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Constraints on perceptual learning: objects and dimensions

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Abstract

The article addresses two questions about perceptual learning: What are the circumstances which produce learning? What is the content of learning? For each question, a critical principle is suggested: (1) Objects are constrained to behave in certain ways. If a violation is detected, an internal malfunction is assumed and subsequently corrected. (2) Learning involves mappings between entire perceptual dimensions rather than associations between individual stimuli. The principles are applied to two phenomena: the classic adaptation to prism distorted vision and the more recent, but equally elusive, McCollough effect. The view suggests a new interpretation of the McCollough effect and accounts for findings difficult to account for in other interpretations including which stimuli can successfully lead to contingent after-effects, the outcome of correlation manipulations, and why the effect exists at all. In addition, the phenomenon is linked to prism adaptation, usually regarded as a distinct type of plasticity. In general, the view advanced is that the two principles help distinguish perceptual learning from other types of learning processes.

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1. Introduction

When cognition emerged as a new field, theories of learning were rejected along with the behaviorist philosophies behind them (see, for example, Adams, 1987, p. 57; Shanks & Dickinson, 1987, p. 256, for discussion). However, recently there has been renewed interest in how people learn and, moreover, ideas have profited from advances in cognition. For instance, the suggestion of a *domain-specific acquisition module* for just biological knowledge (Keil, 1992) is an outgrowth of cognition's interest in domain

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specific modules of processing (Fodor, 1983). The suggestion that *implicit memory* and *explicit memory* should be distinguished from one another (Schacter, 1987, 1992) could be reviewed as resonating with cognition's interest in whether conscious awareness is present or not during processing (e.g., Kihlstrom, 1990). One area of learning that has not yet enjoyed the progress of cognition is *perceptual learning*. The purpose of the present article is to take one small step towards similar modern advances in this domain.

Perceptual learning refers to changes in actual perception of the world, rather than to changes in thoughts, beliefs, knowledge, or reflexes. Two paradigmatic cases are the phenomena known as prism adaptation and the McCollough effect. The former involves a change in the perceived spatial *location* of objects while the latter refers to a change in the perceived *color* of a stimulus. Could processes responsible for such changes in perception have different rules than those responsible for changes in other types of cognition? Evolutionary considerations, as well as the idea of domain-specific modules of processing in cognition, suggest that learning processes with different goals may have evolved to solve those problems differently (e.g., Rozin & Schull, 1988). However, most analyses of perceptual learning phenomena, when they are even considered learning at all, have appealed to the traditional associative rules of learning (e.g., Epstein, 1967; Siegel & Allan, 1992; Taub, 1968), which were supposed to apply generally to all domains.

The present article suggests instead two critical principles that may well be unique to perceptual learning. The principles concern two fundamental topics in an analysis of learning. Rescorla (1988) suggests that there are three primary questions to be asked of any learning process: "What are the circumstances that produce learning? What is the content of the learning? How does that learning affect the behavior of the organism? (p. 151). The first two questions are addressed here. The first principle offered involves a condition necessary before experience will lead to a change in perception. To preview, I argue that constraints about objects play a central, hidden role in initiating perceptual learning. The second is a claim about the content of what is learned, once circumstances have allowed learning to take place. I will argue that perceptual learning always involves entire stimulus dimensions or continua, unlike most learning processes. These principles are applied to the McCollough effect, to produce a novel interpretation of that phenomenon. An explanation for the McCollough effect has remained elusive, and suggested explanations have recently led to controversy. In addition, the same principles are applied to prism adaptation, a phenomenon usually regarded to be quite different from the illusory colors.

In the next section, some background is provided which allows the general framework to emerge. In section 3, the two principles of the theory are introduced. The next seven sections are divided into two parts, for ease of reading a long manuscript. Part I deals with issues relevant to "getting learning to occur" (including sections on which stimuli successfully trigger learning, why get learning at all, and deciding what it is that should change), while Part II deals with "what gets learned" (including sections on contingency manipulations, one-pair training, two-pair training, and multipair training). The final section (section 11) compares the present interpretation to other classes of models and concludes.

2. Background

In the now classic phenomenon of prism adaptation, a wedge prism is placed between the eyes and the world causing everything to appear displaced a few inches to the left or right depending on the size and direction of the prism. Consequently, initial reaching and pointing will be unsuccessful as a person aims for the seen rather than the actual location. Following practice, often given by watching one's own hand through the prism, the error is eliminated. The correction persists when the prism is removed, and will manifest itself as an error in the direction opposite the initial error. The change in pointing that occurs to a visual target, whether measured with or without the prism, is known as adaptation (see Howard, 1982; Welch, 1978, 1986, for reviews). To produce the McCollough effect (1965), a magenta and black striped vertical grating is alternated with a green and black striped horizontal grating. Following a few minutes of induction, a colorless (achromatic) vertical grating elicits the perception of a weakly saturated green, and an achromatic horizontal grating appears pink (see Harris, 1980; Stromeyer, 1978; and Skowbo, 1984, for reviews).

Both phenomena involve changes in perception as a result of experience; prism adaptation involves a change in perceived location, and the McCollough effect involves a change in perceived color. Perhaps as a consequence of this similarity, a few researchers have been interested in both (e.g., Harris, 1980; Held, 1968, 1980; Uhlarik, 1974; Uhlarik, Pringle, & Brigell, 1977). Usually, however, different researchers study the two phenomena, the research questions differ, and in addition, there exists no common explanatory framework.[1] Are the phenomena too different from one another to draw meaningful parallels?

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[1] McCollough's work originated in part by interest in the phenomenon of "phantom" color fringes, where, after wearing prisms for a long time, colors seem to become contingent on vertical edges. She then did her experiment with orientation and color, and isolated the phenomenon without using the prism (McCollough, 1965, see also Held, 1980; Stromeyer, 1978). Since then, the McCollough effect and prism adaptation have been studied independently.

Harris (1980) suggests that the two effects are very different kinds of plasticity. He argues that the change in pointing that occurs in prism adaptation is due to a change in the felt position sense of the hand or some other body part, whereas the McCollough effect reflects a genuine change in vision. However, analogs to the McCollough effect have been found entirely outside the visual modality. For instance, when tw[illegible]nt-length rectangles were felt with the hand while each was paired with a different hand position, opposite-length after-effects became contingent on the different hand positions (Walker & Shea, 1974). Conversely, adaptation to rearranged vision need not involve the motor system or felt positions of body parts in any straightforward way, such as when the visually localized positions of objects are displaced with respect to the positions localized through audition rather than through proprioception. While a distinction based on visual/non-visual change is usually true for the prototypic demonstrations, both phenomena are more general and not limited to particular modalities.

Perhaps a more serious obstacle towards a unitary framework is that the basis of adaptation to prism distorted vision and other rearrangements appears inapplicable to contingent after-affects. Adaptation has been defined as "... a semipermanent change of perception or perceptual-motor coordination that serves to reduce or eliminate a registered discrepancy between or within sensory modalities or the errors in behavior induced by this discrepancy" (Welch, 1978, p. 8). When the hand is seen through the prism there is a discrepancy between where it is seen and where it is felt. Reduction of a discrepancy is virtually never mentioned as applicable to the McCollough effect (but see Dodwell & Humphrey, 1990, for a different use of discrepancy). However, if one considers what underlies the concept of a discrepancy, as it is used in prism adaptation, the general framework begins to emerge.

Why is it considered a "discrepancy" when seen and felt positions have different values? Wallach (1968) suggests that whenever two cues determine the same perceptual parameter and no longer provide the same value, there is a discrepancy between the two cues and this information provides the basis and motivation for adaptation. That is, the seen and felt position *usually* provide the same value about location, and now they don't. Yet one can go one step further back and ask: why is *that* considered a discrepancy? I have argued elsewhere (Bedford, 1993a) that the reason why a difference in the seen and felt position is problematic and requires action is because in our physical world an object can only be in one place at any one time; moreover, it is likely that such a pervasive constraint on our world has been internalized by our perceptual systems (cf. Shepard, 1984, 1987, 1991, 1992). Otherwise, detecting an object in two distinct places would seem unremarkable. The analysis that internal constraints underlay prism adaptation leads to the present interpretation of the McCollough effect and of perceptual learning in general.

3. A perceptual learning theory

3.1. General framework

I will use the term *perceptual learning* to refer, broadly, to a change in perception that results from experience. To be slightly more specific, perceptual learning has occurred if, at time 1, a particular proximal stimulus leads to percept X and then at time 2 the same proximal stimulus leads to percept Y. But why should a change in perception ever occur? Why conclude a proximal stimulus pattern reflects something different in the world than it did before? If perceptual interpretations were to change haphazardly or on a whim, then our perception of the world would constantly shift and be chaotic. The same input from the world would look or sound or feel different from one moment to the next. Consequently, there must be evidence that internal sensory systems are not functioning optimally before there is sufficient motivation for perceptual systems to change. Without this motivation, the experience will be used to change knowledge or expectations or reflexes, but not perception. This, in part, distinguishes perceptual learning from other types of learning processes.

The circumstances which motivate actual perceptual learning then are limited. There must first be evidence that perceptual systems are not operating as they should be. But that makes the problem even trickier. What kind of evidence coming from the world would signal an internal error? Why wouldn't a new proximal stimulus pattern be interpreted as a new, yet to be learned aspect of the world? I believe the answer to this paradox involves basic internalized constraints about the world (see Bedford, 1993b, 1994). Those constraints are either innate, or well in place early. If sensory systems appear to violate the fundamental constraints, then this information conveys that there must be an internal error.

Evidence from both adults (Shepard, 1984) and babies (Spelke, 1990) suggest that many of those constraints center around the nature and behavior of *objects*. This may be why objects are critical to the issue of circumstances necessary to produce learning, as will be seen.

Once the motivation for perceptual learning is present, internal systems change. At this point, I suggest it is *dimensions* which becomes critical. Why dimensions? It may be that perceptual systems in general operate on dimensions, as suggested by psychophysical and physiological evidence (cf. Graham, 1992). I turn now to the specifics of the theory.

3.2. Circumstances necessary to produce learning: object constraints

Perceptual learning will occur only if there is evidence of an internal error. This evidence can be obtained if information coming from the world conflicts with internal constraints on what we know must be true of the world. For prism adaptation, the relevant internal constraint is that an object cannot be in two places at the same time, as discussed earlier. When looking through the prism, an object, such as the hand, is localized in one place visually but a different place proprioceptively.

Considering the McCollough effect, there appears to be a hidden violation. When an experimental induction procedure pairs a vertical grating with red and a horizontal grating with green, I argue that the visual system is being provided with information that as the retinal orientation of an object – the grating – changes so does the object's color. This is problematic because when the orientation of an object on the retina changes, whether due to head tilt or object tilt, color should not. The new relationship between orientation and color can be considered a "discrepancy" because objects do not usually change their selective reflection of wavelength, in an analogous way that the new relationship between seen and felt positions is a discrepancy because objects occupy only one position in space at one time.

