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Discussion

Are long-term changes to perception explained by Pavlovian associations or perceptual learning theory?

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Discrepancies and surprises lead to learning. But when will they lead to *perceptual* learning? Bedford (1995) argues that all changes in perception that result from experience must meet special requirements not needed for other more familiar types of learning. However, it has been suggested recently (Allan and Siegel, 1997b) that certain facts argue against the perceptual learning view, and for a Pavlovian conditioning view, of the McCollough Effect, a visual illusion that results from experience. Closer examination shows that this is not the case.

1. Perceptual learning

According to the perceptual learning theory, all changes in perception that result from experience require the detection of an internal error which in turn depends upon a discrepancy between sensory information and an a priori internal constraint. Once initiated, learning involves a mapping between entire perceptual dimensions rather than individual associations. As applied to the McCollough Effect, we have a constraint which dictates that the color of an object should not appear to change when only the orientation of that object changes on the retina. The constraint helps to maintain perceptual constancy in the face of common internal eye defects that can lead to that very event but would disrupt color constancy if not corrected. The sensory information provided by the McCollough Effect violates that constraint; two orientations presented in two colors is interpreted as a single object changing color as the retinal orientation changes. The vertical-green and horizontal-red pairs are used to extract a relation between the two entire dimensions of orientation and opponent red-green color to correct the detected error in color perception.

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2. McCollough manipulations

2.1. Objects and transformations

Concentric circles colored red alternating with radiating lines colored green will lead to an aftereffect where the circles look pink and the lines look green. Bedford (1995) noted that the finding has no simple interpretation within the perceptual learning framework where the 2 patterns must be viewed as different manifestations of a single object to get the aftereffect. However, these patterns have the feature that all points of intersection are right angles ('Lie transformations'). Consequently, at the local level orientation is critical and color may really be contingent on the orientation rather than the pattern itself (see Broerse et al. (1994) for recent supporting evidence). Color contingent on orientation is easily accounted for in the perceptual learning framework, as discussed by Bedford (1995). Alternatively, Lie transformations may be at the root of object identity. Although at present it is counterintuitive that concentric circles and radiating lines should ever be judged as referring to a single object, theories can progress beyond intuition. Provided that the criteria of object identity – when 2 samples separated in time are judged to refer to a single object – come from an independent source, there is no circularity. Lie transformations and groups have been argued to be relevant for a general theory of perception; how this might relate to objects is at present unclear.

2.2. Objects and form

According to the perceptual learning account, color should not be easily made contingent on arbitrarily chosen forms (e.g. red square, green cross); the extent to which 2 patterns are judged to refer to a single object determines the extent to which those 2 patterns can induce a contingent aftereffect. Allan and Siegel (1997b) assert that contingent aftereffects are readily induced with form, citing 5 studies to support the claim that it is uncontraversial that forms lead to the aftereffects (Allan and Siegel, 1997a; Broerse and Grimbeck, 1994; Humphrey et al., 1994a; Siegel et al., 1992, 1994). However, the investigators of two of the studies conclude on the basis of their own experiments, as well as Allan and Siegel and colleagues' studies, that color is in fact *not* made contingent on form at all, but on local orientation of contours: "Contrary to Siegel et al.'s interpretation, however, the illusory colors seen on the square are not contingent on the square, they are contingent on the orientation components of the induction cross" (Broerse and Grimbeck, p. 83) and "In conclusion, we believe that recent findings of MEs ['McCollough Effects'] to forms are based in fact on local orientation and color contingencies" (Humphrey et al., 1994b, p. 89).

The other 3 studies are from the Allan and Siegel laboratory, their apparent success may then be due to local orientation effects. The 2 sets of investigators discussed above independently suggested that Seigel et al.'s subjects fixated the forms which lead to multiple retinally dependent local orientation effects (specifically, 4 independent pairs of color-contour orientation, where each contour orientation pair consists of a 'corner' rotated 90°; see Broerse et al., 1994). Allan and Siegel (1997a) have also since demonstrated the afterffect when subjects scan the form which Humphrey et al. do not find (condition 3). But the former investigators had subjects scan during testing as well as induction, which raises the possibility that multiple local orientation effects have become dependent on eye movements which subjects may have repeated exactly during testing. In addition, as discussed in Bedford (1995), the testing procedure used in their laboratory is atypical for the McCollough Effect and is suited to detecting very small effects that other more widely used measures cannot detect.[1] If there is a genuine square and cross effect, it is clearly much weaker than vertical and horizontal effects.

