, periods ranging from 2 to 5 min. in length.

Session II. Lines set apparently straight. Ten periods of scanning the lines, periods ranging from 3 to 6 min. in length.

Session III. Lines set apparently straight. Five periods of scanning, each period 5 or 6 min. long. This was followed by two periods, one 3 min. and the other 6 min. long during which *E* moved a pointer along the line and *S* was asked to track the motion with his eye.

Session IV. Lines set apparently straight. Five periods ranging from 5 to 8½ min. in which *S* moved a stylus back and forth along the lines while looking. This was followed by two periods, each 6 min. long, in which *S* simply scanned back and forth.

Session V. Lines set objectively straight. Ten periods, 5 min. each, of scanning the lines.

Session VI. Lines set objectively straight. Six periods, ranging from 5 to 8 min., of scanning the lines.

Section VII. Lines set objectively straight. The *S* looking monocularly through prism in spectacle, 8 periods of 5 min. each of scanning the lines.

The procedure was more standardized for *S*s 2 and 3. All sessions contained eight periods of 5 min. each. The following tabulation gives the exact schedule for each of them:

	Sessions for *S*2	Sessions for *S*3
Lines apparently straight, scanning	I, II, & III	I, II, & III
Lines apparently straight, track pointer	—	IV
Lines objectively straight, scanning	IV & V	V, VI, & VII
Lines objectively straight, track pointer	VI	VIII & IX
Lines objectively straight, scan with prism in spectacle	VII	X

Results and Discussion

In spite of the occasional procedural differences among the three *S*s, it seems most sensible to present the data for all three together. In this way the uniformities among the three will most easily be seen.

Course of adaptation within a day.—Table 5 presents the data for the average daily adaptation to the prismatic distortion for the first three sessions when *S*s scanned an apparently straight line. There were no appreciable differences within any *S* in the course of adaptation among the different days and so the data are presented in terms of 3-day averages. The time point labeled "0" refers to the average settings made at the beginning of the session immediately after the contact lens was inserted in the eye. The time point labeled "10 min." refers to the averages of the setting made after the first 5 min. and after the second 5 min. of scanning the line. The row labeled "20 min." presents the average settings made after the third and the fourth periods of 5 min. of scanning, and so on. For *S* 1 there were minor deviations from this because his scanning periods were not always 5 min. long.

The last row of the table presents the percentage of adaptation calculated as the percentage of the distance between objectively straight and apparently straight that *S* adapted during the day. Thus, *S* 1 set the line as straight with the naked eye at 10.10; apparently straight at the beginning of the sessions with prism averaged to 12.00; the adaptation of .41 cm. divided by the initially perceived curvature of 1.90 cm. yielded the percentage of adaptation of 21.6. It is clear that all three *S*s showed adaptation during the course of the day. For the second *S* the total adaptation was already present after 10 min. while the visual change seemed more gradual for the other two.

It has been well known since Gibson's (1933) article that some perceptual "adaptation" occurs simply by looking at a curved line. If one studies adaptation to prismatically induced curvature by exposing *S* to apparently curved lines, one cannot easily separate this Gibson effect from other possible adaptation processes. It is, hence, not inconsequential to show that, with all three *S*s, definite and appreciable adaptation was observed to an apparently straight line—a situation in which the Gibson effect would not be contributing.

TABLE 5

Course of Daily Adaptation to Prismatic Curvature Distortion While Viewing an Apparently Straight Line

Time of Setting with Prism	Subject		
	1	2	3
0 min.	12.00	12.17	10.88
10 min.	11.80	11.95	10.86
20 min.	11.65	11.94	10.71
30 min.	11.59	11.97	10.71
40 min.	—	11.95	10.69
Naked Eye Setting at Start of Session	10.10	10.10	9.99
Percentage of Adaptation at End of Session	21.6	10.6	21.3

Note.—Average readings (in centimeters) are of settings of apparently straight. Three-day averages for each *S* are presented.