For both phenomena, the resolution to the dilemma includes preserving the real-world constraints. In prism adaptation, the change occurs within one or both modalities such that visual and proprioceptive positions will again coincide. Critically, the assumptions that one object occupies only one place is not relinquished. For instance, following practice with a prism that displaces objects visually to the right, a subject may come to feel as if her arm is also located a few inches further to the right. Consequently, when she is looking through those prisms, both visual and proprioceptive input from an object will again be identical, if adaptation is complete. Note if tested without prisms, the subject will appear to point too far to the left.

For the McCollough effect, the assumption that objects do not change color when the head or object is tilted is also preserved. There will be an internal correction for the perceived color differences, such that different orientations of the same object will no longer have different colors. Red vertical lines and green horizontal lines should eventually appear exactly the same color, if the correction is complete. If tested on achromatic lines, vertical will appear green and horizontal will look red.

According to the present interpretation, both phenomena occur because of sensory information that perceptions are discrepant with internal assumptions about real world objects. Perceptions are modified to preserve the assumptions and to restore the systems to what is believed to be good working order. Both phenomena are manifestation of this internal adjustment.

3.3. *Content of learning: dimensions*

Whereas the first assumption involves circumstances necessary to produce learning, the second is about the content of what is learned. Both phenomena involve acquiring a new mapping between *dimensions*. In prism adaptation, those dimensions are the set of positions from left to right at a particular height as they are localized visually, and the same set of positions as they are localized with the arm, or proprioceptively (Bedford, 1989, 1993a, 1993b). Both dimensions range from roughly −180° to +180°, where the central value, 0°, is straight ahead of the nose. In the McCollough effect, one dimension is a red/green opponent dimension (cf. Hurvich & Jameson, 1957) ranging from one extreme which is activated by imaginary red containing no white, green, blue or yellow, through less strong red responses, through a central point of neither red nor green activity, to maximal green response at the other extreme, which can be produced with a completely saturated green containing no trace of white, red, blue or yellow. The relative activity within the red/green dimension can be described by a scale from −1.0 through +1.0, where negative numbers arbitrarily refer to green and positive numbers to red. The other dimension is orientation, the set of tilts from 0° through 180°, where the ending point is the same as the starting point.

Information about a mapping is obtained by pairing instances from the two dimensions in close temporal proximity. A 10° prism displacement produces a series of visual–proprioceptive [v,p] input pairs: a 10° visual location will co-occur with a 20° proprioceptive location [10,20], a 5° visual location with a 15° proprioceptive location [5,15], straight ahead with 10° [0,10], and so forth. In the McCollough effect, vertical lines (0°) will be paired with a highly saturated magenta of a particular intensity, which together will produce a certain level of "red" activity (y), and horizontal lines (90°) paired with green of approximately the same magnitude of activity (−y). Although only two values from each dimension are paired, it is argued that this training procedure is a degraded version of presenting more complete information, such as pairing 45° with an achromatic stimulus [45,0], 22.5° with 1/2y, 67.5° with −1/2y, and so forth, along with the two usually presented pairs. Varying the level of activation within the red–green mechanism to intermediate values between −y and y can be accomplished experimentally by keeping the overall intensity levels fixed while decreasing the saturation.

Association by temporal proximity has been suggested before as involved both in the McCollough effect and in prism adaptation. For the McCollough effect, the most well-developed associative explanation is that the phenomenon is an instance of Pavlovian conditioning, where vertical lines serve as the conditioned stimulus and the color red as the unconditioned stimulus (e.g., Allan & Siegel, 1986; Murch, 1976; see Siegel, Allan, & Eissenberg, 1992, for review). After repeated pairings of the two stimuli, vertical lines presented alone will produce a conditioned opponent response of green. Prism adaptation also has a long history of being compared to traditional learning processes (e.g., Epstein, 1976; Taub, 1968; Taylor, 1962). Like these explanations, the present interpretation invokes the notion of pairing; however, it is not a conditioning model. In the perceptual learning interpretation, the pairs are used only to extract an underlying relation between entire dimensions of stimuli, whereas in conditioning models it is the individual associations themselves which are learned. Models based on associating single stimuli make different predictions from those based on mappings between dimensions of stimuli (e.g., Bedford, 1989, 1993a, 1993b; Koh & Meyer, 1991). Recent work in my lab suggests that a dimension learning process is more suitable for learning new spatial mappings. I suggest that such a view is also more appropriate for the perceptual learning phenomenon of the McCollough effect.

To summarize the specific application to the McCollough effect, there are two novel interpretations:

(1) Objects should not change their color when the head (or object) is tilted. If they appear to do so, then an internal correction is necessary, the manifestation of which is called the McCollough effect.
(2) The McCollough effect involves learning a mapping between entire dimensions of orientation and color rather than learning two specific red–vertical and green–horizontal associations.

PART I: GETTING LEARNING TO OCCUR

4. Stimuli capable of inducing the phenomena

For both prism adaptation and the McCollough effect, the changes in perception result when internalized constraints about real-world objects appear to be violated. Consequently, if information contained in the proximal stimulus is not contrary to the constraints, then internal changes are not necessary and will not occur. This consideration leads to an important set of predictions about when experience will lead to the perceptual learning phenomena. Specifically, a difference in the spatial localization by visual and touch modalities is problematic only if both values refer to *exactly the same object*, because different objects can be in different places. Similarly, the co-occurrence of colors and orientation is problematic only if the different colors refer to the *same object* in different orientations, because different objects can have different colors. There are no constraints which prohibit different objects from being in different places or being different colors. Consequently, for both phenomena, the extent to which a training/induction/exposure procedure is successful will depend on the extent to which the perceptual system makes the judgement that the same object is involved.

4.1. *Prism adaptation*

For prism-distorted vision then, perceptual learning should occur only when the stimulus localized visually and the stimulus localized proprioceptively are judged to refer to one and the same object. Empirical and theoretical work developed largely by Robert Welch suggests that this is indeed the case ("unity assumption", Welch, 1972, 1978; Welch & Warren, 1980). In one study (Welch, 1972), the experimenter placed his finger coated with luminous paint a few inches to the side of a subject's finger. Subjects pointed to illuminated targets in a otherwise darkened room. They could also see the experimenter's glow in the dark finger – but not their own – at the end of each pointing attempt. When the subject's finger was aligned with the target, the sham finger appeared to the side of the target, much as it would if looking at one's own finger through a prism. Though the subjects looked only through window glass, they nonetheless showed genuine adaptation following a few minutes of training. Objectively, no physical constraint was violated. The seen and felt positions of the fingers were different only because they were judging different objects. Yet a perceptual change occurred anyway because subjects at some level falsely assumed that the experimenter's finger was their own, and assumed that the information from the different modalities referred to the same object. In general, the greater the conviction that a single object was involved, the greater the effectiveness of the training procedure.

The study demonstrates that adaptation occurs when seen and felt positions believed to result from the same object appear to differ, even when in reality they do not. The opposite effect can also occur, whereby adaptation is prevented when an actual difference is present, but the discrepancy between seen and felt positions is falsely assumed to refer to two distinct objects. Hein (1960s; personal communication, February 1991) had subjects hold a pencil while looking through a prism; each subject saw only the pencil, rather than the hand holding the pencil, while pointing to targets. This condition did not produce any adaptation. The position of a subject's hand will be localized through proprioception to be in a certain location; if the discrepant visual location produced by the prism is attributed only to the pencil rather than the hand, then different objects will merely be judged to have different positions. No conflict is detected, despite the presence of a physical discrepancy.

The pencil manipulation may be similar to the procedures used in a few other studies (Wooster, 1923; Lackner, 1974, 1977; Welch, 1978) which used "tactual feedback" where only indirect visual feedback is provided. For instance, a subject sees the top of a rod while looking through a prism, while she feels only the bottom half which is hidden from view beneath an occluding surface. Welch (1978) suggests that these procedures produce less adaptation than more direct visual feedback because the tendency for subjects to register the two sensory events as arising from a single distal source is reduced.

Note that in the study just discussed, the object that gets localized by the two modalities is a rod, rather than the subject's hand. The issue of which stimuli – hands versus rods, for instance – can induce adaptation to prisms has been of little concern. This may be in part because the majority of studies use the subject's *own hand* as a stimuli. When looking at one's hand moving through a prism, the different seen and felt positions of the hand seem to be quite naturally and automatically assumed to refer to only one hand. Why identity is assumed is not precisely known but the richness of the proprioceptive and visual information of one's own moving hand, as well as the temporal simultaneity and synchrony, may be contributing factors (e.g., Held & Durlach, 1991). In the related problem of jointly localizing objects using vision and audition, rather than vision and proprioception, external objects have been used more often, ranging from a single noisy flashing light (Radeau & Bertelson, 1974) to complicated objects such as talking people and whistling tea kettles (e.g., Jackson, 1953). And in these studies, the issue of object identity and effective stimuli has been more central. An experiment may induce a discrepancy between vision and audition by flashing an LED in one location and sounding a noise at the same time which really originates from a hidden speakers nearby. Here too, stimuli are more likely to induce adaptation and visual capture (ventriloquism effect)[2] when they provide many cues to suggest that the visual and auditory signals really come from the same object despite the difference in their locations (Jackson, 1953; Jack & Thurlow, 1973; Radeau & Bertelson, 1974, 1977; see also Radeau, 1994). Stimuli such as a film of a person talking with the voice coming from a few inches away are very effective, whereas a single light and sound which are temporally unsynchronized is not effective at all.

The studies all suggest that the decision on whether the inputs from the two different modalities refer to the same object is critical in adaptation, even though the issue it leads to – which stimuli are effective – has not always been of concern.

4.2. *McCollough effect*

I argue that the object identity decision is critical in the McCollough effect as well. Here, the two inputs are from two different times in the same modality, rather than two different modalities at the same time. This view provides a novel basis for predicting which stimuli are capable of inducing a contingent after-effect.

The issue of which stimuli are effective has become a prolific topic of investigation in this domain. Vertical and horizontal lines are not the only stimuli that can produce a contingent color after-effect. For instance, if green wide bars (e.g., 5 cycles per degree) are alternated with magenta

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[2] Visual capture refers to the short-term resolution to the conflict between two modalities, whereas adaptation is the long-term solution. Many investigators (e.g., Hay, Pick & Ikeda, 1965; Radeau & Bertelson, 1974), though not all (Welch & Warren, 1980) believe both phenomena are due to the same underlying process.

narrow bars (e.g., 10 cycles per degree), then pink is seen when shown achromatic wide bars and green when shown achromatic narrow bars (Harris, 1970; Lovegrove & Over, 1972). The issue has been central to research in part because it is thought to distinguish between two major classes of theories. I first summarize those theories and conclusions, before getting to the current reinterpretation.

Harris (1980) summarized the two classes of theories as follows. In one class, there is a response change, usually a decrease in sensitivity, within single, prewired, neural units that are responsive to combinations of orientation and color. In the other class, there is a change in the linkage between separate units for orientation and color. Harris argued that as the list of stimuli which produce contingent after-effects grows, explanations based upon a change within a single unit become less plausible because too many specialized "double-duty" detectors would have to be proposed. On the other hand, a straightforward interpretation of the most well-developed associative model, Pavlovian conditioning, predicts that any two discriminable stimuli should be capable of inducing different responses. Thus, the former "neural adaptation" model seem to predict that relatively few stimuli should be effective, whereas the later "associative" models seem to predict that most should be. Although there have been many refinements to theories, especially Pavlovian ones (see section 4.2.4), subsequent researchers have agreed with this general division of predictions into "few" versus "many" stimuli (e.g., Dodwell & Humphrey, 1990; Skowbo, 1984, 1986; Stromeyer, 1978; see also Siegel et al., 1992; Westbrook & Harrison, 1984). What do the data look like?