2.3. *Two grids of the same color*

If both vertical and horizontal grids are green during induction, Humphrey et al. (1985) report that color aftereffects do not occur. While this finding makes little sense from a Pavlovian view, the perceptual learning account (1995) was able to explain it: there is no obvious error to be corrected because the object remains the same color when tilted on the retina. Since the 1995 paper, and apparently inspired by the arguments presented there, Allan and Siegel (1997a) report that a same-color effect can be obtained. They argue that their induction phase was longer and that their test procedure was more sensitive than the earlier failure. Yet long induction phases and sensitive test procedures are simply not necessary for the standard McCollough effect; if they are required here, then again we may be dealing with a substantially different or at least much weaker phenomenon. Similarly, they note a procedural difference of whether one or two orientations are presented during test, but that cannot entirely account for the earlier failure because the standard ME can be demonstrated easily regardless of whether one or two orientations, or one or two colors, is present on each test display. Because of caveats about the Allan and Siegel procedures, as well as the earlier contrary Humphrey et al. finding, the data on 2 orientations with the same color are not yet clear.

In the perceptual learning view, 2 pairs of 2 *different* colors indicate unambiguously that there is an internal error to be corrected (one object in two different retinal orientations should not change from red to green), whereas 2 pairs of the same color former situation does not (one object in two different retinal orientation which remains green does not provide evidence of an internal error, though can be taken that way). The 2 pairs, one color, is more like a one pair induction where there is similarly ambiguity about whether any internal error exists at all, and should not lead

[1]New evidence that their assessment procedure produces color aftereffects that other more typical procedures cannot replicate comes from a recent article on text-contingent color aftereffects (Humphrey et al., 1994a). Allan et al. (1989) found that color could be made contingent on words but not on non-words. Humphrey et al. showed that getting the effect at all required using their sensitive technique: They were able to replicate the word phenomenon using the Allan et al. method but when the test consisted of having subjects report what color they saw on each word, a cruder historically more common procedure, they could not replicate the phenomenon. (They went on to show that even with the Allan et al. method, the effect could be traced again to local orientation and not to wordness.)

to an effect which is stronger than one pair, one color. As with one pair inductions, the ambiguous induction conditions may lead to ambiguous outcomes.

2.4. *Black bars on colored backgrounds*

The perceptual learning account was able to explain the finding that a vertical red bar on a black background alternated with a horizontal green bar on a black backround led to color contingent on orientation, but a vertical black bar on a red background paired with a horizontal black bar on a green background did not (Foreit and Ambler, 1978). In the latter condition, the bar remained black as it changed orientation which would not signal an internal error, and the background, while it changed color, did not clearly change orientation; this too would not signal an internal error. Recently, in another experiment apparently inspired by the perceptual learning account, Allan and Siegel (1997a) found that the oriented black bars and colored backgrounds can lead to aftereffects if the black-to-color ratio is controlled for. Assuming that the effect can be replicated with a different paradigm, it is not problematic for the present account. A square background or a circular backround or a vague ill-defined backround in this situation can be interpreted to change orientation as it changes color, because a square tilted 90° is still a square, a circle remains a circle, and a vague ill-defined backround likewise would remain the same. Under the perception that both figure and ground changed retinal orientation together, an internal error would be indicated and an aftereffect obtained.

2.5. *Color and the lightness of a frame*

If a red patch is surrounded by an achromatic light frame and a green patch surrounded by an achromatic dark frame, a white patch will look green when tested with the light frame, and the white patch will look pink with the dark frame (Siegel et al., 1992). In the perceptual learning account, this is sensible because a single object (the patch) should not appear to go from red to green when the illumination changes from bright (as indicated by the light frame) to dim (as indicated by the dark frame). If sensory information seems to suggest otherwise, as this induction procedure does, an error will be detected and corrected to preserve color constancy. The explanation is analogous to the basic orientation explanation, where a single object should not appear to go from red to green when the head tilts. If sensory information seems to suggest otherwise, an error will be detected and corrected to preserve color constancy. The error corrections are what we call contingent aftereffects.