Each *S* also spent several sessions, one each day, exposed to an actually straight, and hence apparently curved, line. Each day the line was set according to *S*'s own initial naked eye measurements at the beginning of that session. Table 6 presents the data for the course of daily adaptation for each *S*, averaged for all the days in which *S* scanned the apparently curved line. It is clear from these data that all three *S*s showed large amounts of adaptation to the apparently curved line, over 40% after 40 min. of scanning. The rapidity and magnitude of these visual changes lend support to the idea that efferent signals to the extraocular muscles are heavily involved in determining perception.

In comparing the data in Tables 5 and 6, it is very clear that the adaptation to the apparently curved line was much larger than to the apparently straight line. In order to have a better basis for evaluating the magnitude of the adaptation effects obtained by scanning the apparently curved line, a measurement was made for each *S* of the Gibson effect on the last day on which *S* was run. The *S*s 1 and 2 wore 25-diopter prism spectacles while *S* 3 wore a 10-diopter prism spectacle. Each *S* was seated farther from the apparatus in an attempt to roughly match the measurement of curvature obtained from

TABLE 6

DAILY ADAPTATION TO PRISMATIC CURVATURE DISTORTION WHILE VIEWING AN APPARENTLY CURVED LINE

Time of Measurement with Prism	Subject		
	1[a]	2[a]	3[b]
0 min.	12.26	12.13	11.19
10 min.	11.73	11.44	10.79
20 min.	11.50	11.48	10.66
30 min.	11.24	11.38	10.55
40 min.	11.13	11.26	10.48
Naked Eye Setting at Start of Session	9.82	9.98	9.67
Percentage of Adaptation at End of Session	46.3	40.5	46.7

Note.—Averages of "apparently straight" settings on centimeter scale.
[a] 2 days.
[b] 3 days.

TABLE 7

ADAPTATION TO PRISMATIC CURVATURE DISTORTION WHILE VIEWING AN APPARENTLY CURVED LINE WEARING PRISM SPECTACLES

Time of Measurement with Prism	Subject		
	1	2	3
0 min.	12.52	12.78	10.84
10 min.	12.41	12.81	10.56
20 min.	12.26	12.40	10.46
30 min.	12.16	12.42	10.51
40 min.	12.18	12.31	10.39
Naked Eye Setting at Start of Session	10.05	9.93	9.68
Percentage of Adaptation at End of Session	13.8	16.5	38.8

Note.—Averages of "apparently straight" settings on centimeter scale.

the contact lens. The line was set in accordance with the initial naked eye setting of straight on that day and *S* spent the rest of the session scanning the line in 5-min. periods with his head fixed by a biteboard. The line was viewed monocularly with the same eye as was used with the contact lens. Table 7 presents the data on adaptation attributable to the Gibson effect and Fig. 1 presents a comparison of the data from Tables 6 and 7, that is, a comparison of adaptation with spectacles attributable to the Gibson effect and adaptation with the prism on a contact lens. It is quite clear that the absolute magnitude of the Gibson effect was about the same for all three *S*s. The large percentage figure for *S* 3 was due to the small magnitude of the initial curvature that was produced. The amount of adaptation with the contact lens was greater for all *S*s than the magnitude that could be attributed to the Gibson effect.

Effect of saccadic and smooth tracking eye movements.—There is some evidence that would lead us to expect that, if the efferent readiness activated by a given retinal input determines the visual perception of contour, then adaptation to curvature distortion with a prism on a contact lens would be greater if the eye engages in saccadic movements than if the eye follows the contour with a smooth tracking movement. Rashbass (1961) reported that these two types of eye movements were controlled by different mechanisms in the central nervous system and that, while the saccadic movement was a fixation response, the smooth tracking movement was a response to direction and velocity of movement across the retina. This perhaps suggests that ef-