4.2.1. *Successes*

There have been many reports of newly discovered contingent after-effects in the last twenty-five years. Besides two orientations, red and green paired with two gratings of different spatial frequencies (Lovegrove & Over, 1972; Breitmeyer & Cooper, 1972), two different directions of motion (Hepler, 1968), two different velocities (Hepler, 1971), or two different lightnesses of a frame (Siegel et al., 1992) all produce contingent color after-effects. In addition, the reverse effects have been demonstrated. Two different orientations have been made contingent on two different colors such that following induction, objectively vertical lines will appear tilted one way when red, and the other way when green (Held & Shattuck, 1971). Motion has also been made contingent on colors, such that a red stationary grating will appear to go up (for instance) while a green stationary grating appears to go down. Orientation can become contingent on aspects other than color, such as spatial frequency. Finally, neither orientation nor color need be present. Motion can become contingent on spatial frequency and on brightness (see Stromeyer, 1978; and Skowbo, Timney, Gentry & Morant, 1975, for reviews). The abundance of demonstrations appears to support an associative account (Allan & Siegel, 1986; Siegel & Allan, 1985; Siegel et al., 1992; Sloane, Ost, Etheriedge, & Henderlite, 1989).

4.2.2. Failures

However, there are also many failures. Though there is a bias towards reporting successes, there are enough reported failed attempts to suggest that there exist many stimuli which are not very effective. When a magenta square and a green cross were alternated every 15 s for 10 min, color was not seen when tested on an achromatic square (Foreit & Ambler, 1978). Yet a single magenta horizontal bar alternated with a single green vertical bar using the identical temporal parameters and procedure did produce contingent color after-effects.[3] The alternation of two concentric circle patterns with different spatial frequencies produces contingent after-effects, but concentric circles of one color alternated with radiating lines of another were reported not to (Fidell, 1968, reported in Skowbo et al., 1975). In a series of 10 experiments (Mayhew & Anstis, 1972), opposite directions of motion of a disk were paired with red and green color, bright and dim light, and on broad and narrow stripes. All conditions produced motion after-effects contingent on the appropriate stimuli. The authors report, although they do not provide details, that they tried pairing one direction of motion with small disks and the other with small triangles, but could not produce any after-effect. Finally, as White and Riggs (1974) note, no one has ever reported color contingent on different makes of automobiles. These authors (Foreit & Ambler, 1978; Mayhew & Anstis, 1972) and others (Dodwell & Humphrey, 1990; Skowbo, 1984, Stromeyer, 1978) have argued that these failures provide evidence against a Pavlovian conditioning explanation.

4.2.3. Reconciliation

The evidence on stimuli capable of inducing the effect seems to fall somewhere in the middle of proposing a separate double-duty detector for each pair, and an association between detectors based on classical conditioning. Researchers who favor the conditioning interpretation have been impressed by the large number of effective stimuli, whereas researchers more inclined towards the single-unit models have been impressed by the large number of failures. The present approach provides a novel way of understanding the failures as well as the successes. I begin with the basic reinterpretation and more detailed considerations will be offered in section 4.2.6.

The induction procedure will be successful only to the extent that the same object is involved. Otherwise, no constraint is violated and there is no discrepancy. The reason the square and cross stimuli were ineffective is because the retinal image of a cross and the retinal image of a square cannot refer to the same object – assuming objects maintain rigidity. Consequently, pairing a red square and a green cross is not a discrepancy. Different objects can reflect different wavelengths of light. Unless the two pairs refer to the

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[3] A recent attempt by Siegel et al. (1992) has had more success with the square and the cross. The issue of stimuli which lead to weak effects but may still be possible are discussed in section 4.2.6, which deals with more detailed considerations.

same object, there is no motivation for an actual perceptual change The same argument applies to pairing small triangles and small circles. There is no normal transformation that turns triangles into circles. That is, retinal images of triangles and circles always refer to different objects. No internal malfunction will be detected, or corrected, and no illusory colors manifested.

This is not to say that nothing will be learned in the situation where a triangle is repeatedly red, and a circle repeatedly green. An organism would be foolish not to take notice of a such a pervasive contingency. But what will be learned will be about the *external world* and not about *internal perceptual systems*. Such learning could manifest itself as changes in thoughts, expectations, beliefs or behaviors, but there is no need to alter what is seen because there is no internal malfunction.

Alternatively, the successful pairings occur when the two members of the pair can be interpreted as referring to a single object. Two concentric circle patterns of different spatial frequencies can refer to the exact same concentric circle pattern seen at different distances, because spatial frequency changes as a function of distance. A vertical bar and a horizontal bar can refer to the exact same bar viewed either with the head upright, or tilted by 90°. A light-gray disk and a dark-gray disk can be the same disk under different overall levels of illumination. Gratings moving up and moving down on the retina can result from the exact same grating viewed with different up and down head motions. Different velocities can result from different speeds of head motion. Once the "same object" constraint is met, then one of the required conditions for a discrepancy is met. When the retinal image of a single object tilts, the apparent color of the object should not change; when the distance between an object and an observer changes, the color should not change; when the distance from an object changes, the velocity should not change, and so on.

Note also that the successful stimuli are different values along one dimension. Vertical and horizontal lines differ along the orientation dimension, bright and dim lights differ in intensity, narrow and wide bars in spatial frequency, etc. Although a square and a cross (or small triangles and small disks) differ in form, form is not a single dimension. One could not unambiguously specify those stimuli that fall in between a small triangle and a disk. This provides a link to the other aspect of the present model: dimensions get associated, not single stimuli. Typically, perceptual dimensions are those where each value along the dimension is related to the other by a simple transformation that occurs naturally through bodily motion or through changes in lighting conditions.

4.2.4. *Pavlovian alternative*

A Pavlovian conditioning explanation also has an account of the failures. Harris (1980) pointed out that associations in conditioning do not seem to be arbitrary, a finding well known in animal learning. A famous example comes from taste aversion learning, where tastes appear to produce better conditioning than sounds or sights when all are paired with illness induced by poisoning (Garcia & Koelling, 1966). If you get sick following dinner, you'd be more likely on a subsequent day to avoid the flavor of the food, and not the dinner plate on which it was served (see, for example, Rozin & Schull, 1988). Harris argues that if in Pavlovian conditioning some relations are more predisposed than others, then this may account for the failures in the McCollough effect as well. This position has been adopted by others (Allan & Siegel, 1986; Siegel & Allan, 1985, 1987; Siegel et al., 1992).

Yet it is not clear that the concept of selective association is being applied to the McCollough effect in exactly the same way as it is found in Pavlovian conditioning. The standard way to demonstrate selective associability phenomena in conditioning is to show that the stimulus which fails to elicit conditioning with one unconditioned stimulus will still succeed with a *different* unconditioned stimulus; this aspect does not appear to be present for the McCollough effect. In the classical animal learning study, Garcia and Koelling (1966) showed that rats avoided a novel taste and not lights and sounds when poisoned, but avoided the lights and sounds and not the taste when given electric shock. This "cross-over", where a conditioned stimulus (CS) which fails with one unconditioned stimulus (US) succeeds with a different US, has become the paradigmatic design for demonstrating selective associations in animals (see Rozin and Schull, 1988, p. 512). Without the "cross-over", it is difficult to demonstrate that the selective association isn't simply due to the CS itself rather than the CS–US relation. For instance, if lights and sounds didn't get associated with shock either, then perhaps the rats simply never saw/heard or noticed the lights and sounds. If tastes always led to superior conditioning with all USs, poisoning and shock alike, then there is nothing special about a taste–poisoning bond. In the McCollough effect, disks and triangles paired with different direction of motion did not produce a motion after-effect contingent on the appropriate form. An exact parallel to the selective associations in conditioning predicts that there should be some feature besides motion to which the form stimuli *can* be successfully associated: color or lightness or size, for instance. This has not been previously demonstrated. (Note that according to the present explanation, it will not be. A disk and triangle will be always be less effective than a small disk and a large disk – regardless of which dimension you choose to pair with them. The retinal images of a small disk and large disk will always be more likely to come from the same object than the retinal images of a disk and a triangle, regardless of whether they appear to change in color or motion or spatial frequency, etc.)

In addition, there is a common-sense appeal to the findings on selective associations in Pavlovian conditioning, grounded in evolutionary considerations, which appears absent when selective associations are applied to the McCollough effect. Tastes and not noises get associated with internal illness, because in nature it is the ingestion of chemicals within food that poison us.

Sounds rather than tastes get blamed for foot shocks, because external stimuli produce most tissue damage. Pictures of snakes produce more effective fear conditioning than pictures of flowers (Ohman, Fredrikson, Hugdahl, & Rimmo, 1976) because it is sensible to come prepared to be afraid of potentially attacking snakes than immobile flowers. All these links would be adaptive to the organism, yet there has been no adaptive reason offered for why a vertical grid and a red color should go together more than a cross and a red color.

Finally, consider that there is no basis to predict which stimuli will be effective and which will not. The imprecise idea of selective associations predicts there can be some failures but provides no guidelines for how to choose which pairs will work and which will not.

What should one conclude from these considerations about a Pavlovian account of the association failures in the McCollough effect? Neither the lack of exact parallels, nor the lack of principled reasons for predicting which stimuli will work, *prove* that a Pavlovian model is wrong. There is no guarantee that a correct explanation must be an elegant one. However, they may help to illustrate that a Pavlovian model simply cannot be disproved from data on the issue of stimuli capable of inducing the phenomenon. Any new pair of stimuli which work are viewed as a testament to the well-known remarkable arbitrariness of Pavlovian associations; any new pair of stimuli which fail are accounted for by the also well-known limits to that arbitrariness. Evidence for or against the revised Pavlovian account must come from a different issue.

The present perceptual learning account is an alternative that does specifically address the issue of effective stimuli. It provides a basis for predicting *which* stimuli will be effective, rather than predicting simply that relatively many stimuli (some Pavlovian models) or few stimuli (neural adaptation models) will be effective. Whether they are considered many or few depends on one's assessment of whether all the perceptual dimensions taken two at a time are thought to be many or few stimuli.

4.2.5. *Some simple predictions*

Small disks and small triangles paired with motion or color will not produce a contingent after-effect. But the same small disks alternating with large disks, or small triangles and large triangles should be effective. This would suggest that it was not the disk or the triangle itself which prevented successful induction. The size manipulation would be effective because the two triangles or different sizes can be interpreted as the same triangle seen from two different distances. Siegel et al. (1992) have found that a green isosceles triangles pointing up and a red isosceles triangle pointing down are effective in eliciting color after-effects, thus showing that small forms other than bars can be used successfully. This was an important demonstration because one interpretation of prior failures was that forms, unlike simple bars, cannot be used to induce a contingent after-effect. Note, though, that the two triangles images can be interpreted as the same triangle viewed from different orientations, thus satisfying the present "same object" requirement. Since forms can be used successfully, and since colors and motions have been made contingent on size (spatial frequency), a demonstration using small and large circles or triangles would not be too surprising.