2.6. *Stimuli that have equal luminance*

In the typical ME, the green bars (for instance) and the black bars not only differ in 'color', but also in luminance. If the grids are instead constructed so that the black and colored bars have the same luminance, contingent aftereffects do not occur (see, e.g. Stromeyer, 1978). Allan and Siegel (1997b) argue that this failure provides evidence against the perceptual learning view: 'Induction with isoluminant grids, as surely as induction with high-contrast grids, violates the constraint that an object does not change color when the head or object is tilted.' However, isoluminant displays diminish many perceptual effects such as Mach bands and stereoscopic depth. A difference in luminance between adjacent regions is required to define a proper edge in vision generally, for reasons that are not completely understood. If luminance differences are needed to define an edge, and edges are clearly needed before orientation can be defined or determined, and orientation is clearly needed to generate the McCollough Effect, then it is plain why isoluminant displays will not induce the McCollough Effect. To argue that this failure provides evidence against the perceptual learning theory is like arguing that the failure to get the McCollough Effect when viewing displays with the eyes closed provides evidence against the perceptual learning theory.[2]

2.7. *Non-visual effects*

The perceptual learning account relied largely on visual examples because there is more data both on contingent aftereffects and on internal constraints in vision. As Allan and Siegel note, an auditory pitch contingent aftereffect can be produced by alternating a high-pitch tone of long duration with a low-pitch tone of short duration. To extend the theory to auditory after effects, parallels between vision and other modalites need to be explored further. Kubovy (1981) argues that space in audition is not analagous to space in vision but is instead analogous to time in vision, whereas it is pitch in audition that corresponds to space in vision. The pitch contingent aftereffect in audition then may be more analagous to the orientation (i.e. space) contingent aftereffects in vision than it first appears. Second, the idea of 'auditory objects' (see Kubovy, 1981) can be pursued further. Third, constraints involving events may be relevent because auditory information often signals meaningful events. What is critical in the perceptual learning theory is not objects per se, but the detection of internal errors. Constraints allow one to solve the paradoxical issue of using the sensory systems to detect an error in sensory systems, as discussed earlier, and constraints often center around objects. Constraints may also center around events, although less research has been conducted.

2.8. *Dimensions and correlations*

If the standard McCollough Effect paradigm is modified by having some of the displays have color but no oriented grid, the size of the effect is not reduced. According to the perceptual learning theory, these extra trials do not intefere because color without an orientation is a missing data point for a system that

[2]Allan and Siegel (1997b) claim that the Perceptual Learning Theory was supported by a selective reporting of the published literature. This is incorrect. The failure of Lie transformations to induce the effect was mentioned in the original paper, the issue of form and contingent aftereffects was discussed extensively in the original paper, and isoluminant displays were judged irrelevant as discussed above. Remaining arguments come from research published after the time the theory appeared, in many instances inspired by the challenges that theory provided. The new data do not the argue against the theory.

takes as its inputs pairs of orientation and color, just like a height value without a weight value would be a missing data point for a system that takes as inputs pairs of height and weight values. Allan and Siegel (1997b) argue that the perceptual learning account does not explain the influence of what they call context cues. In their 'context' experiments, when vertical grids are presented in red they are shown surrounded by a light frame and when horizontal grids are presented in green they are surrounded by a dark frame; the light frame is also shown for trials of red without vertical, and the dark frame is shown for trials of green without horizontal. With these frames present, color-alone trials do diminish the size of the aftereffect. They argue: "chromatic gridless square presentations would be missing data points both when a context is provided and when a context is not provided".

According to the perceptual learning account, chromatic gridless presentations in the presence of the frames remain missing data points for the correlation between dimensions *orientation and red-green color*, but the frames provide information on another relation; there is now a perfect correlation between dimensions *lightness and red-green color* throughout the entire experiment. In fact, there will be more trials of this relation because the chromatic gridless trials are missing data points only for the orientation–r/g color connection, not for the lightness–r/g color connection. When the color of an object changes from red to green, which it should not, it could be 'blamed' either on the orientation in which it is viewed or on lightness conditions under which it is viewed. Knowing which is critical to know what error to fix. Twice as many trials of the lightness–r/g color mapping (if for instance 1/2 the trials are chromatic gridless trials) point to attributing the error to lightness. Thus this 'context cue' decreases the strength of the color aftereffect contingent on orientation not because it decreases the correlation between orientation and color but because it is increasing the bulk of the evidence in favor of a different conclusion, that lightness, not orientation, is responsible for the erroneous color shift.[3]