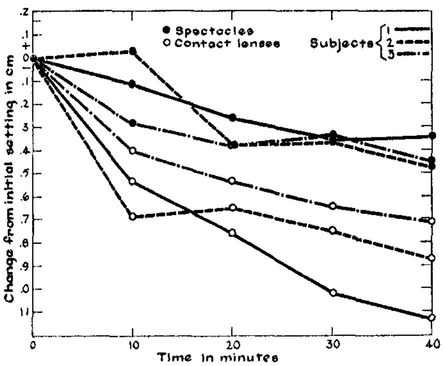

FIG. 1. Adaptation to apparent curvature for prisms in spectacles and on contact lenses.

ference issued to produce the smooth tracking motion is not coded in terms relevant to contour while the efference to produce a saccadic movement, or a series of them, would be more concerned with contour, that is, with specific position in space of the point fixated relative to the point of fixation from which the eye moved. Festinger and Canon (1965) reported data which lend some support to this. They showed that after saccadic eye movements there is better localization of the fixated point in space than after a smooth tracking eye movement.

Some exploration was done to investigate this suggestion. During sessions in which *S* was to engage in smooth tracking eye movements *E* moved a pointer back and forth along the line and asked *S* to follow the pointer. The movement of the pointer in this way obviously did not provide a very uniform smooth motion for *S* to track and, over a 5-min. period there was, undoubtedly, many saccadic movements, but it was felt that this procedure might, at least, provide *E*s with some preliminary information.

The third session for *S* 1 began as a free scanning session with an apparently straight line. After 29 min. of such scanning, *S* spent 9 min. following the tip of the pointer as *E* moved it. The effect was interesting. The initial straight setting on that day with the prism was 12.08; at the end of the 29 min. of scanning (saccadic eye movements) the settings of straight averaged 11.34, an adaptation of .74 cm. After an additional 9 min. of smooth tracking eye movements the settings of straight averaged 11.88, an adaptation of only .20 cm. Indeed, it seemed as though engaging in smooth tracking eye movements served to reduce adaptation that had already occurred during the session. No more "tracking" sessions were conducted with this *S*. This small bit of data was interesting enough, however, so that we explored it more systematically with the next two *S*s.

The *S* 2 spent one session tracking the pointer while viewing an apparently curved line. At the end of this session there was .67 cm. (30.6%) adaptation to the curvature. This is to be compared with .87 cm. (40.5%) adaptation on the previous 2 days when scanning the apparently curved line. The *S* 3 spent one session tracking while viewing an apparently straight line. There was no adaptation whatsoever during this session. The measurement at the end of the session showed a change of −.27 actually in the opposite direction from adaptation. He also spent two sessions tracking while viewing an apparently curved line. The average adaptation for these two sessions was .65 cm. (38.0%). The comparable figure for the previous 3 days of scanning was .71 cm. (46.7%). Thus, in all instances, there was less adaptation when tracking with smooth eye movements than when scanning with saccadic eye movements. The difference was smallest for *S* 3 when viewing the apparently curved line and greatest for this same *S* when viewing the apparently straight line.

Aftereffects of adaptation.—At the beginning, and at the end, of every session *S* was asked to set the line so that it was straight with the naked eye. By comparing these two sets of measurements, one can see whether or not there were aftereffects for the naked eye of the adaptation occurring during the session while *S* wore the contact lens. Table 8 presents these data. Examination of the data shows that, except for the first day, there was an aftereffect on each day for each *S*. After the first session, all three *S*s, on every day, showed a change from initial

TABLE 8

AFTEREFFECTS OF ADAPTATION FOR THE NAKED EYE AFTER WEARING CONTACT LENS

	Subject 1		Subject 2		Subject 3	
	Pre	Post	Pre	Post	Pre	Post
Day 1	10.02	10.11s	9.99	9.78s	9.94	9.96s
Day 2	10.22	10.14s	10.22	9.75s	10.09	9.78s
Day 3	10.06	9.78s	10.10	9.74s	9.94	9.76s
Day 4	9.99	9.80sv	10.04	9.41c	9.93	9.64st
Day 5	9.93	9.51c	9.92	9.27c	9.81	9.41c
Day 6	9.71	9.43c	9.89	9.26ct	9.69	9.33c
Day 7					9.51	9.27c
Day 8					9.54	9.26ct
Day 9					9.57	9.28ct