Somewhat more compelling would be successful induction using a red circle and a green ellipse. Because the retinal image of a circle seen at a slant will be elliptical, circles and ellipses can refer to the same object. The present interpretation predicts that the alternation of a red circle and a green ellipse should be more effective at producing a contingent color after-effect than the alternation of a red circle and a green triangle. Such a color after-effect, if successful, would appear to be contingent on actual shape of a form rather than its size or orientation (though it would really be contingent on slant in the third dimension). In general, whenever two stimuli fall along a single dimension such that an interpretation that it is the same stimulus is possible, the stimuli can lead to a contingent after-effect.

4.2.6. Further predictions: the case of apparent motion

Most of the discussion thus far has divided situations simply into those that will succeed and those that will fail. This would follow if the object identity decision were a simple one. But there is evidence to the contrary from a different domain – that of apparent motion. Apparent motion refers to the illusion of motion experienced when two stationary stimuli are flashed on and off sequentially in two different locations. Central to the phenomenon is the issue of when two stimuli are judged to refer to the same object (e.g., Ullman, 1979), and some have used apparent motion as a tool to uncover those criteria (e.g., Chen, 1985; Warren, 1977). Only when the two alternating stimuli are judged to refer to the same object will a person experience a single object as moving (and transforming) back and forth. Otherwise, two distinct objects will be correctly perceived to be appearing and disappearing. In addition, the type of transformation perceived indicates how identity was achieved. Several experiments have shown that rigid transformations are preferred, supporting the notion that this is the usual basis of object identity. For instance, the alternation of a large polygon and a small polygon of the same shape produces the experience of a single polygon approaching and receding – a rigid translation in depth – rather than changing size (Shepard, 1984). Alternating a rectangle and a trapezoid produces the experiences of a single rectangle rotating in depth rather than changing shape (Ohmura & Saigo, 1982; Warren, 1977). Alternating a square and a diamond (Ohmura & Saigo, 1982) or polygons at different orientations (Farrell & Shepard, 1981; Shepard, 1984) produces the experience of rotation in the plane. The rigid motions are "ecologically valid" (Warren, 1977): the transformations are precisely those that could occur naturally for a single object. For instance, two different size objects can be due to the same object at two different distances. They are also precisely the same transformations that I have argued will be successful in the McCollough effect.

If conditions do not allow the interpolation of a rigid motion, such as the absence of an ecologically valid transformation (e.g., a triangle and a circle) or a very fast rate of alternation (not enough time to instantiate a rigid motion), then a single object in motion is often still seen. Now though, it will appear as if the object is undergoing a non-rigid plastic deformation or shape change, such as a circle turning into a triangle. Shepard (1984, p. 430) argues that "... the system will continue to identify the two views and hence to maintain object conservation, but only by accepting weaker criteria for object identity."[4] Typically, such motions are less likely to occur and when they do they are reported less "vivid" or "good" or "continuous". The research on object identity in apparent motion suggests that for the McCollough effect even stimuli such as a square and a cross may be accepted as referring to the same object, though in nature they never can. Such an effect should be harder to obtain and not as compelling.

This is precisely the result obtained recently. Siegel et al. (1992) report successfully inducing a contingent color after-effect using the square and cross stimuli that were previously ineffective (Foreit & Ambler, 1978). They suggest that the earlier researchers did not find an effect because they used a color-matching test procedure which is not as sensitive as the procedure Siegel and colleagues used: a psychometric function shift.[5] The newer procedure was previously shown effective for measuring small effects (Allan, Siegel, Collins, & MacQueen, 1989). Note first that the color-matching procedure used in the earlier experiment by Foreit and Ambler was sensitive enough to detect an after-effect when the stimuli were a single vertical bar and a single horizontal bar in the same experiment. Color matching has been a common test procedure for the McCollough effect and has been used to demonstrate color contingent on many aspects including orientation, spatial frequency, and motion. This suggests that vertical and horizontal bars will be more effective than a cross and a square, when all other variables are held constant. (Siegel et al.'s study did not include color paired

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[4] The situation in apparent motion arguably forces very weak criteria to be acceptable for identity, because the alternative interpretation of two distinct objects appearing and vanishing repeatedly may be judged more implausible than a single object moving, no matter how odd the transformation required to turn one stimulus into the other. A similar situation may present in the McCollough effect. The alternation of two stimuli repeatedly may eventually convince the visual system that even if the two stimuli are not normally thought of as referring to the same object, it may be better to do so than to accept all the coincidences otherwise.

[5] In color matching, a subject changes a color patch, or chooses a color patch, to match the shade of pink or green or white seen on the (achromatic) test stimuli. The change in the match before and after induction typically serves to measure the effect. In Siegel et al.'s testing procedure, subjects gave a forced-choice red or green response to several stimuli which were different shades of pale pink, green or white. The change in the probability of responding "green" before and after induction was used to measure the effect.

with oriented lines for comparison.) Above it was argued that a cross and square can never refer to the same object – if objects remain rigid. However, given the evidence from apparent motion, it appears that even non-rigid transformations can lead to the inference that a single object is involved. We expect such effects to be smaller in magnitude. It is for these reasons that demonstrating color contingent on the forms (Siegel et al., 1992) required an especially sensitive test procedure not needed for orientation, yet could still be achieved.

The refinement based on the criteria for object identity does not render the current explanation of the McCollough effect post hoc or untestable. As long as the criteria of object identity are provided from a different domain, such as apparent motion, the account of which stimuli will induce the effect will not be circular. Rather, they may even provide a richness to the theory allowing predictions not just of whether stimuli will or won't work, but which stimuli will work better than others. For instance, in apparent motion there is some evidence that one of the weaker criteria for identity may be topological transformations (Chen, 1985; Dawson, 1989), which are transformations which allow virtually any change to a form provided distinct points aren't glued, or continuous points disconnected. Apparent motion seen between a number of pairs related topologically, such as a circle and a square, was better than that seen between pairs not so related, such as a circle and a circle with hole in it. In the McCollough effect, we might expect then that the alternation of red circles and green triangles (topological transformation) should also be effective with special attention, and more so than the red square and green cross (non-topological transformation). Both should be weaker than orientation. Since the criteria for object identity used by the visual system needn't always match our intuitions about when two stimuli are similar (e.g., Chen, 1985), expanding the current explanation of the McCollough effect in this direction allows it to progress beyond the intuitions behind the theory.

4.2.7. *A final example*

This section will close with one final example of a failure to induce the McCollough effect. It is singled out from the failures discussed above because it involves color and orientation, which usually are highly effective stimuli. As noted earlier, a single vertical magenta bar alternated with a single horizontal green bar, both on a homogeneous black background, led to a contingent color after-effect (Foreit & Ambler, 1978). However, when the background and foreground colors were reversed, such that the two oriented bars were black on magenta and green backgrounds, then no color was seen on the test patterns (oriented black bars on achromatic backgrounds or achromatic bars on black backgrounds). Because both conditions involved pairing orientation and color with the same contingency relation and temporal parameters, a straightforward Pavlovian model predicts that they should be equally effective. The authors of the study suggested that color in a figure might be more important for successful induction than color on a ground.

According to the present interpretation, it is not figure/ground per se, but rather that when the figure changed orientation it did not change color – it stayed black. Consequently, there is no discrepancy. Though the background changed color, it did not clearly change orientation. A contingent color after-effect should occur if orientation of the background changes along with the color change. For instance, the alternation of a black vertical bar on a square magenta background with clearly visible borders and a 45° bar on a green diamond should be effective and would imply that it is the discrepancy rather than figure/ground which is the controlling variable.[6]

5. Existence of corrective mechanisms

Section 4 showed how the present approach helps understand and predict which stimuli will be effective in inducing the McCollough effect. The present approach also helps to understand why the McCollough effect can be induced at all. The question of function, purpose, or teleology has been of interest to some researchers (e.g., Held, 1980), especially recently (e.g., Barlow, 1990; Dodwell & Humphrey, 1990; Siegel & Allan, 1992). As discussed earlier, both perceptual learning phenomena reflect internal corrections of perceptual systems judged to be malfunctioning. A malfunction is inferred because the perceptual systems detect what would be an impossible state of the world. An object can not be in two places at the same time, and the selective reflectance of an object does not change with head tilt. These claims in and of themselves help answer the question of "What is the McCollough effect?" and go further than many accounts. Yet one may go even one step further back and ask: why should there be a corrective mechanism at all? Why have a mechanism prepared for the possibility of detecting an object in two different places when such an event is impossible? Why have a mechanism prepared to correct for observed color changes with head tilt? Surely not all impossible events are similarly prepared for. If you suddenly detected a yellow elephant flying upwards, it seems unlikely the perceptual system would adjust itself such that you would instead see a gray elephant not flying anywhere.

5.1. Prism adaptation

For prism adaptation, a widely cited reason for the existence of a

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[6] There are a handful of effects that do not yet have an obvious explanation in the perceptual learning framework. One is the finding that color can be made contingent on words, but not on non-words (Allan et al., 1989). A second involves lie transform pairs (Emerson, Humphrey, & Dodwell, 1985). Pavlovian models are also not particularly effective at accounting for these results.

corrective mechanism is growth (Held, 1965). Because of many bodily changes, including an increase in the distance between the eyes and in the length of the arms, objects may initially be mislocalized when systems accurate for the smaller-sized body are used. Moreover, because the growth in one modality may not exactly offset the growth in the other, there will be natural situations where an object is detected in two places at the same time by the two different modalities. Detection of this discrepancy allows the corrective mechanism to update the systems and restore them to veridicality for the new body size. In adulthood, prism adaptation may reflect vestigial remnants of this plasticity. Alternatively, it may serve the function of continuously correcting for spontaneous drift between vision and touch (Howard, 1982), where similar situations on a smaller scale may be present during adulthood.

5.2. McCollough effect

Reasons for the existence of the corrective mechanism have proved more elusive for the McCollough effect. However, for this phenomenon as well, Held (1980) has a thought-provoking suggestion. Held suggests that the McCollough effect results from the same process which corrects for color fringes produced by chromatic aberration of the eye. He notes that one source of chromatic aberration is that the optical axis of the lens is not aligned with the fixation axis, a common optic defect which will differ in different people and in two eyes of the same person. This misalignment produces the appearance of color fringes at edges. Critically, those color fringes will change with head tilt as the fixed "ocular prism" will move with the eye. Held shows that even before any type of training subjects see illusory colors which depend on the orientation of the stimulus grating with respect to the observer. Thus, there appears to be a naturally occurring situation that would create the otherwise impossible covariation between orientation and color. Consequently, it is sensible that a corrective mechanism already exists to handle the natural discrepancy, which can also be tapped by experimenters who artificially induce a similar discrepancy.