2.9. Dimensions and one-pair induction

Successful contingent aftereffects have almost always used 2 values from each of two dimensions. Is this a historical accident? Why is the phenomenon not usually demonstrated with only one pair? In a Pavlovian account, the core phenomenon involves a single pair, e.g. vertical and red. In the perceptual learning account, the core phenomenon involves 2 entire dimensions, e.g. orientation and red/green color. Systematic studies of contingent aftereffects which genuinely restrict training to only a single pair (one color value, one orientation value) have not yet been under-

[3]Whether this is *like* 'blocking' the way other cognitive domains show blocking-like effects as I have argued (Bedford, 1995), or *is* Pavlovian blocking as Allan and Siegel would argue, is a matter of debate. Allan and Siegel are also incorrect that the view is based on a misunderstanding of the Rescorla–Wagner model and applications to 'correlation' and the McCollough Effect. In addition, Bedford suggested that conducting the correlation experiment in an illuminated room would provide an appropriate context based on a straight-forward application of Pavlovian conditioning. Finally, note that Bedford did not claim that the *Rescorla–Wagner* model is convoluted. The model is a set of equations. What is convoluted is the application of certain Pavlovian ideas to perception.

taken (see e.g. Allan and Siegel, 1997b; Bedford, 1995; Humphrey et al., 1985). If the perceptual learning view has forced that exploration, that is a positive consequence.

3. Pavlovian associations

There are many specific problems with a Pavlovian account (e.g. Siegel et al., 1992) of perceptual learning phenomena. For instance this view cannot predict which pairs of stimuli will lead to perceptual contingent aftereffects and which will not. Pairs that work are attributed to the well-known arbitrariness of conditioning, and pairs that do not work are attributed to the well known limits to that arbitrariness – selective associations. With no independent way to specify which associations will be effective for contingent aftereffects, selective associations as applied to perception become circular. Another problematic example is the Bedford and Reinke (1993) finding that pairing the *retinal* orientation of grids with color leads to the McCollough Effect, but pairing the *perceived* orientation of the grids with color does not. Why would 'conditioning' work for retinal orientation but mysteriously go away for perceived orientation?

More generally, Pavlovian conditioning has undergone a great deal of changes; it is no longer clear where Pavlovian conditioning ends and some other learning process begins. For instance, the idea behind a 'UCS' – that of a powerful biological motivator such as food – was extended to include more neutral stimuli. Is 'Pavlovian conditioning' even one learning process? This would be a good time for advocates of a Pavlovian interpretation to clearly state the tenets of their current theory, including what types of evidence they believe would disprove it as an explanation of perceptual learning phenomena. Adding to the confusion, the Pavlovian conditioning interpretation of contingent aftereffects is now more often referred to as 'the associative' theory (e.g. Allan and Siegel, 1997b). This is puzzling because lots of theories can be associative that are not Pavlovian conditioning. The perceptual learning theory can also be referred to as an associative theory of the McCollough Effect because it too requires the pairing of color and orientation in close temporal proximity. Does this terminological shift reflect a theoretical shift? Finally, Pavlovian conditioning can be used to refer to a procedure, a phenomenon, or an explanation. Unless one is explicit, the application of 'Pavlovian conditioning' can become more of a religion than a theory.

The idea of a simple individual association still holds appeal. One profitable approach would be to drop the jargon and baggage of Pavlovian conditioning as has happened elsewhere in cognition. Instead of accepting the approach as a package, individual ideas hold promise. For instance, the Rescorla–Wagner model applies to many different domains (e.g. Siegel and Allan, 1996); no one would argue that all those areas *are* conditioning. Instead, these ideas may point to more general ways we learn. Dissociating the general rules from the unique rules of peceptual learning would lead to more advances than trying to force a phenemonon into a questionable framework. There are many gems hidden in the volumes of

Pavlovian literature, and I admire those who are hunting, but there is also a lot of fool's gold.

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