Note.—Averages of "apparently straight" settings on centimeter scale. s = viewed apparently straight line, c = viewed apparently curved line, t = tracked pointer, v = on this day *S* 1 moved a stylus along lines himself.

to final measurements with the naked eye in the same direction as the adaptation changes.

The data revealed another interesting result. There seems to be a cumulative effect over days in the settings made at the *beginning* of the session with the naked eye. Each of the three *S*s shows the same pattern. From the first to the second day the settings changed in a negative direction, that is, opposite to what would be expected on the basis of adaptation to the prism. From then on, however, each day showed a progressive effect, the naked eye settings at the beginning of the session becoming progressively more and more curved in the direction expected from adaptation.

There is no compelling reason to expect a carryover of adaptation to the prism from day to day. The *S* spent less than an hour each day looking through the prism and then had some 15 hr. of normal vision in which to readapt. It is, on the other hand, perfectly possible that a conditional adaptation and a conditional aftereffect might develop. That is, the stimulus conditions of the head in the biteboard in front of the apparatus could revive, or have become specifically associated with, the adaptation to the prism curvature and the progressive day to day cumulative effect could be due to the gradual development of this conditional learning.

This would be an attractive interpretation except for the fact that there exist data which make it implausible. If the progressive changes in initial settings with the naked eye at the beginning of each session are, indeed, due to conditional adaptation, then one would also expect to observe a similar cumulative effect on the first settings made on each day with the contact lens in the eye. No such trend for these settings was observed. Indeed, if anything, there was a tendency to perceive more and more curvature rather than less and less. It is difficult to believe that a conditional aftereffect had developed while, at the same time, a conditional adaptation had not developed.

Interocular transfer of aftereffects.—About midway through the period of experimentation with *S* 2, it occurred to *E*s that it would be interesting and valuable to obtain data on interocular transfer. Taylor (1962) implied that the aftereffects of adaptation with a prism on a contact lens did not transfer. He wrote: "The clearest evidence of adaptation came about half an hour after removal of the lens. Sitting in a stationary car I got the impression that the vertical lines of a tall building in front of me were not quite straight. I then inspected the lines monocularly, and found that with the right eye they were straight but with the left eye they were curved, the convexity being to the left, that is, the opposite of what I had seen through the lens [p. 225]."

Theoretically, the issue is important. If the change in visual perception is actually due to a change in the efferent readiness activated by the retinal input, then there is every reason to believe there would be considerable, if not complete, interocular transfer.

The first time that initial and final measurements with each naked eye were taken was in Session V for *S* 2. The change from initial to final setting for the naked right eye (the one that wore the contact lens during the session) was +.65 cm.; for the left eye the change was +.33 cm., about 50% transfer of the aftereffect from one eye to the other. These measurements were repeated in Session VI in which *S* 2 visually tracked the pointer that *E* moved. This time the aftereffect for the right eye was .63 cm. but for the left eye was only .07 cm., indicating virtually no transfer at all.

Interocular transfer of the aftereffect was measured systematically for every session with *S* 3. With this *S* there is no question but that the aftereffect transferred completely from the right to the left eye. The simplest way to present the data is by showing, on the same figure, the initial and final naked eye measurements on each day for each eye. This is shown in Fig. 2. It is clear that there was about 100% interocular transfer on every day except

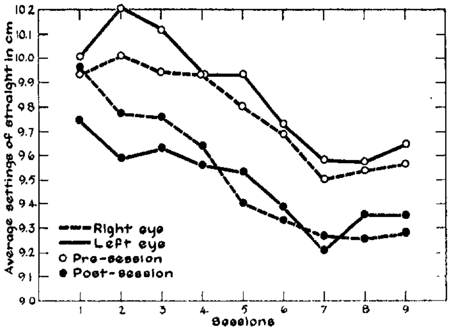

FIG. 2. Aftereffect and transfer of adaptation to apparent curvature for *S* 3.