5.2.1. Primary and secondary constancies

The reasoning can be extended to contingent after-effects other than those involving orientation. For instance, properties of the visual system can potentially make the color of an object appear to change with viewing distance (Hurvich, 1981). To ensure color constancy, a mechanism which corrects for any color changes as a function of distance would be sensible. I suggest that laboratory demonstrations where color is made contingent on spatial frequency are reflecting this process. In general, the argument for the existence of all contingent after-effects may be formulated in terms of maintaining perceptual constancy. I distinguish here between two types of constancy: *primary constancy* and *secondary constancy*.

Primary constancy is the classic accomplishment where the perception of the property of an object remains constant despite continually varying input. For instance, size constancy refers to the perception of the size of an object remaining constant, despite changes in retinal size with distance. Color constancy refers to the perception of color of an object remaining constant despite changes in relative luminance which result from different lighting conditions. Secondary constancy has the same general description, except the cause of the varying input is less *direct*. Whereas different lighting conditions directly cause different luminance distributions, head tilt or change in distance is not causal in the same way. Yet they can cause a different distribution (as with misaligned optical axes) and will undermine the purpose of primary constance, if they too are not corrected. It may therefore be useful to insure that when you tilt your head, for instance, not only shouldn't perceived orientation change (primary constancy), but neither should perceived size or color or motion (secondary constancy). Due to the importance of keeping perception constant and veridical while besieged with bodily movements and changes in lighting conditions, these indirect corrective mechanisms may have proved adaptive.

5.2.2. Monocular and retinal dependence

Basic properties of the McCollough effect resonate with this view. As Held notes, the lack of interocular transfer is sensible because the optics of each eye is different and would need different adjustments for chromatic aberration. The high effectiveness of gratings as stimuli may be due to the fact that chromatic aberration is particularly visible at light–dark boundaries. The dependence on predominantly retinal, rather than spatial or real-world properties (Bedford & Reinke, 1993; Ellis, 1976; Harris, 1980; McCollough, 1965) is an often overlooked aspect of the phenomenon that is also made sensible in this view.

McCollough (1965) observed that when a subject tilted her head 90° during testing, the colors seen on the vertical and horizontal stimuli switched places. The data suggested that color became contingent on retinal orientation, which changes with head tilt, rather than the real and perceived orientation, which remains unchanged with head tilt. Recently, Bedford and Reinke (1993) pursued this finding by asking whether color *could be* made contingent on real-world orientation. They dissociated the two coordinates during induction by having subjects view red vertical and green horizontal stimuli with head tilted on half of the trials. This removed the retinal contingency entirely, leaving only a relation between color and spatial orientation. They found that induction led to little or no after-effect. A condition which instead removed the spatial contingency leaving only a color-retinal orientation linkage led to an after-effect as strong as the standard McCollough effect. That is, retinal orientation is sufficient for induction and, moreover, a clear statistical relation between color and only the real-world orientation does not lead to a contingent after-effect.

Consequently, any process that specifically evolved to gather new information from the world is unlikely to also underlay the McCollough effect, because the McCollough effect is clearly not about gathering new information from the world. Pavlovian conditioning may become an unattractive candidate as an explanation if, in fact, conditioning is a process whose function it is to apprehend new relations among events *in the world* (e.g., Rescorla & Holland, 1976; Rescorla, 1988). A phenomenon based entirely on retinal properties is naturally accommodated within the present framework of internal corrections and the general attainment of perceptual constancy.

6. Which system gets corrected?

Section 5 speculated on why the specific error correction mechanisms might exist at all, and section 4 discussed which conditions are necessary to trigger those mechanisms. The purpose of this section is to discuss the issue of *source* of the error. That is, in the present framework it is not enough for the system simply to decide there is an internal error. The system must also identify which system is in error in order to know what to correct. Interestingly, research relevant to the question of locus of error has been prolific in prism adaptation, but the question previously unformulated for the McCollough effect.

6.1. Prism adaptation

In prism adaptation, the issue can be seen in the extensive work on which system changes following exposure to the prism. When vision and touch disagree about the location of an object, agreement can be restored by changes either within vision or within the arm, or by a combination. Elegant work by Harris (1965) showed how empirically to distinguish between such visual and proprioceptive shifts. Since then, a predominant empirical question has been about which training procedures lead to which end-products (see Redding & Wallace, 1988a, 1988b, 1992a, 1992b; Welch, 1978). For instance, watching one's had through a prism continuously moving from side to side leads to a change that affects the arm, but seeing one's hand only at the end of a visually unguided (sagittal) ballistic pointing response, adds a change that affects vision as well.

How does the system decide which modality is to blame? Objectively, the mismatch between vision and touch is due to faulty visual information – the prism causes the visual location to be incorrect. However, there is no evidence that this information is used. Subjects aren't always aware they are looking through prisms, and even when they are it is not clear how this conscious knowledge influences adaptation – a process that needn't require conscious awareness of the error and may not be penetrable by such conscious knowledge when it exists. The training procedures in prism adaptation experiments rarely intentionally provide information to bias a judgement about which component is malfunctioning. Yet the system does seem to reach a decision by using whatever information is available, even if subtle.

For example, the position sense of the arm may be recalibrated more frequently than vision because vision is generally more precise than position sense (Harris, 1980). In addition, when the usual precision enjoyed by vision is reduced by having subjects look through stained glass which clouds vision, the usual dominance of vision over touch seems to reverse (Heller, 1982). Individual difference in modality precision influence which system will change (Warren & Platt, 1974; see Howard, 1982). Momentary attentional changes can also be influential – the modality to which one is not attending is more likely to change: "presumably there is more uncertainty about the position of something to which one is not attending than there is about the position of something to which one is attending" (Howard, 1982, p. 511; see also Canon, 1971). In the absence of better information about which system to blame, these decisions all seem sensible.

The availability of auditory information leads to even better decisions. Consider an experiment where half of the subjects heard a talking experimenter while they walked around a corridor looking through prism glasses, whereas the other half heard and saw the experimenter (Redding & Wallace, 1987). Subjects who saw the talking experimenter showed greater shifts specifically within the visual modality than subjects who did not. Walking around a hallway produces a visual–proprioceptive discrepancy, due in part to bumping into a wall that visually was localized further away (Redding and Wallace, 1988c). Without additional information, either modality can logically be at fault. The addition of a visual–auditory conflict, experienced by those who saw the talking experimenter, helps disambiguate that situation. Only a change within vision would resolve both the visual–proprioceptive and visual–auditory conflicts, thus making that the parsimonious inference. A similar logical inference may explain an early finding where subjects who wore prisms for an extended period of time first showed limb changes which were subsequently replaced by visual changes (Hay & Pick, 1966). The more precise visual modality wasn't blamed until a number of different conflicts, such as visual–auditory and visual–proprioceptive, pointed to the visual modality as the true source of error.

The examples demonstrate that considerable sophistication can be used to infer whether the detected malfunction is due to vision or touch. The system judged least precise through a combination of general biases, individual biases, and current information available from the world is the one blamed for the detected error. That particular system is then updated.

6.2. McCollough effect

Likewise for the McCollough effect, we expect there to be logical decisions about where the error resides. I suggest that the issue of "source of error" is manifested in the McCollough effect by an issue that is rarely made explicit, that of the "direction of contingency". When orientation and color covary, it is usually color that becomes contingent on orientation. But why this direction of contingency, when color and orientation are presented at exactly the same time? In fact, the reverse relation has been demonstrated (Held & Shattuck, 1971; Held, Shattuck-Hufnagel, & Moskowitz, 1982). Held and colleagues alternated a red grating tilted 15° to the right with a green grating tilted 15° in the opposite direction, rather than alternating the standard 0 and 90° gratings. During testing, red vertical lines appeared to lean to the left and green vertical lines appeared to lean to the right. In the standard McCollough effect perceived color is changed, and in the Held experiments perceived orientation is changed. Was it the smaller separations that led to the different result, or some other feature of the procedure? What is the logic behind why different procedures produce different end-products? Similar issues exist for other dimensions. Direction of motion may become contingent on spatial frequency, for instance, or spatial frequency contingent on motion.

An approach based on internal correction suggests that the perceptual system must act as an intelligent problem solver to infer the source of the error in order to determine what needs to be corrected. If the interpretation is that colors are inappropriately changing with head tilt, then color will become contingent on orientation to nullify that error. The reverse interpretation is also possible. The change from red to green may reflect a natural variation in illumination that occurs depending on height of the sun and the amount of water vapor in the atmosphere (Shepard, 1991, 1992).[7] Orientation of an object may be judged to change inappropriately with changes in illumination, which would lead to orientation contingent on color to correct that error. There may be more reports of color contingent on orientation than vice versa because it is a more likely source of error that colors will erroneously change with head tilt, than orientation with illumination.

Note there should be a measurable tradeoff of the two possible outcomes: conditions which lead to large color after-affects will lead to small orientation after-effects and vice versa. This raises a methodological issue. Until the factors that determine which system will be "blamed" are known, it is critical that experiments include test of *both* possible outcomes. The standard McCollough effect experiments test only for perceived color changes, which could produce misleading conclusions. For instance, whereas

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[7] Shepard suggests that the red–green and blue–yellow opponent mechanisms may exist to achieve color constancy in natural illumination which changes along red–green (water vapor), blue–yellow (direct sunlight), and white–black dimensions (daytime/nighttime).

strong color after-effects were found following induction with orthogonal orientations, the strength and incidence of the after-effects decreased with decreasing angular separations of 45°, 22° and 11° of separation (Fidell, 1970). The author suggested that patterns which are similar in orientation fail to stimulate different populations of edge detectors, which in turn was viewed as support for edge detector explanations of the McCollough effect. However, separations of 11° may not cause color to be contingent on orientation, but may instead produce orientation after-effects contingent on color; if true, then it is likely that different populations of detectors were stimulated. Given Held's result, it would not be an unlikely outcome. In general, any conclusion about the effectiveness of a procedure towards producing contingent after-effects, or the relative effectiveness of two procedures, requires measuring changes in orientation as well as color. Because in general we expect a tradeoff, small or non-existent changes in color may be accompanied by large changes in orientation.

Though it hasn't been an explicit issue, there are findings consistent with the general interpretation of searching for the source of the error. People with amblyopia show a greater color McCollough effect in the amblyopic eye than in the normal eye (Seaber & Lockhead, 1989). As in prism adaptation, more uncertainty about precision may make changes easier. The phenomenon of "blocking" usually used to support a Pavlovian interpretation can be viewed instead as a search for the underlying source of error. Blocking, a term from Pavlovian conditioning, refers to a phenomenon where the same conditioned stimulus can be made more or less effective depending upon the prior conditioning history with other stimuli. An analogy from contingent after-effects (Brand, Holding & Jones, 1987) is first to prevent vertical and horizontal gratings colored red and green during induction, followed by joint presentation of both the colored oriented gratings and colored moving spirals for a second induction phase. Following induction, testing on each stimulus separately showed color is less likely to become contingent on the moving spirals compared to a group where the first stage of induction with only the colored gratings had been eliminated. The oriented gratings are said to "block" learning about the moving spirals. (For other examples, see Siegel & Allan, 1985; Sloane, Ost, Etheriedge, & Henderlite, 1989; Westbrook & Harrison, 1984.)