Day 8 when the transfer was not quite as large, only about 75%.

DISCUSSION AND CONCLUSIONS

Toward the end of the nineteenth century many psychologists held that the efferent system was importantly related to consciousness. Such theories fell into disrepute, however, and remained only as historical curiosities.

Recent evidence, both of a psychological and physiological nature, indicates the value of reexamining such theoretical positions. Several persons have also, recently, proposed new theories that afford efferent activity and readiness for efferent activity an important place in determining conscious perception.

We have reviewed the evidence relating to this question and have stated an experimentally testable theory of visual perception of contour. This theory, which seems to fit known facts, holds that visual perception of contour is determined by the particular sets of preprogrammed efferent instructions that are activated by the visual input into a state of readiness for immediate use.

Four experiments were done to test whether or not the conscious experience of visual perception is determined by the efferent readiness activated by the visual input. In three of these experiments *S*s wore prism spectacles producing apparent curvature of straight lines and made arm movements corresponding to the objective contour of the lines while viewing them through the prisms. In each experiment one set of experimental conditions was designed to facilitate learning to issue new efference to the arm in response to the retinal contour and one set of conditions was designed to hinder such learning of a new afferent-efferent association. In all three experiments there was significantly more change in the visual perception of "straight" in the conditions that encouraged learning a new afferent-efferent association.

Theoretically the data support the view that visual input activates a whole set of learned efferent readinesses and that these latter determine the conscious experience of visual perception. In these three experiments *S*s in the Learning conditions learned to issue efference to the arm appropriate to a curved path in response to visual input of a straight path. During the measurements of the perception of straight no relevant arm movements were involved. Consequently, it seems reasonable to conclude that, having learned such a new afferent-efferent association, the visual input of a straight line now activates efferent readiness relevant to arm movement corresponding to a curved path. There is a consequent change in the visual perception.

In a fourth experiment change in the visual perception of curvature was measured for three *S*s who viewed a line monocularly through a wedge prism mounted on a contact lens. For each *S* the head was fixed by a biteboard and the only movement relevant to the contour was movement of the eyes. There is an important difference in the pattern of eye movements that *S* must make depending on whether the prism is mounted in spectacle frames or on a contact lens. In the former case, the eye in scanning the contour must move in accordance with the retinal image if fixation is to be maintained along the contour. However, if the prism is mounted on a contact lens so that the face of the prism moves as the eye moves, then the eye movements must conform to the objective contour in order to maintain fixation along the line. Under these circumstances the old, well-learned efference for an eye movement to fixate that is activated by visual input will result in a loss of fixation. To move the eye and maintain fixation along the contour, *S* wearing the contact lens must learn a new set of efferent instructions to issue in response to the visual input. If the conscious experience of visual perception of contour is, indeed, determined by efferent readiness activated by the visual input, then to the extent that *S* learns a new afferent-efferent association and, hence, a different efferent readiness is activated by the visual input, he will have a different visual perception of the contour.

In accordance with these theoretical expectations all three *S*s showed appreciable change in the visual perception of curvature as a consequence of simply scanning the line while wearing the contact lens. This occurred whether *S* viewed an apparently straight line or an apparently curved line. Further evidence suggests that there is appreciable, perhaps complete, interocular transfer of this change in perception of contour. The data also provide a hint that, if the eye movement involved is a smooth tracking movement, there is less change in visual perception than if the eye movements are saccadic.

While the data are not conclusive with regard to an "efference readiness" theory of visual perception, they do support the theory. All four experiments taken together provide considerable evidence that such a theory has some validity and merits further consideration and exploration.

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