The phenomenon of blocking is consistent with an error correction mechanism that must first identify the source of error. If color is already thought to change erroneously with orientation from the first stage of the experiment, then it would be parsimonious to assume the same cause in the second stage when oriented gratings are presented again. The examples from prism adaptation show the same type of logical and sophisticated decision processes. Perceptual learning and Pavlovian conditioning are probably only two of the many processes where blocking-like phenomena can be demonstrated. For instance, conscious problem solving leads to the same conclusions about causality in a situation with the same formal structure (Shanks, 1989; Shanks & Dickinson, 1987). Although one conclusion from these parallels is to argue that conscious problem solving *is* conditioning, or that the McCollough effect *is* Pavlovian conditioning, there are other interpretations. Distinct mechanisms may develop the same solution through convergent evolution if they are subject to the same external pressures (Futuyama, 1979). Causality in the world is subject to various physical constraints on time and other properties. Any psychological processes which involve judgements of causality should reflect those constraints so as not to systematically make the wrong inferences. Since many different psychological processes involve causal attributions, the rules about the causal inferences will all look the same.

PART II: WHAT GETS LEARNED

The last three sections followed from consideration of the present general framework of error correction and specific conditions necessary to get learning. The next three sections focus on the second novel principle, which involves the "content of learning" once correction has been initiated. To review, the second principle is that for both prism adaptation and the McCollough effect what is learned involves a new mapping between entire dimensions rather than the independent associations of individual stimuli. Whereas objects appear to play a critical role in getting correction started, dimensions are central to what gets learned. I have argued elsewhere (Bedford, 1989, 1993a, 1993b) that data on adaptation to prisms and other rearrangements of space are better explained with dimensions than individual stimuli. Here, I suggest that the McCollough effect is better understood that way as well. I begin with a detailed section on "contingency manipulations" in the McCollough effect. This issue, like the issue of which stimuli are capable of inducing the phenomenon (section 4), has recently received a great deal of attention because it too is thought to distinguish between the two classes of theories.

7. Contingency manipulations

7.1. McCollough effect

7.1.1. The basic contingency finding

Skowbo and Forster (1983; see also Skowbo, 1984) conducted an experiment which manipulated the contingency, or logical relation, between the color-orientation pairs, and concluded a Pavlovian interpretation was wrong. In addition to the typical red-vertical pairs, they interspersed trials of just a uniformly colored red patch without the vertical lines (and likewise for green-horizontal and just green). They discovered that neither presenting an equal number of color-alone trials along with the orientation–color trials, nor interspersing nearly triple the number of color-alone trials, reduced the amount of color seen on appropriately oriented gratings. The after-effect strengths were equal to two different control inspections: one without any trials between orientation–color pairs and one where homogeneous achromatic stimuli were substituted for the color-alone trials.

To argue against a Pavlovian interpretation, the authors drew attention to the well-known fact from conditioning that it is not the *contiguity*, or mere pairing, of the CS and US that determines learning, but rather the *contingency*, or logical relationship, between the two stimuli (see Rescorla & Holland, 1976). In Pavlovian conditioning, manipulations which decrease the correlation between the two stimuli interfere with learning. For instance, interspersing trials of just shock along with the trials of shock preceded by tone reduces conditioning to the tone (Rescorla, 1968). Tone is less effective predictor of shock because shock appeared in the absence of tone as well as in its presence. By analogy, interspersing trials of a red homogeneous patch with trials that pair the vertical grating with red should decrease the green after-effect seen on vertical lines. Yet this manipulation has failed on more than one occasion to interfere with induction of the McCollough effect (Skowbo & Forster, 1993; Siegel & Allan, 1987). (Recently, a different, but related, manipulation was used by Siegal et al., 1992, to interfere with the McCollough effect. This experiment will be discussed in section 7.1.3.)

7.1.2. The dimension interpretation

In the present view, the data suggest that *individual stimuli* are not what is associated. If individual stimuli are what is associated, as in a Pavlovian model, then the system would learn that vertical lines and red color go together in the sense that they are likely to *appear and disappear* together.[8] When two individual events are correlated, four permutations together determine contingency. On each trial, each of the two stimuli can either be present or absent; if we assume for convenience that one stimulus is a CS and one a US then the four permutations are: presence of CS and presence of US; presence of CS and absence of US; absence of CS and presence of US; absence of CS and absence of US. No other information is needed to determine if a logical relationship exists between the two stimuli. For instance, if the CS and US co-occur often, but the frequency of occurrence of US is just as high in the absence of the CS, then there is no logical relation between the two stimuli despite the accidental pairings of the CS and US on some trials. The McCollough effect experiment found that even when red ("US") is equally likely (or even less likely) to occur in the

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[8] That would be the interpretation if a "simultaneous association" model is used. If a successive association model is used instead, then the interpretation changes from red and vertical appearing and disappearing together to the prediction of red by vertical. For either interpretation, the subsequent argument remains the same.

presence of the vertical grating ("CS") than in its absence, learning to the vertical grating still occurred. This should not occur according to the 2 × 2 contingency analysis. I suggest this implies that the presence of one event (vertical) is not correlated with presence of another event (red).

Instead, what is correlated are entire *dimensions* of orientation and color. The presentation of a color without an orientation, as in Skowbo and Forster's experiment, would then be interpreted as the presentation of a "Y" value without an "X" value; "absence of orientation" is not a value along the dimension of orientation. That is, the trial is simply a missing data point. Consider an analogy of calculating the correlation between height and weight by recording the height and weight of a large number of people. If the weight data are missing for a few people, or even for many people, the detected relationship between height and weight remains unchanged. Those missing values do not affect the calculation. While the presentation of red alone trials would decrease the correlation (contingency) between the stimuli "vertical" and "red" it should not decrease the correlation between the dimensions "orientation" and "red–green color opponency". What is learned is not that vertical lines and red color appear and disappear together, but rather that *if* color and orientation co-occur, then the values of one dimension are related in a particular way to the values along the other.

7.1.3. Pavlovian alternative

Proponents of a Pavlovian model have explored different explanations for the core finding that interpolation of red-alone stimuli did not reduce the strength of the McCollough effect. First, it was thought (Siegel & Allan, 1987) that a longer training period might be needed because in Pavlovian conditioning interference from US-alone trials is not always apparent early in training. But they found that lengthening training did not change the results. Next, it was thought (Siegel, Allan, Roberts, & Eissenberg, 1990) that a more appropriate way to reduce the contingency was spatially rather than temporally. There are at least two different ways to apply Pavlovian conditioning to the McCollough effect: simultaneous and successive associations. Paradigms which use successive associations are the most familiar: a biologically important stimulus, such as food, is preceded in time by an initially neutral stimulus. More recent paradigms which use simultaneous associations pair two stimuli both of which are relatively neutral, and present them both at exactly the same time (Rescorla, 1981). Siegel et al. point out that interpolation of trials containing only the unconditioned stimulus, a temporal manipulation, may only be effective for successive associations. They suggest that McCollough effect may be more like simultaneous associations, in which case a spatial manipulation may be more effective. In their study they reduced the contingency spatially by extending the red color beyond the confines of the grid. They found that the McCollough effect was not reduced, thus disproving their hypothesis.

Most recently (Siegel et al., 1992), a somewhat more complicated explanation was put forth. Briefly, they point out that in conditioning one account of how US-alone trials reduces the amount of conditioning to the stimulus is through conditioning to the background. They also point out that McCollough effect experiments are conduced in the dark where only the relevant stimuli are present, whereas in Pavlovian conditioning experiments there are many background stimuli present as well. Note, first, that this analysis should predict that if a McCollough effect experiment were conducted in the light, like Pavlovian experiments, then, like Pavlovian experiments, many background stimuli would be present and now presentation of color-alone trials should diminish the effect. This was not the experiment conducted by the authors, and it seems highly unlikely that this predicted outcome would occur. What Siegel et al. did was to add a second stimulus present throughout induction to serve as a background stimulus. Interspersing these color–stimulus trials did diminish the after-effect. However, this result should not be a surprise to anyone. By using color–stimulus trials rather than color-alone trials, the experiment essentially replicates "blocking" – a phenomenon already known to occur and discussed earlier (see section 6.2).

In the view that Siegel, Allan, and Eissenberg were exploring, interpolation of US-alone trials and blocking are traceable to a single explanatory framework (see Rescorla, 1972). It is possible that their latest explanation of why color-alone trials do not reduce the McCollough effect is correct; however, we are asked to believe an increasingly convoluted account of a rather simple finding. To make the account work, a model based on "successive associations" rather than "simultaneous associations" must be used, even though if one were making an analogy to Pavlovian conditioning simultaneous associations are a closer match. One must adhere to a particular view of US-alone interference that not everyone studying conditioning agrees with. We must also buy that for the McCollough effect only some stimuli can serve as background, even though no special backgrounds need be created for Pavlovian conditioning, and we are given no guidelines that come from the theory on how to pick these stimuli. The present interpretation is an alternative: individual associations between vertical and red are not formed at all.

7.1.4. More contingency manipulations

Interspersing red-alone trials during induction has no influence on the strength of the McCollough effect, but interspersing vertical-alone trials does diminish the effect (Siegel & Allan, 1987). This finding is also readily accounted for by the present interpretation based on dimensions rather than individual stimuli. While the presentation of a homogeneous red stimulus does eliminate the dimension of orientation, the presentation of achromatic vertical lines does not eliminate the dimension of red–green opponency. Vertical-alone trials are actually vertical–white trials and consequently will interfere with the vertical–red presentations. White is a value along the opponent dimension, namely the central point of neither red nor green. Thus, unlike a red-alone presentation, a vertical-"alone" presentation is not a missing value but instead provides new information about the relationship between orientation and color.

In general, we can predict when interspersing trials will or will not have an effect. Whenever you can successfully remove one dimension, those trials with the missing dimension will be completely uninfluential. On the other hand, whenever apparent removal of one dimension is really just the substitution of one value along that dimension for another, then those trials will affect the relation and hence the strength of the effect. For instance, if color is made contingent on a direction of motion rather than on orientation, such as up–green and down–red, then *both* the addition of motion-"alone" trials (achromatic moving stimuli) and of color-"alone" trials (stationary colored stimuli) should diminish the effect. The dimension of up/down motion, like that of red/green color, cannot be eliminated because even a stationary stimulus is a value along that dimension (the central point). To consider another example, if spatial frequency is made contingent on motion, such as up–wide and down–narrow, then motion alone (moving homogeneous patches) will not reduce the effect but spatial frequency "alone" (stationary gratings) will. Spatial frequency, like orientation, can be eliminated though by removing an extended pattern. Note that from a Pavlovian perspective it would appear as if sometimes CS-alone trials interfere and sometimes they do not. These predictions have not yet been tested.

7.2. Prism adaptation

An analogy to the contingency manipulations of the McCollough effect would be to have an object localized visually but not proprioceptively, or vice versa. While these manipulations are not referred to as contingency manipulations in prism adaptation, they are nonetheless done all the time. The intent has not been to determine if "proprioception alone" trials interfere with adaptation; instead there is an assumption that such trials will in fact not interfere with learning. Trials where visual feedback of the hand is withheld – that is, open loop pointing – are used to test subjects precisely because they are expected not to interfere with what has been learned. Such trials have been intermixed with regular trials to track the acquisition of adaptation. (Note that if spontaneous decay occurs, it is attributed to the mere passage of time, rather than an influence of vision or proprioception per se.) Neither the visual presentation of an object without getting to touch it, nor the felt position of the hand or some other object without getting to see it, is expected to interfere with adaptation.

According to the perceptual learning account, the logical relation that exists for pairs of spatial locations also involves dimensions rather than individual stimuli. The basic argument for color–orientation pairs was that we don't learn that red and vertical appear and disappear, or that the appearance of vertical signals that red is soon to follow. Rather, it is as if we learn that if color and orientation will be present together, then what goes with vertical will be a particular red, rather than some other color. Orientation and color do not always have to co-occur, but when they do the values of one dimension are mapped onto the values in the other according to a particular relation. This relation determines which contingency manipulations will and will not affect what we learn. Analogously for spatial tasks, the existence of a linkage between vision and touch does not imply that the two modalities always have to co-occur, but rather that *if* both looking and touching do co-occur, then the values from the two dimensions are arranged in a particular way. Objects are often localized visually without reaching for them, and are localized proprioceptively without vision when looking elsewhere or in darkness. Perhaps in this domain it is intuitively more obvious that visual and proprioceptive judgements of an object also do not go together in the sense of appearing and disappearing together.

8. One-pair training

An account based on mappings between dimensions assumes that one pair is a severely degraded input to the actual learning process. An account based on establishing individual associations assumes that one pair of associated stimuli is the core unit of learning. What happens when only one pair is used in training?

8.1. McCollough effect

One of the most salient features of the McCollough effect is rarely emphasized. The standard effect involves the alternation of *two* distinct color–orientation pairs, rather than just one. As noted, any account which is based on the association between individual stimuli assumes that the core phenomenon is a single associative connection. For instance, in a Pavlovian model, the two-pair induction reflects "conditioned discrimination". Two discriminable stimuli lead to two distinct outcomes, such as light followed by shock, but tone without shock. Effective conditioning requires explicitly pairing only one stimulus and consequence, such as trials of light followed by shock. The standard two-pair McCollough effect induction procedure then should be an unnecessary embellishment of the real phenomenon which involves one color and one orientation. Yet the majority of studies continue to use two pairs, and the relatively few studies that have investigated the properties of one pair training have found conflicting results.

An early study by Stromeyer (1969) found that pairing only vertical lines with red is in fact sufficient to elicit a green after-effect on a vertical achromatic grating – a finding that has since been replicated (Allan & Siegel, 1991; Ellis, 1977; Ambler & Foreit, 1978; Humphrey, Dodwell, & Emerson, 1989). However, Stromeyer also found that when the colors used were closer to pure yellow, the data were not as clear. Repeated presentations of a single yellowish red or yellowish green grid often produced no after-effect at all, even when induction with both the color-oriented pairs produced vivid color after-effects. No one has attempted to replicate those results. In addition, a more complicated contingent after-effect could not be induced with a single pair (Stromeyer & Mansfield, 1970). If an expanding moving spiral that is red on the left half and green on the right half is alternated with a contracting spiral that is green on the left and red on the right, then an achromatic expanding spiral will appear green on the left and red on the right, and an achromatic contracting spiral elicits the reverse colors. But when only one of these pairs was presented and alternated with periods of darkness, achromatic moving spirals did not elicit any perception of color. It appears that induction with one pair may not always be sufficient for all contingent after-effects, though this has never been systematically investigated.

Another source of conflicting findings concerns the effects of a single inducing pair on non-induced orientations, in those instances where a single pair is sufficient to induce a contingent after-effect. As discussed by Humphrey et al. (1989; see also Allan & Siegel, 1991), studies which pair only red–vertical alternated with darkness or a dark screen sometimes find a red after-effect on non-induced horizontal lines (e.g., Stromeyer, 1969), and sometimes do not (Ambler & Foreit, 1978). The conflicting results have occurred more recently as well; Allan and Siegel find the "indirect effect" when alternated with a black screen and Humphrey et al. do not.

According to the present interpretation, one pair is not the fundamental unit of this learning process. Rather, a single pair is a severely degraded version of connecting entire dimensions of opponent color and orientation. Consequently, ambiguity is created by using only one value from each dimension, which in turn can lead to different resolutions of the ambiguity in what seem to be very similar experiments and perhaps in different people.

Three sources of ambiguity follow from the present interpretation. One source concerns a decision about whether there should be any internal correction at all. According to the present interpretation, the impossible situation of having *different* (retinal) orientations of an object accompanied by different red/green colors produces the discrepancy. A single color–orientation pair may be judged to reflect this discrepancy anyway, but it needn't because there is nothing impossible about having an object with only one color. Chromatic aberration may be so common that minimal information involving orientation and color will initiate correction, whereas more complex displays such as the bicolored moving spirals may require less ambiguous evidence that an error exists as well as what the error is.[9]

Note that two pairs resolves this ambiguity. An illustrative example involves the alternation of a green vertical grating and a horizontal grating with the same color green, rather than the usually presented opposite color red (Humphrey, Dodwell, & Emerson, 1985). Following training, subjects did not see any color on either stimulus, but presentation of a single grating colored green (Humphrey et al., 1989) does produce a contingent after-effect. Whereas a single orientation may be ambiguous with respect to whether there is a discrepancy, the presentation of two orientations of exactly the same color should make it clear that there is not. If the object does not appear to change color when the retinal orientation changes, then systems are working properly and there is no error to correct. A model which assumes the core phenomenon involves only one pair would have a harder time accounting for this simple and intuitive finding. In Pavlovian conditioning, for instance, a procedure where an animal receives shock following both light and tone on separate trials would not produce an animal that was afraid of *neither* stimulus.

A second source of ambiguity concerns the identification of the relevant dimensions. Suppose a particular vertical grid is colored red. Assuming the judgement is made that there is an error, why should the inference be that color varies with orientation and not with spatial frequency (for example)? Two pairs disambiguate that problem. If the other pair is a horizontal grid, then orientation is relevant and if it is a grid whose bars are twice as wide, then it is spatial frequency. Presentation of a single grid could lead to either conclusion, the outcome of which would influence what is seen on non-induced stimuli. Experiments with one orientation and color where nothing was seen on the orthogonal orientations may be ones where spatial frequency was "blamed". Had spatial frequency been varied during testing instead, perhaps the indirect effect would now be apparent. Or viewed from the other perspective, a situation which produces a very strong indirect effect on non-induced orientations would be expected to produce little or no

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[9] There is also a methodological concern with all one-pair inductions. Humphrey et al. suggest that pairing green–vertical may also indirectly pair red–horizontal. The presentation of a green stimulus leads to a brief pink after-image when the stimulus is extinguished. Analogously, the presentation of a vertical stimulus shifts the balance of orientation coding away from vertical and towards horizontal. The authors suggest that this indirect red–horizontal pairing is responsible for the indirect effect, where the non-explicitly presented horizontal lines appear green. It seems possible then that the indirect pairing affects not only non-induced orientations, but also the induced orientation. One-pair induction may actually be pairing two orientations and colors. After-images have indeed been found to induce the McCollough effect (Day & Webster, 1989). Consequently, any investigation of the properties of one-pair induction, including its sufficiency, its effect on non-induced orientations as well as how it compares to two-pair induction may require elimination of the simple after-effects. One approach would be to introduce a pattern mask following each trial to override the imbalance of orientation coding mechanisms.

effect on non-induced spatial frequencies. The indirect effect has not been investigated for other dimensions, such as spatial frequency.

Assuming that the relevant dimensions have been guessed, there is finally ambiguity about the *relation* between those dimensions. A green color on a vertical grid provides little information about the color for other orientations. For instance, will the grid when viewed horizontally be red or will it be white? The inference made from the one induction pair will determine what color after-effect will be seen on non-induced orientations. Yet a single pair provides little information from which to extract the underlying relation between the dimensions.

8.2. Prism adaptation

An experimental analogy to "one-pair" consequences in this domain is initially hard to identify because most experiments on spatial adaptation involve training with a large continuous range of spatial positions. For instance, a subject may watch her hand moving from far left to far right through a prism, which provides information at many positions. However, in one study (Bedford, 1989) training was restricted to only one, two, or three discrete locations. The intent of the study was to determine if a mapping between spatial dimensions is reducible to a list of independent associations, in which case a single pair of locations is the fundamental unit of learning, or whether one pair reflects instead degraded input to a dimension learning process with additional constraints.

The primary conclusions were that one pair is degraded input, a mapping is not a collection of independent associations, and that the learning process instead involves calculating parameter values for relations between entire dimensions (See Bedford, 1989, 1993a, 1993b). To briefly summarize one experiment, subjects were trained that only one location was visually shifted to the right (e.g., $V = 0$, $P = -10$). If each pair is independent, then training should essentially have no influence on other locations, and we would expect a typical generalization gradient. Instead, generalization conformed to a rigid shift, such that pointing (motor space) shifted to all visual positions equally.

There has not been enough one-pair studies to determine if some of the same kinds of conflicting results that occur in McCollough effect studies will also occur here. Note though that many of the same type of ambiguities that result from only one input pair in the McCollough effect are also present here. There is ambiguity identifying the right dimensions. In the study on spatial adaptation (Bedford, 1989), the two intended dimensions were a set of horizontal positions from left to right as localized visually, and the same set of horizontal positions as localized proprioceptively. One of the one-pair training conditions required the subject to point further to the left whenever the visual stimulus appeared straight ahead. In the absence of additional information, the shift in pointing could become associated with the vertical position of the stimulus, the circular shape of the target light, or any other feature, rather than the horizontal position intended by the experimenter. Assuming the dimensions are guessed correctly, there is also ambiguity about the relation between those dimensions. For instance, if the visual location is 5° and the proprioceptive location is 15°, then this pair could reflect a uniform displacement, where all visual locations are displaced 10° with respect to proprioceptive locations ($Y = X + 10$), but it can also be an instance of magnification where proprioceptive locations are three times as far away as the visual ones ($Y = 3X + 0$). Alternatively, it is consistent with a bizarre many-to-one mapping where all objects are to be found at 15°, regardless of the visual position ($Y = 0X + 15$). There are an infinite number of functions that can accommodate the single point, and consequently no single correct way to generalize.

The data from the one-pair study, however, suggests that one-pair training is still sufficient to produce change, despite the ambiguities. Rich internal structure, as well as pre-experimental learning, may substitute for the external information which is lacking. This suggests that the existence of a one-pair McCollough effect does not imply that a single red–vertical association is the core phenomenon. Ambiguity in the input needn't preclude learning.

While the dimension interpretation does not preclude learning from a single pair, it does imply that single pairs are not independent of one another, both for learning new spatial mappings and for contingent aftereffects. The outcome of training with more than one pair cannot always be predicted based on the outcome of each pair in isolation. For learning mappings between spatial dimensions, there is evidence that individual pairs are not independent (Bedford, 1989, 1993a). For the McCollough effect, there is some suggestion that each pair is not combined additively to produce the standard two-pair effect (Ambler & Foreit, 1978; Stromeyer, 1969) but not all the data are consistent (MacKay & MacKay, 1977). A systematic test of independence would require both consideration of the methodological problem with one-pair induction (see footnote 9) as well as combining a wider variety of colors and orientations than the standard McCollough effect.

9. Two-pair training

For both prism adaptation and the McCollough effect, training with two pairs of stimuli resolves some of the ambiguity found with one pair. Yet in the present interpretation, two input pairs still provide degraded input. They provide incomplete information about the nature of the mapping between the two dimensions.

9.1. Prism adaptation

There are few two-pair exposure procedures in the domain of spatial adaptation, as noted earlier. Bedford (1989, 1993a, 1993b) trained subjects under a variety of two-pair conditions and that research pointed to a dimension-learning process with constraints. For instance, in one manipulation, during training a target localized visually at 15° to the right was found proprioceptively 25° to the right and a target localized visually 15° to the left was found proprioceptively 25° further to the left. Testing at untrained locations between the two trained locations revealed that behavior (pointing) always conformed to a linear function. Although there were an infinite number of potential generalization patterns, the data suggested a linearity preference when forming mappings between visual space and motor space. Because two visual–proprioceptive pairs provide only ambiguous or underdetermined experimental information about the mapping for all of space, this training condition allows the constraints that the system itself brings to bear to be uncovered.

Indeed, the interpolation data from two-pair experiments are so clean that if, though some historical accident, two-pair experiments had come *first*, one could easily be misled into believing that the core phenomenon of prism adaptation involved the association between two pairs of spatial locations. I believe this has essentially happened in the McCollough effect.

9.2. McCollough effect

The McCollough effect training procedure, which uses only two pairs for all experiments, may be viewed in an analogous way. Two pairs underdetermine the mapping between orientation and red–green dimensions, but is sufficient along with the internal structure to assume a particular relation.

Note this leads to a different interpretation of colors seen on non-induced orientations. In this view, a testing stimulus that is slightly off from vertical looks less saturated, and a 45° stimulus looks white, and so forth, because of an *active process of rule-governed application*. The underlying function extracted applies equally to all orientations, not just those used in training. Contrast this with the more standard account that the colors seen on non-induced orientations are due to *generalization decrement*, where the effect will simply fade as the stimuli get increasingly dissimilar from the training stimulus. It is difficult to tease apart these two different interpretations using the standard McCollough effect induction. One possibility is to compare the variances at induced and non-induced orientations. If connections between the individual stimuli are what is learned then the explicitly trained stimuli must be stored and behavior between trained and untrained stimuli discernible in some way, such as through variance. If the individual training stimuli are used only to extract the underlying relation between the dimensions, then it should be impossible to determine from performance which stimuli were explicitly trained and which were not.

More importantly, whereas many of the current experiments use orthogonal orientations, and nearly all use complementary colors, the current approach calls for two-pair studies where orientations and colors are systematically varied – for instance, vertical green lines alternating with horizontal green lines of half the saturation rather than the opposite color red. Is linearity a preferred relation for dimensions of orientation and color as well as for visual space and motor space? If so, the interpolated colors on non-induced orientations will be linear under a variety of different two-pair training conditions. If not, then investigation of the patterns of generalization can be used to uncover the built-in functions and constraints. This is a different type of research question than has been asked previously about the McCollough effect.

10. Multiple-pair training

Because standard two-pair induction is here viewed as a degraded case of dimensional learning, this approach dictates a new line of research for the McCollough effect which uses multiple induction pairs. For instance, a training procedure which presents not only red vertical lines and green horizontal lines, but additionally white diagonal lines, and lines of intermediate orientation colored with appropriate reds and greens of intermediate saturations, should yield the strongest contingent after-effects. Conversely, any approach which instead emphasizes single pairs as the fundamental unit predicts added difficulty as the number of pairs is increased and additional bits of information need to be stored.

Using multiple pairs also allows the investigation of different relations between color and orientation, particularly non-linear relations which are not possible with two pairs. Is the error correction reflected by the McCollough effect constrained to linear corrections? Can non-linear relations be acquired? Will a linear function be imposed on non-linear mappings between orientations and red–green color as they often are for spatial dimensions?

Finally, increasing the number of induction pairs to the limit would produce continuous information, whereby color is gradually and continually transforming from green to less green to red as a function of continuous change in orientation of lines. This continuous induction procedure more closely parallels standard prism adaptation experiments and perhaps also natural situations where the discrepancy would be encountered.

11. Conclusion

What type of theory is the present perceptual learning account? Two classes of models for the McCollough effect were summarized earlier:

associative and neural adaptation. Is the present interpretation an instance of the associative or the non-associative class of theories? I suggest it does not fit cleanly into either division, as they are typically construed. Associative models usually imply that two entities never before connected are brought together and a link forged between them. In this sense, "dimension learning" as applied both to the McCollough effect and to prism adaptation is non-associative. Orientation and color are already related before experimental training trials, as shown by Held's (1980) empirical demonstration. Indeed, it is the pre-existing relation between the two dimensions that motivates the system to detect any deviation. In the spatial domain, there is already a linkage between vision and proprioception which is manifested not only by normal (open-loop) visual-motor coordination in adults, but also by infants. On the other hand, dimension learning is associative in the sense that pairs of values from each continuum presented in close temporal proximity provide the information for new learning to take place.

The apparent contraction can be reconciled by considering that "associative learning" is too often viewed as synonymous with Pavlovian conditioning. This in turn leads to undue emphasis on forging a connection between previously unconnected entities. If the entities to be associated are two individual stimuli, as in conditioning, then those two stimuli can either be unconnected, or connected in an excitatory or inhibitory fashion. Consequently, a central issue becomes whether there is or is not a relation between them and uncovering the conditions necessary to establish the connection. Once they are connected, there appears little left for associative processes to do. Contrast that with associating entire dimensions, where many stimuli from each dimension become connected. Here, rather than just an excitatory or inhibitory relation, there are countless ways in which the stimuli can be connected and reconnected. This shifts focus from simply whether there *is* a relation to the *type* of relation. When more broadly construed, associative learning processes can do more than establishing initial connections. It is likely that both Pavlovian conditioning and dimension learning are two instances, but distinct instances, of learning processes that should be considered associative.

Whereas the associative class of models have been equated with Pavlovian conditioning, the non-associative class has been largely equated with physiological models (e.g., Stromeyer, 1978). This is an unusual contrast because all the theories of the McCollough effect, whether they be Pavlovian or non-Pavlovian, associative or non-associative, learning or non-learning, require physiological instantiation. Physiological and non-physiological models are different levels of discourse, rather than adversarial. The dichotomy may have developed in part because the early physiological model, fatigue within double-duty detectors that code for both orientation and color, contained within it an implication for psychological theorizing. Such a view precludes associative learning in the narrow sense, since color and orientation are already processed together. Not all physiological models need have the same implications for psychological theorizing: more recent models (e.g., Barlow, 1990) are consistent with an associative view. Because reduction to physiological underpinning do not substitute for a psychological theory – both levels are necessary – it is not surprising that one of the few developed psychological approaches to the McCollough effect, Pavlovian conditioning, has held appeal.

A dichotomy of "associative/Pavlovian" and "non-associative/neural adaptation" classes then is not a very useful categorization of learning processes in general. An alternative classification involves three broad divisions (Bedford, 1993b, pp. 2–5). One division involves processes that function to apprehend new information about the external world. Examples include Pavlovian conditioning and (explicit) memory. The second division consists of processes designed not to learn about the world, but instead to improve upon the perceptual systems themselves. It is here that prism adaptation and the McCollough effect belong, as well as others such as Helson's adaptation level, and the entrainment of circadian rhythms. (The third category involves matching internal states with those of others, including language acquisition and motor skills.) Because of their vastly different functions, learning mechanisms known to help learn about the external world, such as Pavlovian conditioning, may have only limited applicability to those responsible for internal correction, such as manifested by the McCollough effect.

Consistent with this very general view would be Dodwell and Humphrey's (1990) recent work on the McCollough effect. They attempt to answer two questions: what is the effect for, and what are its physiological underpinnings? The second question is beyond the scope of the present article. Considering the first question, a similarity between their view and the current view is that both interpretations explicitly assert that the McCollough effect reflects a process of internal error correction, along with only a few others (Held, 1980; Warren, 1985). However, the two views differ on what they believe triggers the correction. According to Dodwell and Humphrey's interpretation, in the long-run there is statistically a zero correlation between orientation and color (see also Savoy, 1987, section 4). Induction trials pair orientation and color such that after a number of trials there will be a non-zero correlation which is discrepant from the usual zero correlation. According to the present interpretation, there is an internal constraint that objects do not change color when the head is tilted. Consequently, if they appear to do so, the sensory information is discrepant from knowledge about the world. Rather than assuming the constraint is wrong, it is assumed the internal systems must be wrong, which leads to the internal correction. This view leads to a number of reinterpretations and predictions that do not follow from Dodwell and Humphrey's analysis. For instance, on the issue of which stimuli are effective at inducing contingent after-effects (section 4), the present view predicts that the two stimuli of different colors need to represent the *same object* for a discrepancy to be detected.

Another aspect of Dodwell and Humphrey's interpretation concerns use of Helson's adaptation level theory. Similarly, Warren (1985) suggested that both Helson's adaptation level and the McCollough effect are two examples of the more general "criterion shift rule", whereby the norms of a perceptual dimension change in the direction of previous stimulation. One appeal of these ideas is that it calls attention to an entire perceptual *dimension* – a view which is central to the present interpretation. Note that many other studies also use the term "dimension" to refer to orientation or color, without explicitly considering how that may differ from models which use individual stimuli. While Helson's adaptation level or the criterion shift rule operates on dimensions, it is a process concerned with changes that result from repeated stimulation of only a single dimension. Such processes differ from those which map one dimension into another. Both Helson-like processes and McCollough-like processes are likely instances of perceptual learning, which differs from other types of learning (See Bedford, 1993b). It is likely not a coincidence that both processes use dimensions; as noted earlier, perceptual systems in general operate on dimensions and any update of these systems may be expected to operate at the level of dimensions as well.

This article began with the hope that progress in the field of cognition could be used to advance perceptual learning the way it has for other areas. I believe it has done this by helping to solidify ideas that perceptual learning is a unique domain-specific learning process, distinct from other kinds of learning. Perceptual learning has (1) different *inputs* from other learning processes: incoming data must provide evidence of an internal error, often by violating internal constraints that we know must be true of the world; other learning processes have no such requirement. (2) The processes have different *internal states*: learning affects stimulus dimensions in their entirety, unlike other learning processes that can operate on individual stimuli. (3) They differ in *output*: it is perception which gets modified by experience, not thoughts, knowledge, or reflexes as in other learning processes. (4) And finally they differ in *function*: the purpose of perceptual learning is to correct internal malfunctions or to otherwise sharpen the ability to perceive whereas other more familiar learning processes serve to apprehend new information about the world. Thus, processes involved in perceptual learning also improve our ability to interact with the world, but they do so indirectly rather than through a direct representation of environmental properties. The perceptual learning processes keep the sensory systems in good working order to allow world learning to occur.

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